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**DEVELOPING A VIRTUAL MODEL OF A SECOND ORDER SYSTEM TO
SIMULATION REAL LABORATORY MEASUREMENT PROBLEMS**

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ABSTRACT

Most of the student's educational exposure is to well behaved, deterministic problems with known results. Most courses expose students to material in compartmentized modules (chapters of a book) with exercises/problems (at the end of the chapter) where the majority of the material is readily found in the compartmentized module. Unfortunately, real world problems never fit this simple mold. Laboratory is the perfect place for students to become exposed to real world problems and solutions to those problems. Laboratory is the perfect place to put all the student's knowledge of basic STEM material to the test. However, many times the real world measurement is much more complicated than the textbook problems and students often struggle with methods and procedures to solve a given problem (with no answer at the back of the book).

This is true for a mechanical measurement of a simple second order mass, spring, dashpot system which is measured with displacement and acceleration instruments in an existing mechanical engineering laboratory exercise. The measurement is plagued with measurement errors, drift, bias, digital data acquisition amplitude/quantization errors, etc. In order to understand the basic underlying measurement and associated "problems" with the measurement, a simple simulation model was developed. The simulation model allows the students to define a basic second order system and then add different types of "problems" (drift, bias, quantization, noise, etc) to the measurement to see their effects. The simulation module further allows the student to "cleanse" the distorted data using common measurement tools such as coupling, filtering, smoothing, etc. to understand the effects of processing the data. The simulation model is built using Simulink/MATLAB and allows a simple GUI to modify the model, the "problems" added to the data and the "cleansing" of the data, to obtain a better understanding of the problem and tools to process the

data. The simulation model is presented and discussed in the paper. Several data sets are presented to illustrate the simulation module.

I. INTRODUCTION

The mission for all instructors is to educate their students in the most efficient manner possible. Teaching techniques should challenge, educate and promote innovative thinking from students. Students learn best with hands-on projects and problems with practical purpose [1]. Laboratory based, experimental problems are very good for demonstrating many aspects of engineering problem solving.

Students must be afforded the experience of problems that require them to formulate solutions to problems with no specific straight-line structure to the solution – they must learn how to "think outside the box" [2]. The laboratory environment is an excellent opportunity to force the students to "think on their own". Real-world laboratory exercises and experimental approaches clearly show that there is not always an "answer at the back of the book". While students at times become frustrated by this, they learn that they need to employ many of their STEM skills in order to solve even the simple problems. Industry advisors have clearly identified the need for students to be exposed to a real-world laboratory environment where modern instrumentation and computers interface in performing data acquisition and data reduction [3, 4, 5].

Experiments play a very critical role in validating analytical models and hypotheses. Students must feel comfortable in a laboratory environment and must not feel foreign to lab equipment, instrumentation, etc. Students must also feel comfortable formulating solutions to real engineering problems using all of the STEM tools available to them. The STEM must become an integral part of their learning process throughout their entire educational and professional careers –

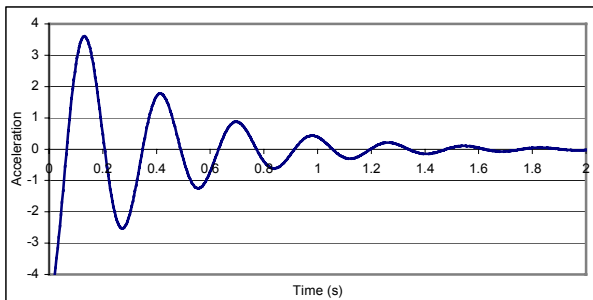
the students must, in essence, “live the material” every day and in every course. The disjointed presentation of the material must cease if this is to happen.

However, at times, these real-world measurements are too confusing to the student. They do not know how to break down the measurement and its related problems into pieces that can be dissected and interpreted.

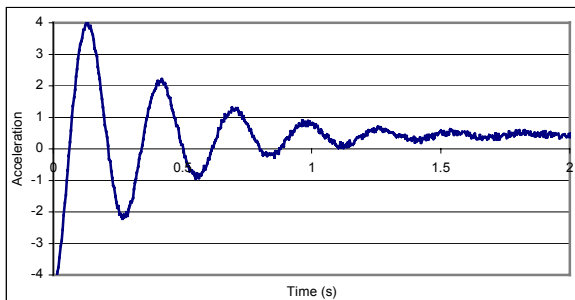
II. PROBLEM FACED

Many structural applications involve displacement and acceleration response as important design parameters. The relationship between these responses is well known from a theoretical standpoint and numerical assessment is fairly straightforward and well behaved. Any educational curriculum addresses these fundamental concepts in science and introductory engineering courses.

These responses can also be acquired in a laboratory environment with displacement or accelerometer recording devices to obtain system response. A typical analytically derived response shown in Figure 1(a) may be significantly different than the corresponding laboratory measurement shown in Figure 1(b) due to a variety of factors. While not easily seen with the naked eye, the laboratory measurement system response contains the basic expected analytical response in Figure 1(a) but also contains noise and bias which are easily seen along with drift that is not so obvious in the measurement at first glance.



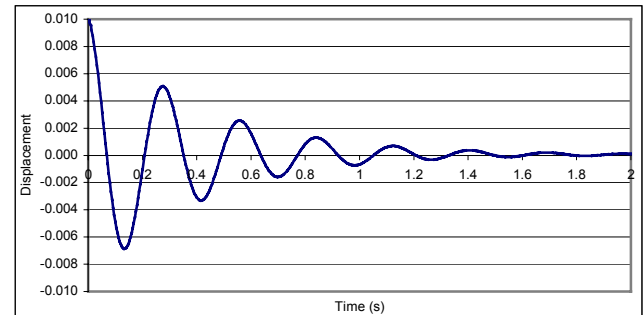
(a) Analytical Response



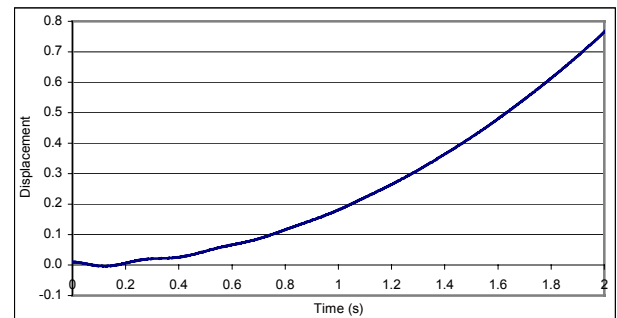
(b) Measured Laboratory Response

Fig. 1 – Typical Acceleration Response from a Second Order System

If these acceleration signals are integrated to obtain displacement, the response is shown in Figure 2(a) and 2(b), respectively. Notice that perfect analytical response is as expected but the laboratory measurement response is not what would be expected. Students sometimes struggle with these issues since the effects that cause the erroneous response are not easily identified. Of course, the measurement shown here is one that is fairly well behaved – typical student measurements are generally not as well behaved and cause considerable difficulty in regards to interpretation.



(a) Analytical Response



(b) Measured Laboratory Response

Fig. 2 – Typical Displacement from Integration of Acceleration Response

The measurements acquired in the laboratory are not as “clean” as those from an analytical representation. The degradation of the signal is heavily dependent on many factors related to instrumentation, signal conditioning and of course noise effects. Upon acquiring data that contains other effects superimposed on top of the actual expected response, students are often confused as to how to handle these effects. Generally, none of the previous courses have addressed any data with these effects included with the data. While most of the effects can be treated with very simplistic models, the students are overwhelmed with all the effects occurring simultaneously. Another important consideration is that there is NO answer at the “back of the book” and often both the student and professor need to interpret the data to determine what effects appear to be prevalent in the data (although in many cases the true answer is

not known and is generally different each time a new set of data is collected further complicating the issue).

Typically students become frustrated with this open-ended environment. The students don't stop to think about what the expected result was, what errors could possibly have been introduced by the instrumentation and signal conditioning, and what effects are totally unexpected. In order to solve the problem and understand how effects of the laboratory compromise the measurement made, the problem must first be addressed from an analytical statement of the predicted response. The various effects expected due to the introduction of instrumentation, signal conditioning, etc. can then be analytically added. The students need to ask

- 1) Why does the data look like it does?
- 2) What could affect the data from a measurement standpoint?
- 3) What bias or offset could the instrumentation contribute?
- 4) Is there any drift on the data?
- 5) What other external effects appear to be superimposed on the data?
- 6) How can the data be cleansed to address some of the issues?
- 7) Should the cleansing be done through filtering or done analytically?

While these are all relatively simple effects that can be seen on the measured data, students do not always realize that most of their problems are really fairly straight-forward and hit the panic button before thinking. (Of course, the Monday morning quarterback professor is in a position to better understand the problem and needs to mentor or guide the students through the problem.)

Fig. 3 shows a Mechanical Engineering Laboratory problem in which the displacement and acceleration of a simple single degree of freedom mass-spring-dashpot system are measured. An LVDT and accelerometer with a digital data acquisition system are used. The laboratory exercise requires the acquisition of the response data and then the integration/differentiation of the signals for comparison to each other. Of course the measurements are riddled with all the potential problems that could possibly be encountered. This laboratory exercise proves to be quite difficult and is the culmination of many other laboratory projects which contain pieces of issues addressed in this one lab. Since real-world measurements have many effects, some controlled environment would be beneficial for the students to better comprehend the problems they face.

In order to help students better deal with these types of issues, a Simulink/MATLAB model was generated to encompass many of the real world measurement and instrumentation issues that might typically be encountered in measuring the response of a single degree of freedom mass-spring-dashpot system. The basic model is described in the following paragraphs.

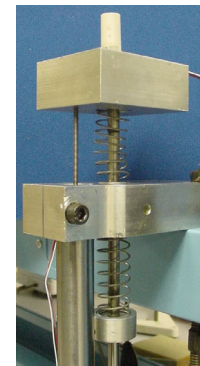
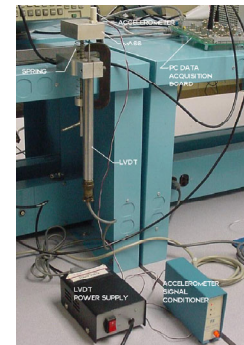
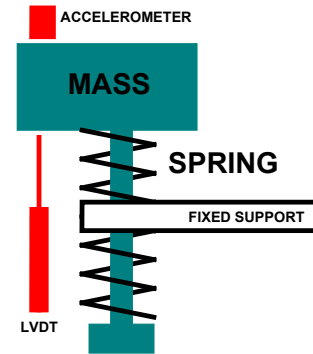
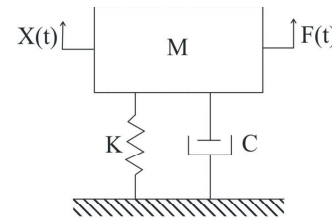


Fig. 3 – Photo of MCK System along with Schematic of Configuration

III. VIRTUAL MEASUREMENT SYSTEM (VMS)

This Simulink model (and the graphical user interface “GUI” used to control it) attempts to analytically replicate the real-life problems seen with data from these transducers. These problems can then be more easily identified and understood. The dynamic system modeled is a simple single-degree-of-freedom (SDOF) second-order system like the mass-spring-dashpot shown in Fig. 3. To this basic model, components are added which simulate the output from an LVDT and accelerometer placed on this system. Various corrupting factors can then be added and varied to observe the resulting effect on the output. The use of a simple RC circuit low-pass filter to reduce sinusoidal noise can also be explored.

The basic Simulink model is shown in its entirety in Figure 4. It consists of three basic sections: the central portion which describes the SDOF second-order dynamic system (in blue), the simulated accelerometer output (in red), and the simulated LVDT output (in green). These sections will now be discussed in more detail. The properties of these various components can be altered using the GUI.

III.1 THE CENTRAL SYSTEM OF THE VMS

The main part of the Simulink model is shown in Fig. 5. This is the foundation of the Simulink model: a single-degree-of-freedom, second-order system. This system has three characteristics which determine its response: its mass (m), damping (c), and stiffness (k). For loading considerations, three different types of inputs can be applied to the system: a step function, an impulse, or a displacement input.

III.2 THE ACCELEROMETER PORTION OF THE VMS

The section of the model which imitates the behavior of an accelerometer is shown in Fig. 6. The acceleration of the system is converted to an accelerometer output by multiplying by a sensitivity to produce an “ideal” accelerometer output in volts. This accelerometer output is considered ideal because it assumes that the accelerometer perfectly measures the acceleration. In practice, however, the accelerometer output could be corrupted by any of several problems. The problems which are modeled here are bias, drift, and random noise.

The bias introduced is a DC offset of the signal which can be caused by the accelerometer’s signal conditioning circuitry. This DC bias could be eliminated by AC coupling the signal, but for the measurements here this feature is not considered available. In addition to DC bias, the drift may manifest itself as a small linear decay over the time that the measurement is acquired. And of course, random noise can also be introduced which is common in most measurement systems.

These factors are combined, and the resulting accelerometer output is referred to as the “real-world” accelerometer output, because it simulates issues that are seen in actual measurements. The plot shown in Fig. 1(b) is an example of this.

III.3 THE LVDT PORTION OF THE VMS

Fig. 7 shows the section of the Simulink model which models the LVDT. Similar to the accelerometer, an “ideal” LVDT output is produced by multiplying the displacement of the system by a sensitivity in V/m.

The bias introduced is a DC offset which can be attributed due to incorrect adjustment of the LVDT null position. Another important issue of electrical 60 cycle noise can also be added to the LVDT signal. These factors are combined and the resulting “messy” signal is referred to as the “real-world” LVDT output. Since the signal contains noise, an additional low pass filter is included for the LVDT output signal. The filter appears as the “RC circuit low-pass filter” subsystem in Figure 7.

III.4 THE LOW PASS FILTER PORTION OF THE VMS

Fig. 8 shows the contents of this subsystem. This is a simple first-order system, an RC circuit, which acts as a low-pass filter. By changing the RC value of this model, the cut-off frequency of the filter is changed. The input and output points before and after the filter are available to view the frequency response of the filter.

IV. THE GRAPHICAL USER INTERFACE OF THE VMS

While the elements of the Simulink model can be changed manually, a GUI was developed to allow for easy, systematic adjustment of the various parameters that affect the model. This GUI is shown in Figure 9 and further elaborated upon in the following sections. The interface consists primarily of slider bars (analog adjustment of parameters) and text boxes (specific values of parameters) which can be used to change the parameters of the model.

IV.1 THE SYSTEM CHARACTERISTICS GUI OF THE VMS

This section of controls, shown in Fig. 10, allows the user to set the mass, damping, and stiffness properties of the mass-spring-dashpot system. It should be noted that the damping can be set to a negative value, which will result in an unstable system.

IV.2 THE INITIAL CONDITIONS AND FORCING FUNCTION GUI OF THE VMS

The initial displacement of the system and the forcing functions (impulse or step) can be set using the controls shown in Fig. 11

IV.3 THE CONTROLS GUI FOR THE ACCELEROMETER OF THE VMS

The properties of the accelerometer can be set using the controls shown in Fig. 12. The user can set the sensitivity of the accelerometer. In addition, a bias, or DC offset in volts, can

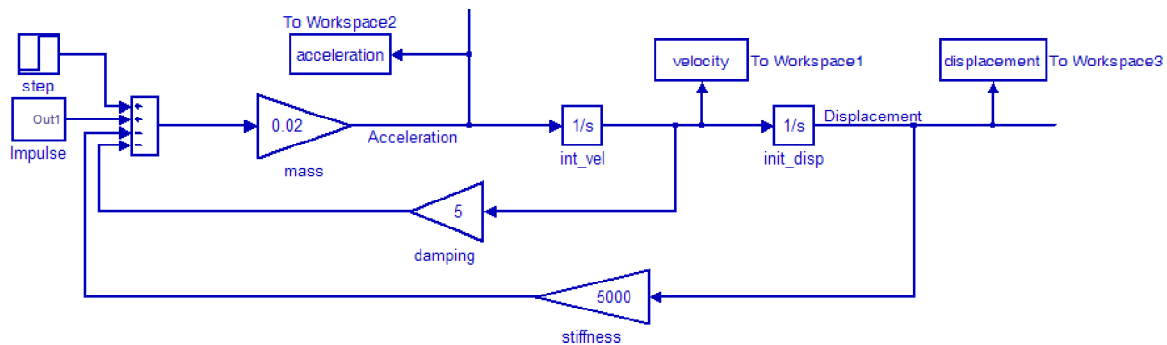


Fig. 5 - Portion of Simulink model which models the basic SDOF system.

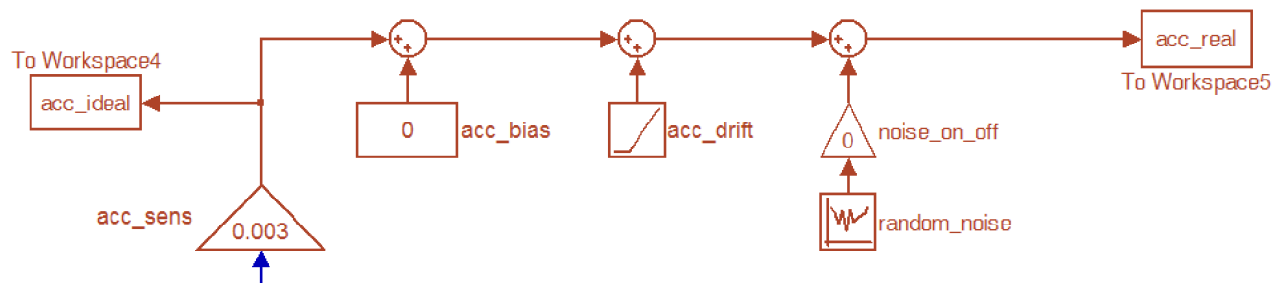


Fig. 6 - Portion of Simulink model which models the accelerometer.

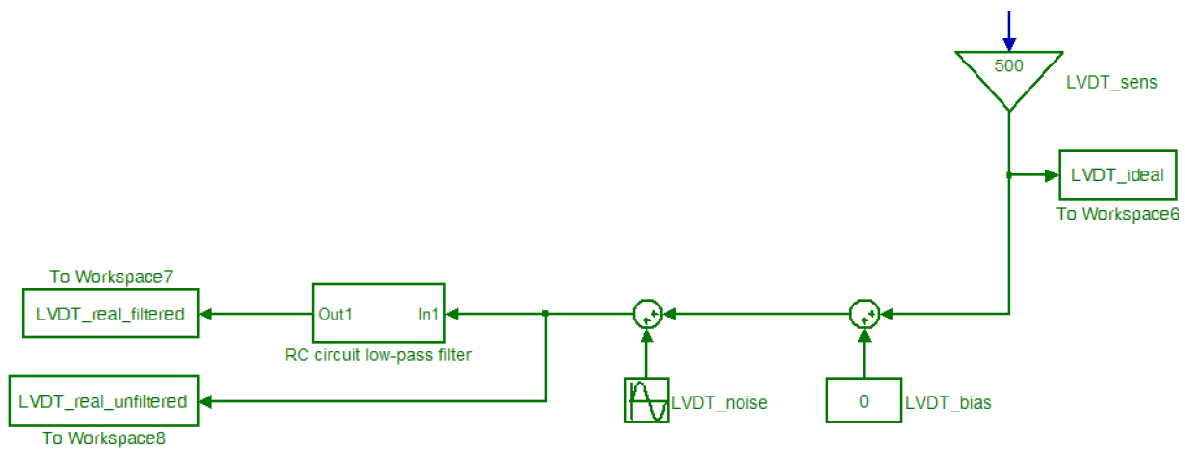


Fig. 7 - Portion of Simulink model which models the LVDT.

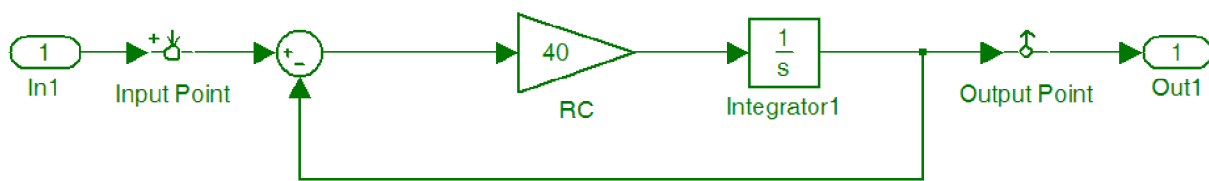


Fig. 8 - Contents of RC circuit low-pass filter subsystem.

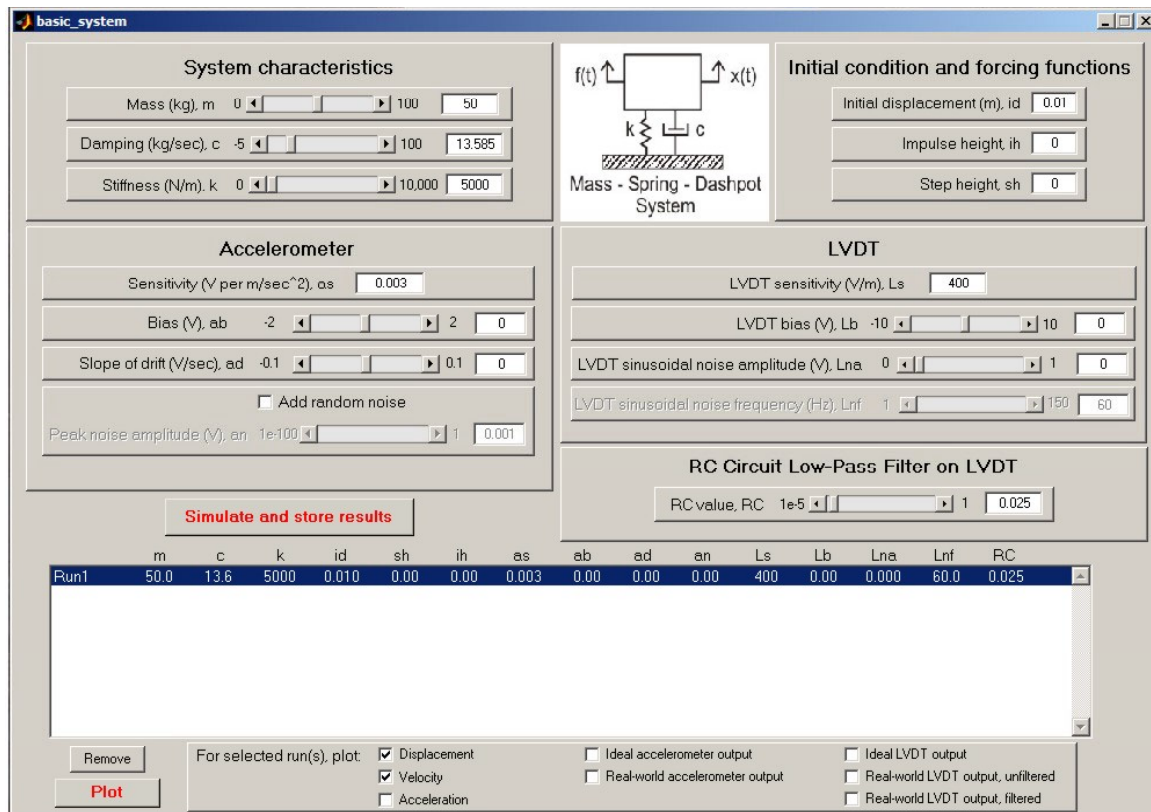


Fig. 9 - Graphical User Interface of Virtual Measurement System

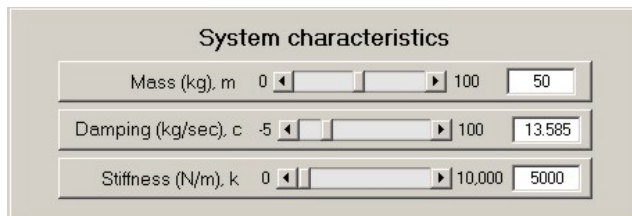


Fig. 10 - Controls for setting the system characteristics.

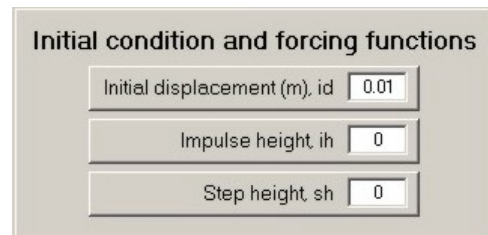


Fig. 11 - Controls for setting initial condition/forcing functions

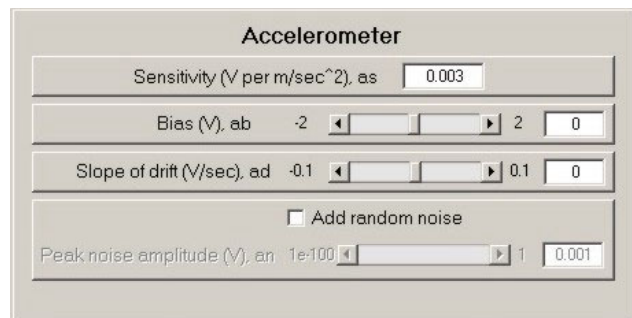


Fig. 12 - Controls for setting the properties of the accelerometer.

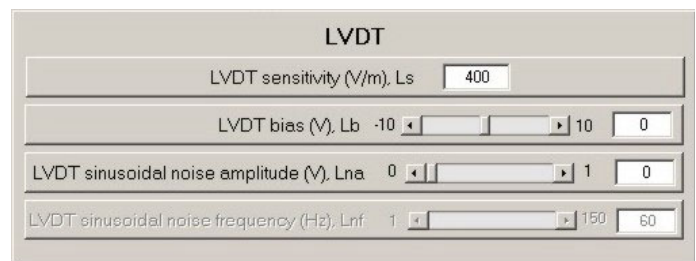


Fig. 13 - Controls for setting the properties of the LVDT.

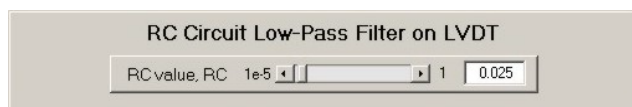


Fig. 14 - Control for setting the RC value of the low-pass filter.

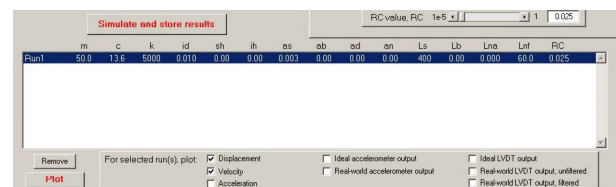


Fig. 15 - Controls for simulating, storing results, and plotting.

be added along with a drift which is specified as either positive or negative slope. Finally, random noise can be added to the to the accelerometer signal.

IV.4 THE CONTROLS GUI FOR THE LVDT OF THE VMS

The controls for the LVDT portion of the model are shown in Fig. 13. Similar to the accelerometer, the sensitivity of the LVDT can also be set. A bias or DC offset can be included along with a sinusoidal noise component.

IV.5 THE CONTROLS GUI FOR THE LOW PASS FILTER OF THE VMS

Fig. 14 shows the control to set the RC value of the low-pass filter circuit on the LVDT.

IV.6 THE CONTROLS GUI FOR RUNNING AND SIMULATION OF THE VMS

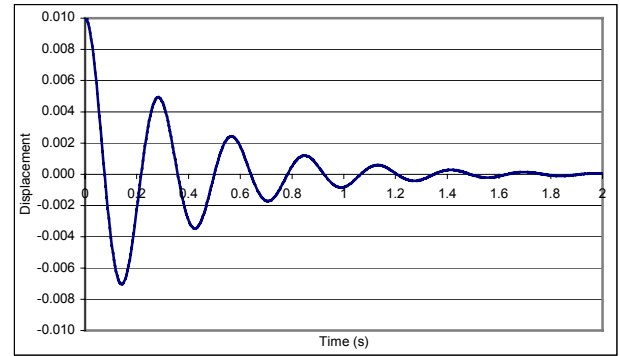
Figure 15 shows the controls for running the overall system. Multiple runs can be made for comparative purposes. Controls are available for plotting as well as storing of the results for further processing in other applications.

V. SAMPLE CASES OF THE VMS

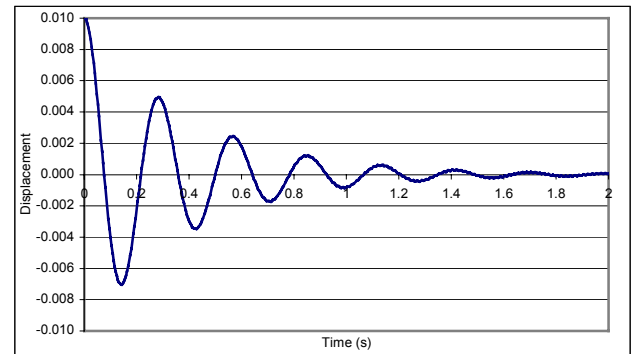
In order to show the use of the VMS system, two different data cases are presented. The first is a case for the LVDT and the second is for the accelerometer.

V.1 LVDT SAMPLE CASES OF THE VMS

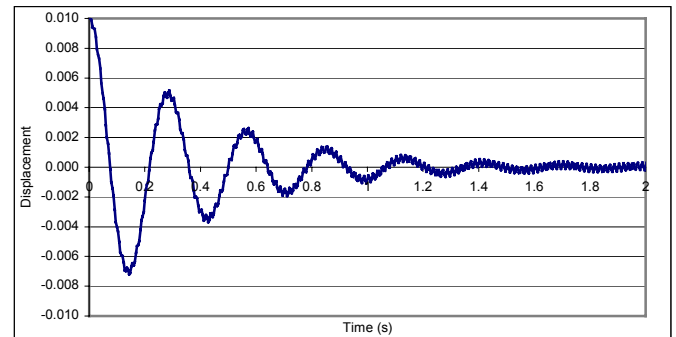
Real-world signals invariably have noise and in many cases there is 60 cycle electrical noise on data signals. This causes problems when differentiation is performed. Three subcases for the LVDT were considered here for measuring the response of a single DOF second order mechanical system. One with no noise at all, one with a fairly small level of noise and one with a fairly high level of noise. All three signals were generated as shown in Figure 16 (a), (b), (c), respectively.



(a) Displacement, no noise.



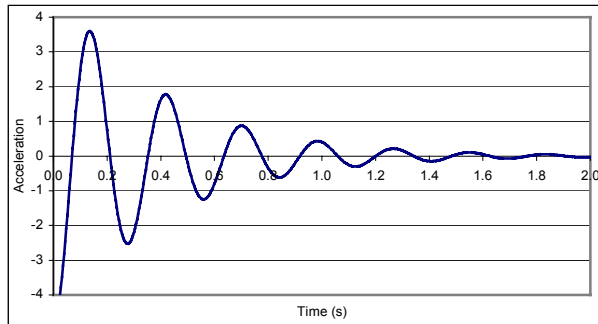
(b) Displacement, low level of noise.



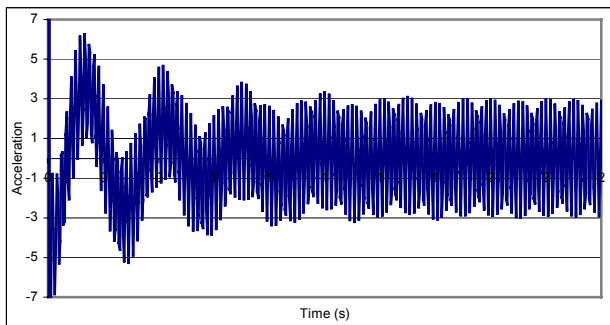
(c) Displacement, high level of noise.

Fig. 16 – Typical displacement response with varying levels of noise.

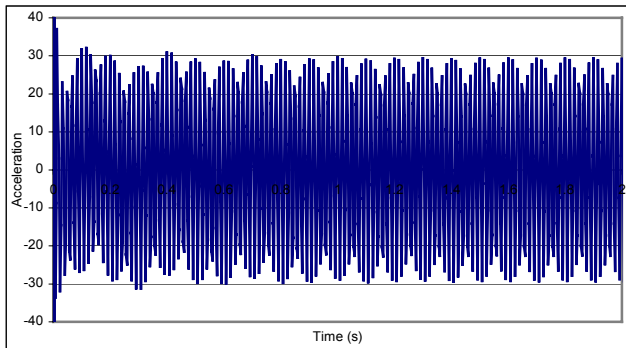
All three signals were then differentiated to see the effects of noise and its amplification in the differentiation process; these are plotted in Figure 17 (a), (b), (c), respectively.



(a) Differentiation of signal with no noise.



(b) Differentiation of signal with low noise.



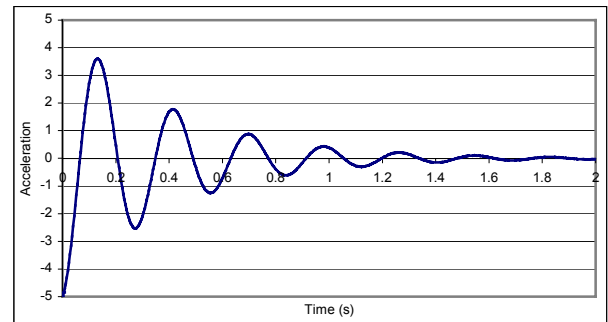
(c) Differentiation of signal with high noise level.

Fig. 17 – Typical acceleration from differentiation of displacement response.

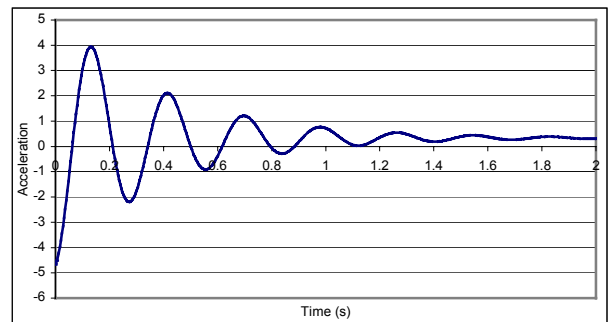
This case is an important feature for the students to comprehend. If only the results of the (c) case were available, the students could possibly arrive at the wrong conclusion that the differentiation does not work. Since their only earlier exposure to numerical differentiation highlighted that the delta t time increment is critical to the estimation of the differentiated signal, then the students naturally tend to blame the distortion of the resulting differentiated signal on too coarse of a time step for the differentiation process.

V.2 ACCELEROMETER SAMPLE CASES OF THE VMS

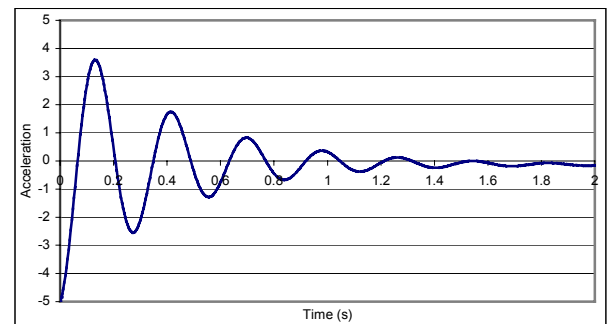
Measured signals may be affected by instrumentation and signal conditioning which may have drift and offset issues. This causes problems when integration is performed. Three subcases for the accelerometer were considered here for measuring the response of a single DOF second order mechanical system. One with no drift or offset at all, one with only DC offset and one with only drift. All three signals were generated as shown in Figure 18 (a), (b), (c), respectively.



(a) Acceleration, no drift or offset



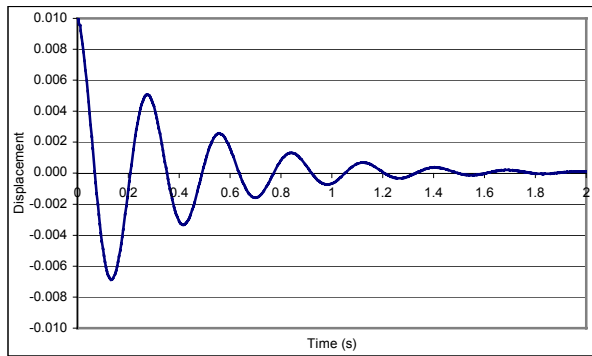
(b) Acceleration, positive offset.



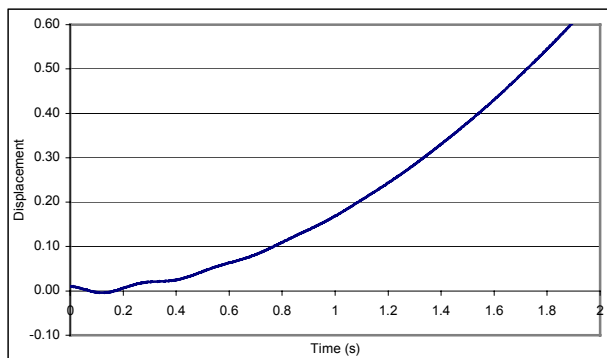
(c) Acceleration, negative drift.

Fig. 18 – Typical acceleration response.

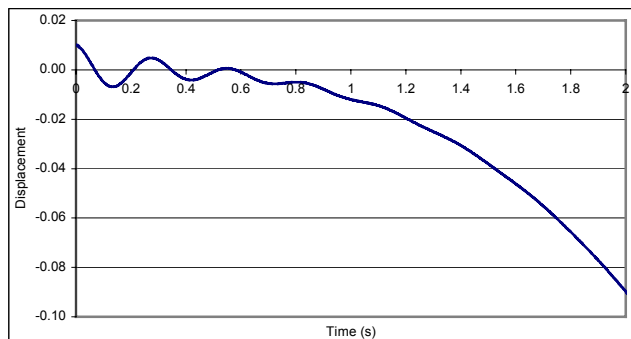
All three signals were then integrated to see the effects of drift and offset in the integration process; these are plotted in Figure 19 (a), (b), (c), respectively.



(a) Integration of signal with no bias or drift.



(b) Integration of signal with positive bias.



(c) Integration of signal with negative drift.

Fig. 19 – Typical displacement from integration of acceleration response.

This case is an important feature for the students to comprehend. If only the results of the (b) or (c) case were available, the students get confused with the integration results. The interpretation of the results becomes confusing since the students do not see the underlying effects clearly to understand the issues at hand.

VI. CONCLUSIONS

A new Virtual Measurement System (VMS) has been developed to supplement the student understanding and interpretation of real-world measurements that are plagued by many different measurement issues. The VMS allows the student to selectively pick various measurement distortion items to contaminate a “known” second order system response. In this way, the students can better understand each effect and understand how the effect is manifested in their resulting processed data.

VII. ACKNOWLEDGMENTS

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