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ABSTRACT

A program designed to increase studnet interest and provide motivation in a third-year systems and measurements laboratory in mechanical engineering is provided. The philosophy of the course, instructional techniques, equipment design (including schematics and photographs), suggested activities, and student reactions to the course are presented. An elimination of much "black box" electronic equipment in favor of transparent, simple, yet functional, laboratory equipment is advocated. (CP)

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A DESIGN PHILOSOPHY FOR INSTRUMENTATION EQUIPMENT IN A DYNAMIC SYSTEMS AND MEASUREMENTS LABORATORY

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INTRODUCTION

Can a dynamic systems and measurements laboratory for Mechanical Engineering students at the third year level be designed to be stimulating, challenging, relevant and above all interesting? Can instrumentation equipment, in spite of its primarily electronic nature, be made transparent to students having no particular background in unraveling the mysteries of electrical networks? Can a motivation for delving into electronic systems be instilled in students who are essentially mechanically oriented? The answers are generally affirmative, provided that suitable equipment is designed or selected to assist the instructor. Above all the equipment must not only work reliably to guard against "turning off" the student but it must also be transparent to the user in both purpose and function. For example, it is far better to have the student start by designing and building his own filter using resistors and capacitors as opposed to twisting the knobs of a factory-built "black box" which is resplendent with all the features one could ever need. Obviously there is a limit to the nature and extent of this do-it-yourself approach to the study of instrumentation systems. Readout systems such as oscilloscopes, digital multimeters and strip chart recorders are perhaps better purchased than made. But the extreme case of providing only factory built, state-of-the-art instruments in an educational laboratory is, we think, a narrowing rather than a broadening experience.

Having presented a few generalities about one approach to an instrumentation laboratory, the remainder of this paper will strive to support these hypotheses with examples drawn from real pieces of hardware and their underlying design philosophy. But first some description of background and purpose of the laboratory facility itself. The dynamic systems sequence of courses in the School of Mechanical Engineering at Purdue University consists of a sophomore level course in elementary circuit analysis, a junior level course in dynamic systems and instrumentation systems analysis and a senior level course in feedback control systems analysis and design. The Systems and Measurements Laboratory was established to provide a facility for the laboratory activity associated with both the junior level course and also a graduate level course in the dynamics of instrumentation systems. Some 250 students divided in laboratory sections of sixteen students with two students per laboratory bench set-up make use of the Systems and Measurements Laboratory per year. A minimum of fifteen three-hour laboratory periods make up the undergraduate student's involvement with this laboratory. Some eleven structured laboratory exercises are performed as well as a special project of the student's own choosing in consultation with his laboratory instructor. The laboratory instructors are for the most part of professorial rank, as well as some teaching assistants.

The purpose of the junior level course in the systems sequence is two-fold: 1) To provide the basics of modeling and the transfer function approach to the study of dynamic systems; 2) To acquaint the student with the principles and practice of a limited variety of transducers and measurement systems. Of particular interest are those measurement systems which are most important to mechanical dynamic systems studies such as the measurement of force, displacement, velocity and acceleration. Some work is also done in the measurement of temperature, pressure and flow. In all measurement systems considered, the two concepts of both static and dynamic behavior are stressed. A typical laboratory experiment includes the static calibration of the instrument in question as well as its performance in making a dynamic measurement. Some analog computation is also performed in the laboratory.

EQUIPMENT DESIGN PHILOSOPHY

In the course of having developed a number of equipment set-ups for laboratory experiments a six-point design philosophy has clearly emerged which might serve as points of dialog among engineering educators. One noticeably absent point in the enumerated philosophy of laboratory equipment is the mode of actual performance of the exercise -- shall it be self-paced or shall it be by conventional laboratory instruction? The evidence either for or against self-paced instruction is not overwhelmingly persuasive and need not affect the points to be discussed. First, a brief statement of the six-point design philosophy and then a description of the equipment that was designed and which utilizes some or all of the design objectives.

1. Reduce every device to its most elementary building blocks.
2. Separate these blocks and have the student make the interconnections.
3. Make each block as transparent as possible; don't hide the function of the block inside a "black box."
4. Admittedly, some sacrifice in performance is made due to physical separation of components.
5. Use bench top "homebuilt" systems rather than "off the shelf" real engineering systems.
6. Allow mistakes to happen and/or require the student to perform a part of the exercise which has no clearly established end result.

The most graphic illustration of item 1. is found in the area of strain gage bridge transducer systems such as those found in load cells, pressure transducers, etc. Most commercially available signal conditioners designed for bridge transducers combine a host of functions inside a single enclosure, including -

a) Bridge completion resistors;
b) Bridge excitation;
c) Bridge balance;
d) Conversion from double-ended to single-ended voltage and voltage gaining;
e) Demodulation for AC bridge excitation;
f) Span adjust.

It goes without saying that a student's first exposure to all of these individual tasks is far better accomplished by clearly separating these individual functions. To this end, a simple strain gage measurement system has been designed as shown in Figures 1a) and 1b). This equipment includes a cantilevered beam with strain gages mounted on the upper and lower surfaces to form two active arms of a bridge circuit; a battery for DC excitation and a simple bridge breadboard for completion of the bridge circuit. The breakboard itself is an aluminum panel with convenient five-way jacks and all connections clearly traceable without dismantling any covers. A balance potentiometer is included for nulling the bridge. The low level bridge output is processed by a simple operational amplifier circuit described in the next figure. Obviously the output signal will be more prone to noise because of the unshielded and unprotected configuration of the various components. But this loss in performance is more than offset by the increased grasp of the individual concepts.

Operational amplifiers have plummetted in price over the past five to ten years. At the same time reliability, ease of application and versatility have all increased. In particular, the advent of operational amplifiers have vastly reduced the complexity of circuit designs which formerly depended on discrete transistors for activation. Many instrumentation operations are now being carried out by the use of operational amplifiers, such as signal conditioning, impedance buffering, signal processing, analog to digital and digital to analog interfacing and many others. Teaching the theory and application of op amp circuit design provides the student with a very versatile tool for a host of instrumentation applications.

Several levels of op amp equipment can be envisioned. At the most elementary level the student should have the opportunity to connect the op amp to the power supply as well as the flexibility of a reasonably large assortment of resistors and capacitors which can be easily interconnected to form the passive input and feedback circuits associated with an op amp. Figure 2a) shows a set of op amp equipment that breaks down the use of the op amp into its most fundamental components. The op amp is mounted in its own separate enclosure with a non-reversible connector for interfacing with the positive and negative voltage power supply. Both the inverting and non-inverting input jacks are available for use as opposed to the traditional hard-wired connection from the non-inverting terminal to ground. The patchboard is designed to accommodate a wide variety of circuit configurations formed by resistors and capacitors individually mounted on dual-banana plugs. The patchboard also includes several potentiometers with all three terminals uncommitted. As in the case of the bridge breadboard, the patchboard is simply an aluminum panel mounted on standoffs so that all interconnections can easily be traced. Thus the three separate entities, namely, the op amp, the power supply and the external circuit parameters, are all clearly separated in the student's mind. Again there is a small degradation in performance because of the necessity for patch cord interconnections and the inevitable noise input due to lack of shielding. A valuable learning experience is the significant difference in performance between a well-patched circuit and a poorly patched circuit. Also, the problems associated with improper grounding procedure are more likely to occur with the design shown in Figure 2a).

The three circuits of Figures 2b), 2c) and 2d) are examples of three levels of sophistication in using op amps to provide gain for the strain gage bridge system of Figure 1b). The simple inverter circuit is the most elementary circuit but suffers from loading down the bridge output and/or a large value of feedback resistance for a reasonably gain value. The follower circuit eliminates the loading problem and the large feedback resistor problem but does not offer the possibility of common mode noise rejection as in the differential voltage input circuit. This last circuit is relatively easy to use and preserves the differential output nature of the bridge itself. Noise is substantially reduced because of the circuit's common mode rejection capability.

The point to be made with regard to the three signal conditioning circuits is that the relative merits of each circuit can easily be tested with the demodularized equipment shown in Figures 1a) and 2a). If a commercially available signal conditioner is incorporated in the laboratory on strain gage measurements, it is highly likely that the student would be unable to determine what the circuit configuration of the given signal conditioner is, let alone studying a comparison of the performance of a number of different circuits. The student is ready to appreciate the prepackaged conveniences of a commercially available signal conditioner only after he has been exposed to the basic concepts manifested by the circuits of Figures 1b) and 2b,c,d) and after he has experienced the performance degradation due to the demodularized equipment shown in Figures 1a) and 2a).

One of the most simple yet most meaningful laboratory experiments is performed with the equipment shown in Figure 3a). The filter patchboard is again of a two-dimensional panel design with all short circuits and open circuits easily traced. A variety of filter transfer functions can be quickly synthesized by appropriate connection of resistors, capacitors and an inductor mounted on double banana plugs as shown in Figure 3a). Figures 3b,c,d,e) show a number of circuits that can be constructed, including two cascaded low pass filter stages, a bandpass filter, a second order lightly damped filter and two cascaded low pass stages with buffering. Again the point to be made is that some simple equipment of a home built nature can be designed to be very transparent to the student and at the same time extremely versatile as well. The effects of interstage loading as well as loading due to the input stage impedance of the readout device are but a few of the very profound topics that can be explored with the filter equipment shown in Figure 3a). Just as in the case of the strain gage signal conditioners, only after the student has been exposed to the "do it yourself" brand of filter construction is he ready to appreciate the convenience and performance capabilities of a commercially available black box filter system.

An experimental setup that illustrates the concept of utilizing a bench top home built system as opposed to a real engineering system is shown in Figure 4a). The need for two rather widely different groups of laboratory experiments were the driving forces that led to the design of the spring-mass-dashpot system shown in Figure 4a). On the one hand a second order lightly damped system was needed so that the concepts of frequency response and transient response could be studied in the context of a collection of real physical elements. On the other hand a dynamic system was needed to provide a source for the study of force, displacement, velocity and acceleration measuring devices. Since the junior level course includes the two-fold objective of teaching dynamic system behavior as well as the performance and characteristics of measurement devices, the system shown in Figure 4a) is a very versatile experimental apparatus. Within the category of experimentally exploring the characteristics of a second order system, one laboratory exercise consists of simulating a second order system on an analog computer. Figure 4b) shows an analog computer diagram of the equation

$$\frac{\ddot{x}}{\omega_n^2} + \frac{2\zeta}{\omega_n}\dot{x} + x = S_{xf}\, f$$

where e_f represents the force f, e_a represents the acceleration $\ddot{x}$, e_v represents the velocity $\dot{x}$ and e_x represents the displacement x. Since the bench top system is fully instrumented to yield voltages proportional to all the above variables, the standard form parameters S_{xf}, ζ and ω_n can be found experimentally by modifying the appropriate potentiometer settings on the analog computer.

The second area of laboratory exercises is the study of the measuring systems themselves. The input force to the beam supported by a set of cantilever leaf springs and a dashpot is measured by means of two strain gages mounted on a u-shaped link between the drive spring and the beam. The displacement is measured by means of a linear variable differential transformer (LVDT) and the velocity is transduced by a stationary multi-turn coil surrounding a movable permanent magnet. The accelerometer is a commercially available piezoelectric crystal unit. A dial indicator to calibrate the LVDT is also included on the system. The input amplitude generated by the gear motor can be changed to any one of four discrete settings. The frequency of the input can be continuously varied by means of a silicon-controlled-rectifier circuit.

A third area of study reserved for a graduate level course which also makes use of the spring-mass-dashpot system is the problem of computing a velocity signal from a displacement signal or computing a velocity signal from an acceleration signal. The circuits shown in Figures 4c) and 4d) are an approximate double differentiation and an approximate double integration. Since both displacement and acceleration signals are available, the former can be differentiated twice and then compared with the actually measured acceleration signal. Also, the acceleration signal can be integrated twice and then compared with the displacement signal. These signal processing tasks have been found to be both frustrating and highly informative. The bench top model, while not a real engineering system, does exhibit many very real factors such as frequency drift and high frequency noise. The engineering design process of choosing the appropriate break frequencies for the approximate differentiators and integrators confronts the student with a number of tradeoffs. For example, accurate differentiation is achieved at the expense of noise. Accurate integration poses special problems in that a larger DC gain is required to compensate for greater AC attenuation. In both integration and differentiation operations a restricted frequency band is important if the results are to be reasonably accurate. Finally, the realism interjected by actual measurement signals as opposed to simply using function generator signals is a large plus insofar as student acceptance and enthusiasm for the experiment is concerned.

The final piece of laboratory equipment to be discussed in this paper is a self-contained analog to digital and digital to analog conversion system shown in Figure 5. Before discussing the function and operation of the constituent components of this system, a few background statements are in order. Consistent with the concept of physically separating the independent functions of an overall system, it is believed that the use of an existing mini-computer based data acquisition system tends to obscure the identity of the separate components. In keeping with this philosophy a system including the following modules was designed:

1) sample and hold amplifier; 2) analog to digital converter; 3) digital to analog converter; 4) adjustable frequency clock to control the sampling rate; 5) comparator to "freeze" a particular value of a time varying signal; 6) a triggering module. Using the sample and hold module controlled by the clock demonstrates the nature of a discretized analog signal very simply and quickly. The comparator module is useful for studying the subsequent error if the A/D module is required to convert the analog signal directly without benefit of a S/H amplifier. In operation an input sine wave is applied to both the A/D converter and the comparator. When the analog signal reaches some pre-selected level the converter is commanded to perform the conversion process. Unfortunately, since conversion requires some nonzero time increment, the input signal to the converter changes during the conversion interval. A more accurate approach consists of "freezing" the input signal by the use of a S/H amplifier, the output of which is connected to the input of the converter. The comparator is now used to trigger both the conversion operation and the "hold" mode of the S/H amplifier. Thus the analog to digital converter is called upon to convert a constant signal, namely, the discretized version of the input analog signal.

The digital to analog conversion process is generally much faster than the analog to digital conversion process. But the very real limiting factor known as amplifier slew rate is easily demonstrated by causing all input bits to go to logic "1" simultaneously. This is done by using the clock output as the input to all bits of the D/A converter. In effect the D/A converter is driven with a step input but because the converter amplifier is velocity limited the analog output is a ramp with a slope equal to the rate limit of the amplifier.

When the clock frequency which controls the sampling and digital conversion rate of the incoming analog signal is less than twice the highest frequency in the signal to be converted, extraneous frequency components appear in the output. This effect is known as aliasing. The system shown in Figure 5 exhibits this phenomenon very clearly. Some other exercises that can be conveniently performed include static calibration of both the A/D and the D/A converters and determination of converter nonlinearity. Because inexpensive modules were purchased, the departures of the various converter specifications from their ideal values are relatively easily noticed. The fact that the system does exhibit error is considered an asset in terms of its use as a teaching tool.

SUMMARY

This paper has presented a design philosophy for undergraduate laboratory equipment. This philosophy was implemented in the development of some laboratory hardware for a dynamic systems and measurements course. Without question the response to the course and to the laboratory experiments has been very favorable. Approximately five years ago the measurements course was among the most disliked courses in the required undergraduate program in Mechanical Engineering. That disfavor is no longer prevalent. No doubt this turnaround in student acceptance is due in large measure to the nature of the laboratory equipment and to the exercises performed in the laboratory.

If it hasn't been made clear by now it should be reemphasized that in order for a concept to be extended to more complex situations it must be understood and not simply memorized. This understanding is best brought about through the use of simple equipment which transparently illustrates the concept. For example, the strain gage measurement equipment probably brings this point home most clearly. A commercial bridge signal conditioner accepts four wires from the load cell and delivers one output signal. The structure of the bridge is not in evidence, the presence of a bridge exciter is not clearly shown, the conversion from a differential output to a single-ended response is not at all clear.

While it is true that a capable instructor can point out these constituent elements to the student, if they are not clearly identifiable they will be lost to all but a few students.

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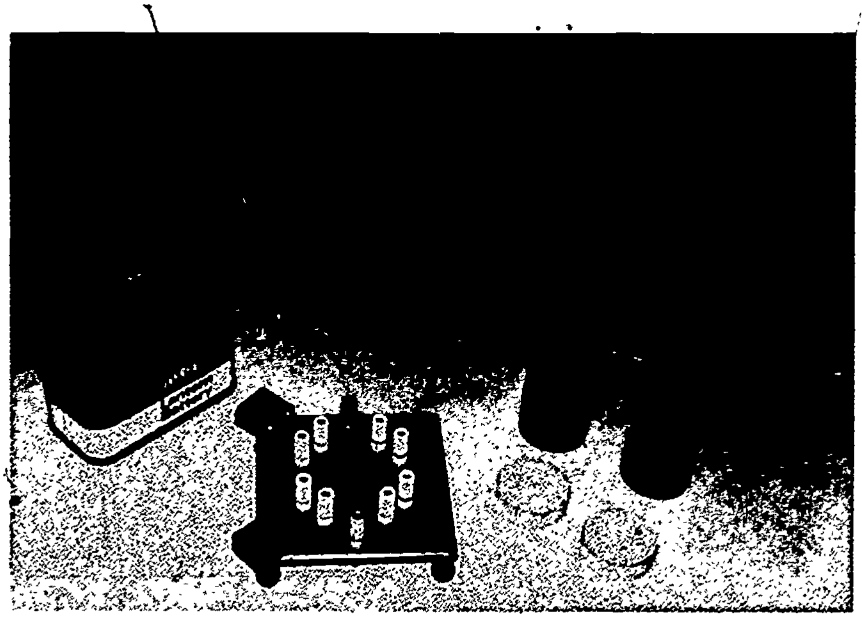


Figure 1a) Strain Gage Bridge Transducer Equipment

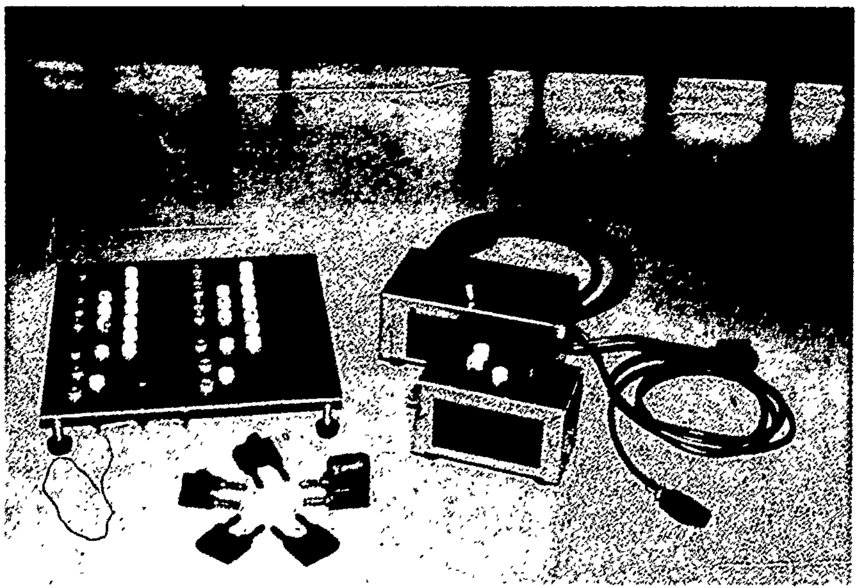


Figure 2a) Operational Amplifier Equipment

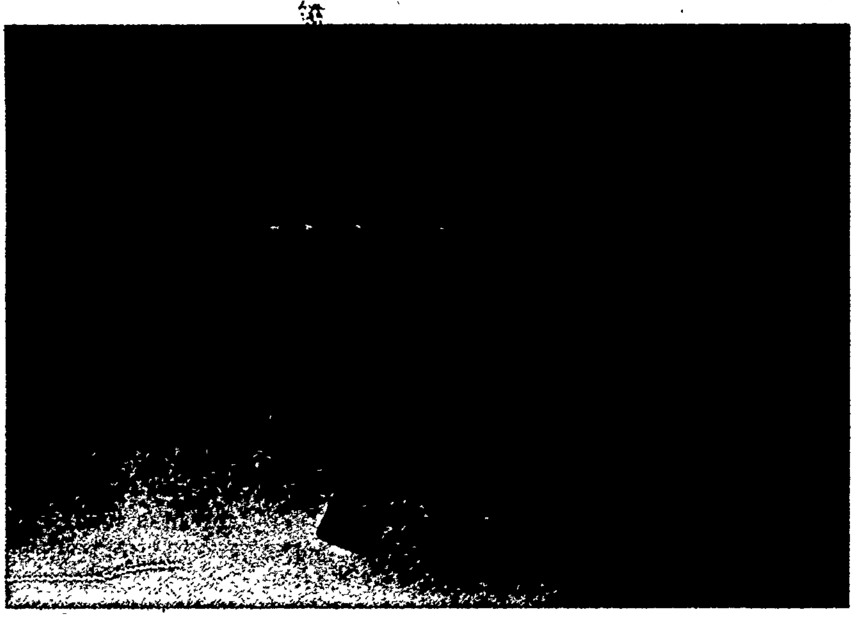


Figure 3a) Filter Breadboard Equipment

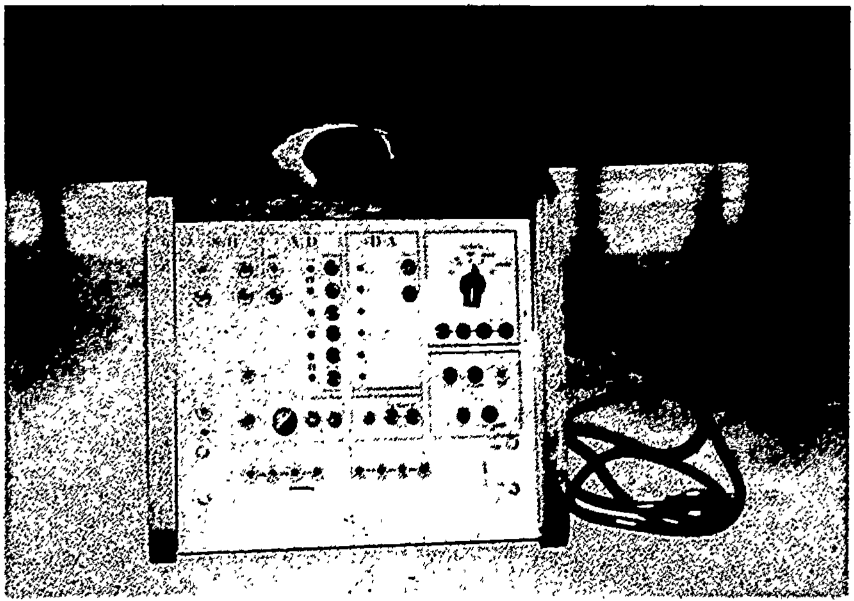


Figure 5a) Analog to Digital and Digital to Analog Conversion System

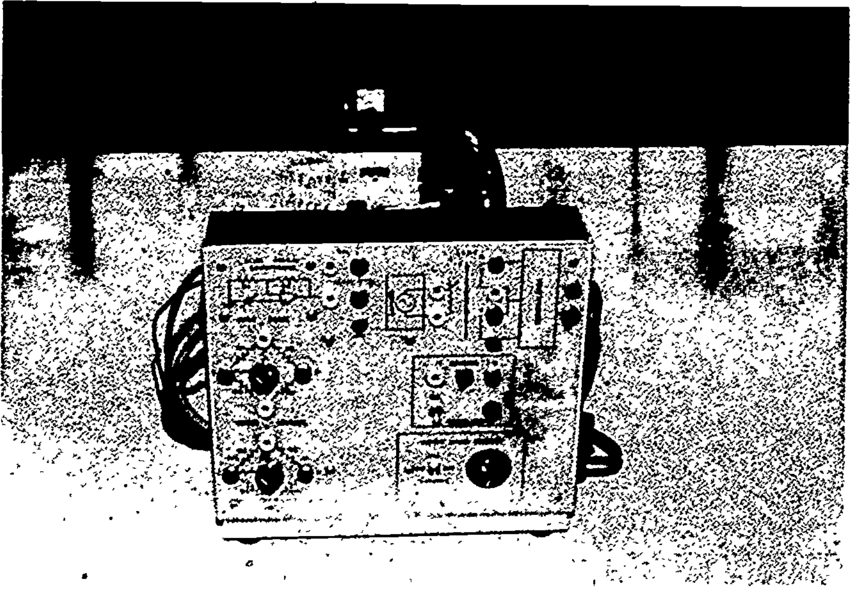
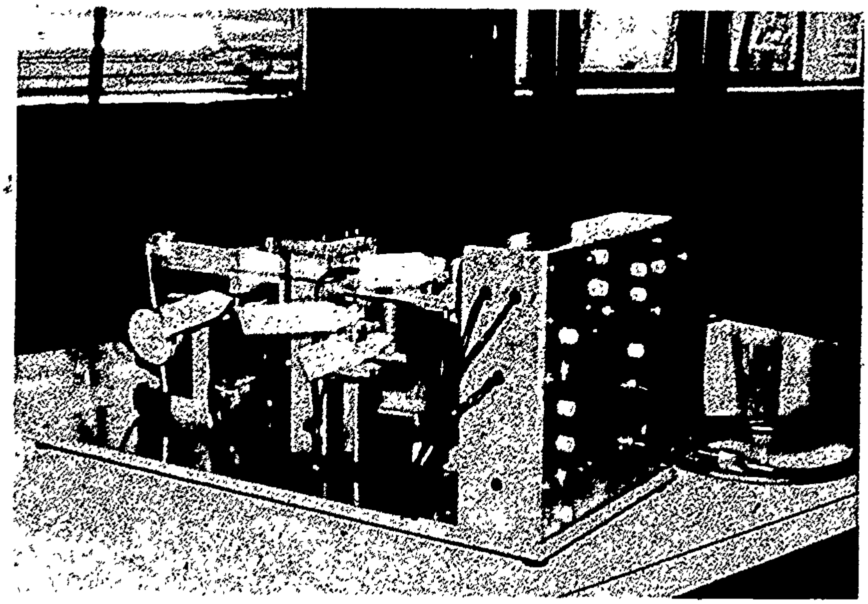


Figure 4a) Spring-Mass-Dashpot Mechanical System With Force and Motion Instrumented Signals



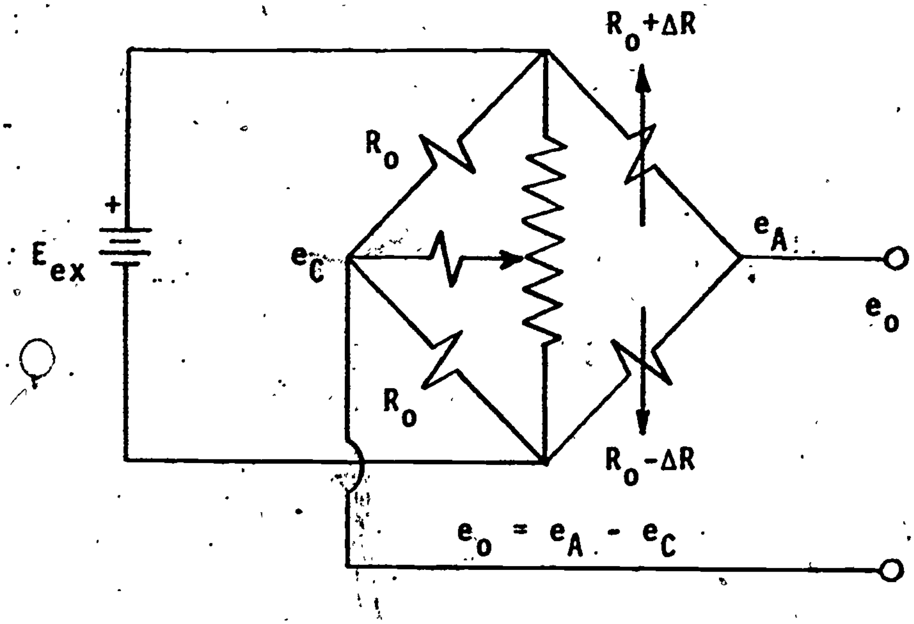


Figure 1b) Strain Gage Bridge Schematic

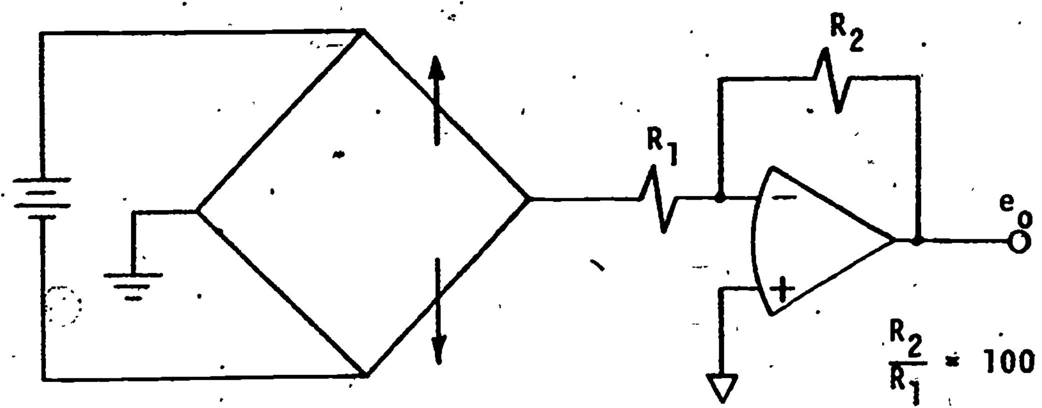


Figure 2b) Inverter With Gain Bridge Amplifier

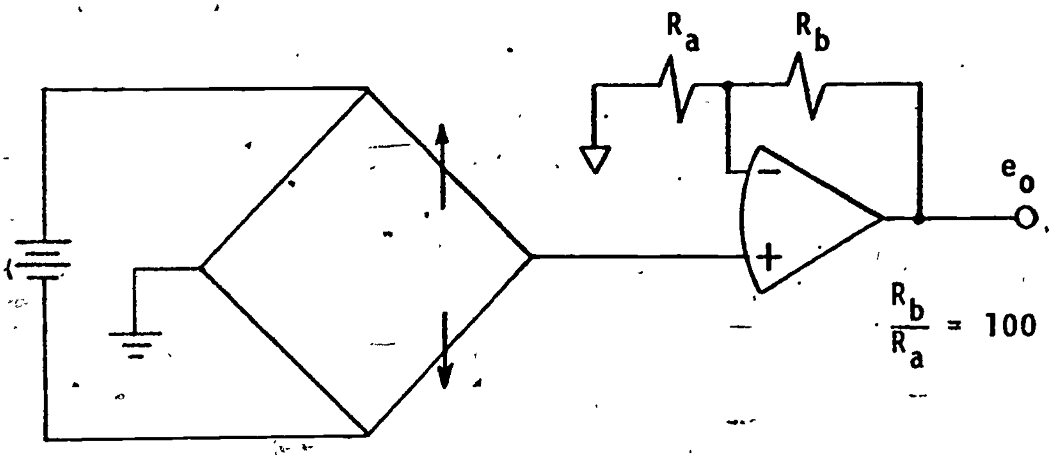


Figure 2c) Follower With Gain Bridge Amplifier

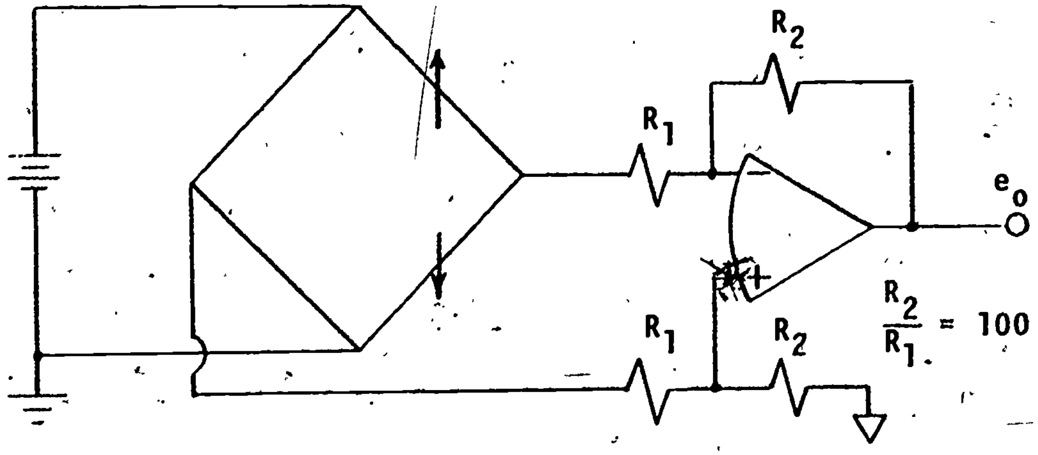


Figure 2d) Differential Voltage Input With Gain Bridge Amplifier

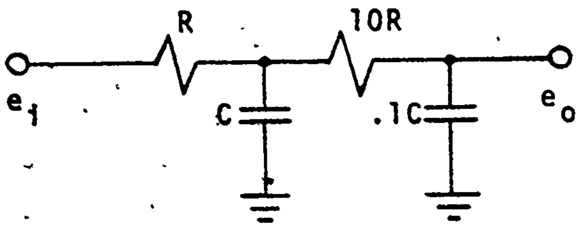


Figure 3b) Cascaded Low Pass Filter Stages

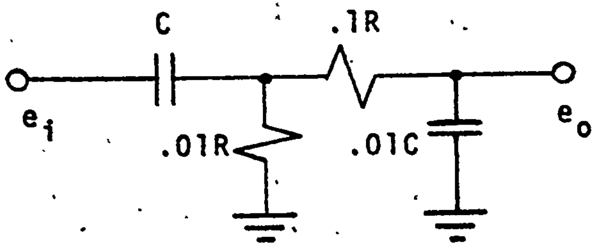


Figure 3c) Bandpass Filter

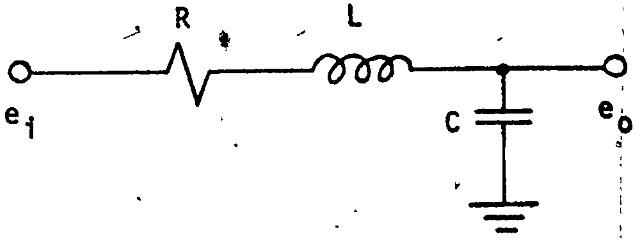


Figure 3d) Second Order Subcritically Damped Filter

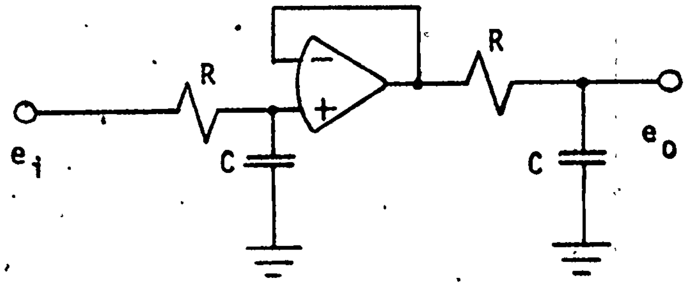


Figure 3e) Cascaded Low Pass Filter With Intermediate Buffering

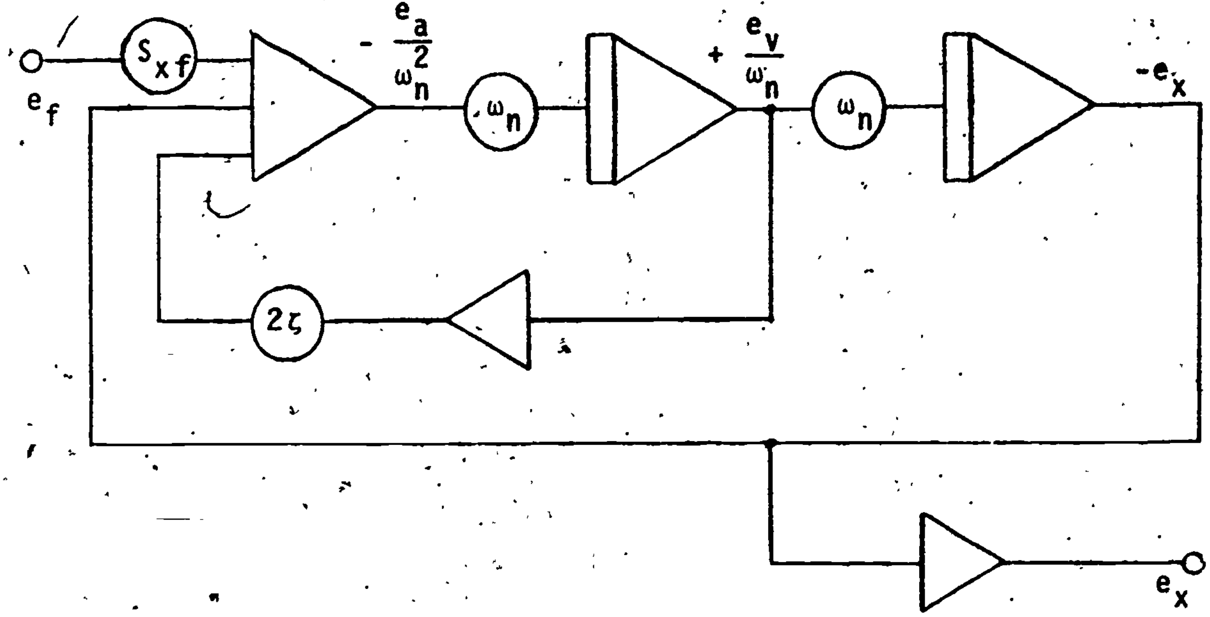


Figure 4b) Analog Computer Program Diagram of a Second Order System

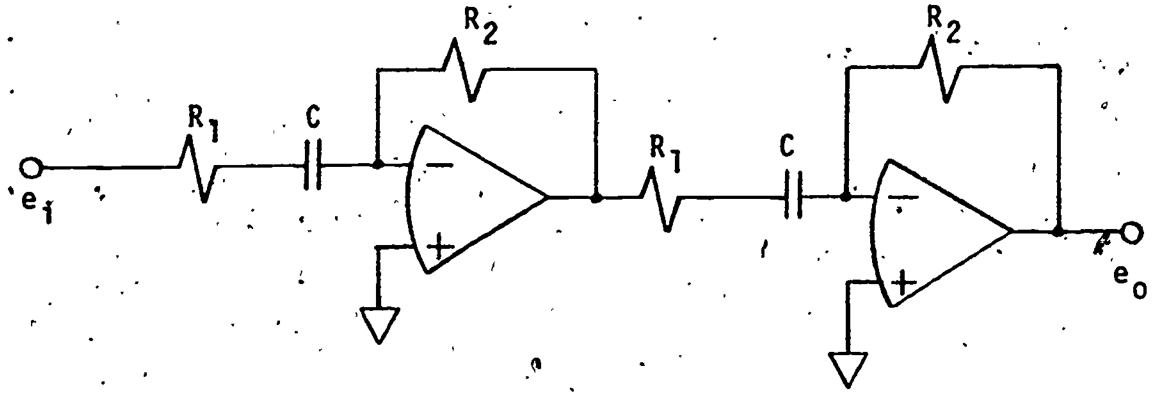


Figure 4c) Schematic of an Approximate Double Differentiation Circuit

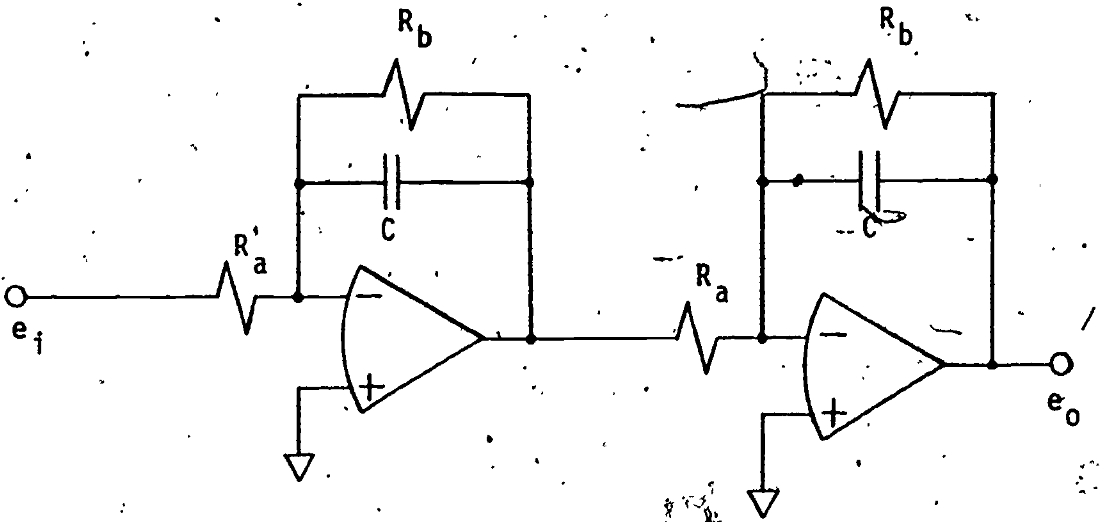


Figure 4d) Schematic of an Approximate Double Integration Circuit