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A Unified Approach for Design and Analysis of Engineered Systems Using HyPneu

Abstract

The design and analysis of most engineered systems involves many and sometimes diverse technical disciplines. For example, in the design of a fluid power system, the input to the system is usually some type of prime mover. In addition, the output may include gears, linkage, etc. The output may be used in a feedback circuit which will normally encompass instrumentation, logic elements, and controllers. In order to evaluate the total performance of such systems analytically, a software package must be available which can unify the interactions of these diverse components.

This paper will present a new computer program which will unify hydraulic, pneumatic, electronic, and mechanical components permitting the analysis of complete engineered systems on a P.C. Several example systems will be shown which originate in actual machinery designs. These example systems will be simulated and output type information will be presented.

Introduction

The design of the fluid power system is many times the most critical part of the development of a machine. In the performance of an airplane as well as that of a backhoe, the most noticeable system outputs are a function of the operation of the hydraulic system. For example, if the hydraulic cylinder is too small for the application, the vehicle will be “touchy” and “underpowered”. This means that the motion is very rapid and prone to overshoot while it will not move the anticipated loads. If the displacement of the pumps is too large, the system again will be described as “touchy”, although the size of the load which it will handle may be adequate. Design errors can be made in the other direction as well, which will also compromise the operation of the machine.

In the past, fluid power systems were designed by hand starting at the load. The machine specification would define the size, speed, and total displacement required for the load. This information would permit the designer to establish cylinder dimensions, along with the required fluid flow and pressure needed. If the system is small, say one cylinder, a valve and a pump, the designer can either select the pump or the valve next.

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However, if it is a complex system having several cylinders, hydraulic motors, and valves, the task becomes infinitely more difficult. Moreover, if the operation sequence must be factored into the design along with valve metering and valve operation performance, design by hand becomes impractical.

Nearly all the systems with which an engineer may work are dynamic. That is things are usually constantly changing with time. The actual output of a system is as much of a function of time as of the size of a component. In practice, many of the important facets of a design may be based on steady-state consideration which is the limit of design by hand. However, a machine or system will fail if it cannot

withstand transient peak loads, respond quickly enough to a changing input, or operate without violent oscillations when disturbed. A design without considering dynamic effects is very likely to be worthless.

In today's environment, the fluid power system designer is being asked to create systems which will perform more tasks, faster, and will have less undesirable dynamic effects. The answer, of course, to this dilemma, is to provide the engineer more powerful tools. It is totally unacceptable to permit the design factors of a machine or system to be estimated and then fabricate the machine to see if it works. However, a more useful and powerful tool available today is the use of a computer in the design. Never the less, the computer can not be useful without the proper analysis and design procedures being implemented and perhaps someone who knows how to operate it.

In the early days of using the computer as a design tool, the engineer not only was required to be intimately familiar with fluid power components and system, but he needed to be a mathematical whiz and a computer expert as well. Obviously, this combination is very unique. Moreover, fluid power systems, in essence, involves many and sometimes diverse technical disciplines. For example, in a hydraulic system, the input to the system is usually some type of prime mover. The output may include gears, linkages, etc. In addition, the output may be used in a feedback circuit which will normally encompass instrumentation, logic elements, and controllers. Such a complex interaction among system elements makes the implementation of system models onto a computer very different. Fortunately, many of the dynamic properties occur in analogous ways in difficult kinds of systems. Very often, one may employ dynamic analogies to unify system modelling.

This paper will present a computer program which will unify hydraulic, pneumatic, electronic, and mechanical components, permitting the analysis of complete engineering systems on a personal computer. In addition, the basis of system unification will be discussed. Several examples will be shown to illustrate the unified approach for design and analysis of engineering systems.

System Unification Approach

The behavior of a real engineering system is controlled by the flow, storage, and interchange off various forms of energy [1, 2, 3]. Therefore, system dynamics can be explored if one can describe mathematically all the energetic actions and interaction in a given system. Depending on the way system elements handle the power flow and energy transfer, system elements can be classified as energy storage or dissipation elements. Further, there are two kinds of energy storage elements either by virtue of their A-type variables or by T-type variables. The A-type variables are across variables which act across the elements such as velocity, pressure, and voltage. The T-type variables are through variables which pass energy through the element, such as force, current, flow rate, etc. The energy dissipation elements are called the D-type elements such as friction, resistor, orifice, etc. Therefore, regardless of the type of an engineering system, its elements can always be represented as an A-type, T-type, or D-type energy element. This leads to the possibility of unifying any engineering system.

Fig. 1 shows a tetrahedron of state relating the A-type, T-type, and D-type elements [1]. Since only A-type and T-type are energy storage elements, they are the variables which determine the state of the element. In other words, if a system does not have any A-type or T-type elements, its dynamic characteristics can not be described mathematically.

As shown in Fig. 1, the co-energy variables x and h are defined as the integration of across-variable and through variable individually. In addition, the branch connecting f and x represents all T-type elements, and the branch connecting v and h represent all A-type elements. The diagonal connecting f and v represent all D-type elements. The above description provides the basis to formulate element equation.

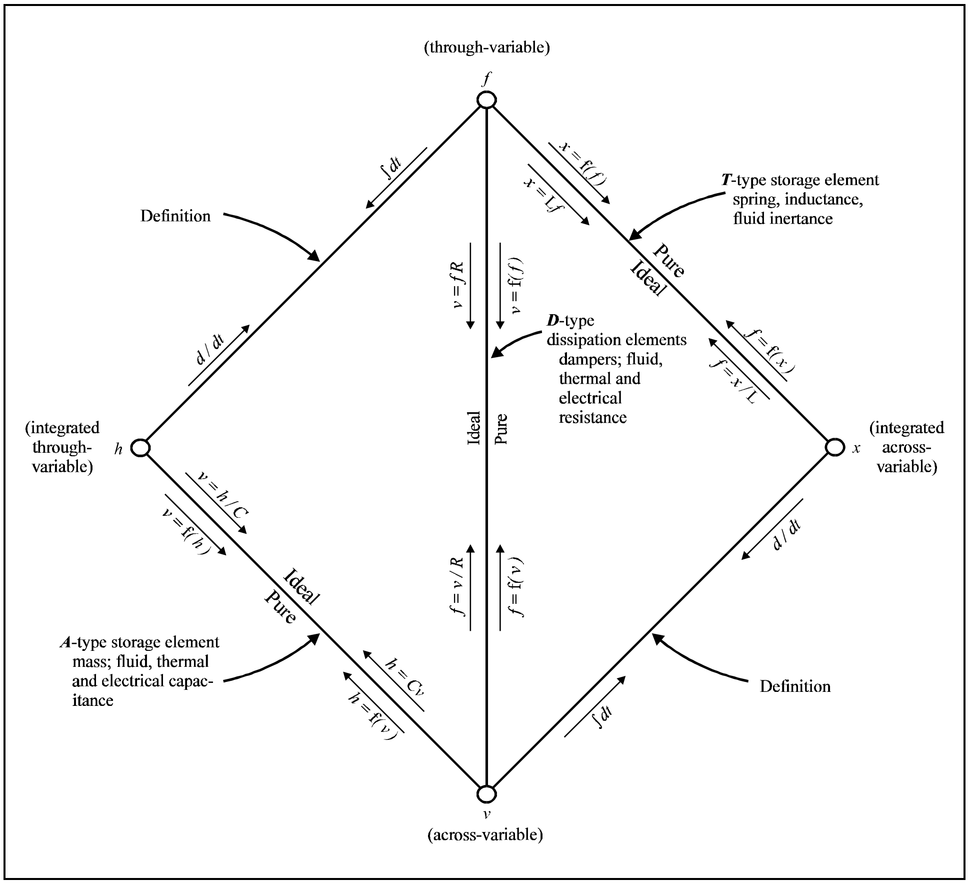


Figure 1
Tetrahedron of state for single-port elements

A system is composed of interacting elements. Consequently, a system model is a mathematical description of the way elements interact. In physics, two critical conditions must be satisfied when elements are connected together. These two conditions are compatibility and continuity. The compatibility requirement is applied to the across variable. For example, hydraulic pressure at a connecting point (node) must be equal regardless of the value of each individual branch flow to the node. On the other hand, the continuity requirement is applied to the through variable. It signifies the conservation of mass or energy. For example, for a node, the sum of all branch flows connecting to it must be zero, otherwise, the node pressure will change to reflect the flow imbalance. Therefore, if the across variables are defined as state variables, then the rate of change of the state variables can be obtained from the through variables using the continuity property. Applying any appropriate integration method, the state variables can be found. Then using the elemental law describing the A-type, T-type, and D-type characteristics along with the calculated values of state variable and the compatibility requirement, the value of through variables can be obtained. Repeat the above process for each time step to produce the time history for both the across variables and thorough variables or the variable derived from them. This is the approach HyPneu used to unify engineering system analysis.

Case Studies

The versatility and simplicity of the HyPneu program are a result of subscribing to a unified approach. It is not possible in this paper to completely describe all of the basic details of HyPneu, however, the following case studies will illustrate a few of the many industrial applications which have been analyzed using this unique software on a P.C. (4).

CASE STUDY NO. 1

This case study involves the analysis of a hydraulic component. One of the more complex components which hydraulic designers must work with is the pressure compensated piston pump. As can be seen in Fig. 2a, this pump consists of a pumping mechanism (pistons and cylinder block), a swash plate and swash plate actuator, a control connected to the actuator, orifices to control the speed of response, and a relief valve to establish a pressure setting. This design can be directly translated into a HyPneu schematic, as shown in Fig. 2b. In this program, all component icons are identified by a six digit code such as SI1110, SI2221, SH7332, etc. In order to actually evaluate this pump through computer simulation, a drive motor, system compliance (accumulator) and a variable load must be added to the component circuit, as was done in Fig. 2b.

It should be noted in Fig. 2a that the control valve is actuated by hydraulic pressure on both ends of the valve spool. This configuration is modelled in HyPneu by summing the appropriate pressure levels and directing the difference to the control valve. The dynamics of the swash plate and actuator are represented by a second order transfer function which is designated TF2 in Fig. 2b. The spring loading of the swash plate actuator is represented by a non-linear input (SI4355) to the transfer function. The results of a HyPneu simulation are shown in Fig. 2c as a curve of the system pressure measured at the load valve versus time and a curve of the pump flow rate measured at the pump outlet port. In Fig. 2c, the system load was raised from zero to 138 bar by partially closing the systemload valve at time equal zero and remained in this position for the first two seconds of operation. Then the system load valve was quickly closed resulting in a complete stoppage of flow to the system. In this case study, the compensator was set at 214 bar. At four seconds, the system load valve was completely opened.

CASE STUDY NO. 2

The rapid development of digital computer based controls has spawn a dramatic escalation in the need for pulse width modulated control elements. This case study illustrates the use of the HyPneu approach in the analysis of a PWM controlled system. The schematic in Fig. 3a shows a cylinder system controlled by a bang-bang valve (SH6220). The actual response dynamics of the control valve are represented by the transfer function (TFI). The analysis by the HyPneu program of the PWM system is given in Fig. 3b for a frequency of 6 hz and various duty cycles. experimental results at 6 hz and at 50% duty cycle are shown in Fig. 3c to demonstrate the close agreement between the HyPneu analysis and the laboratory verification using the same system.

Figure 2a
Pressure Compensated
Pump Schematic

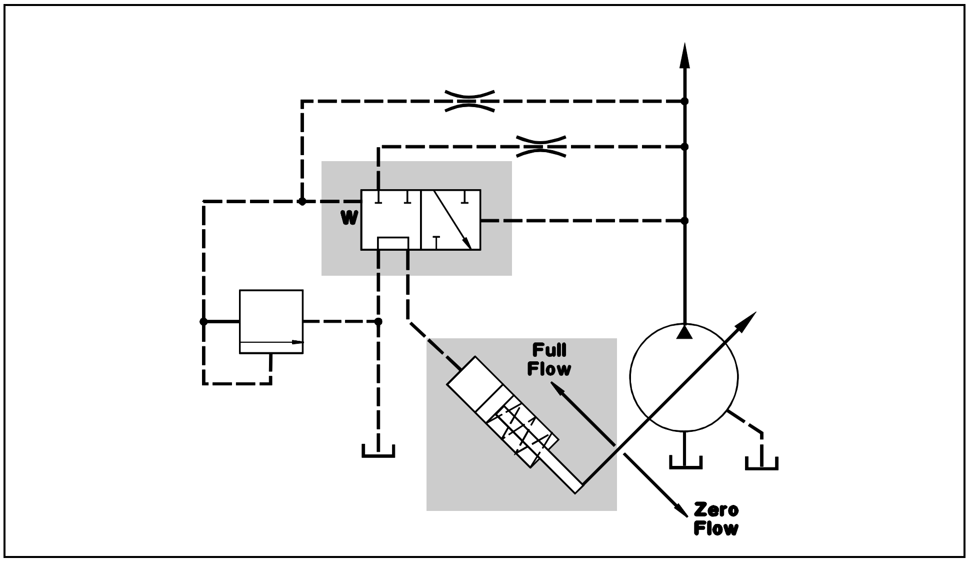


Figure 2b
Circuit Design for Pressure
Compensated Pump

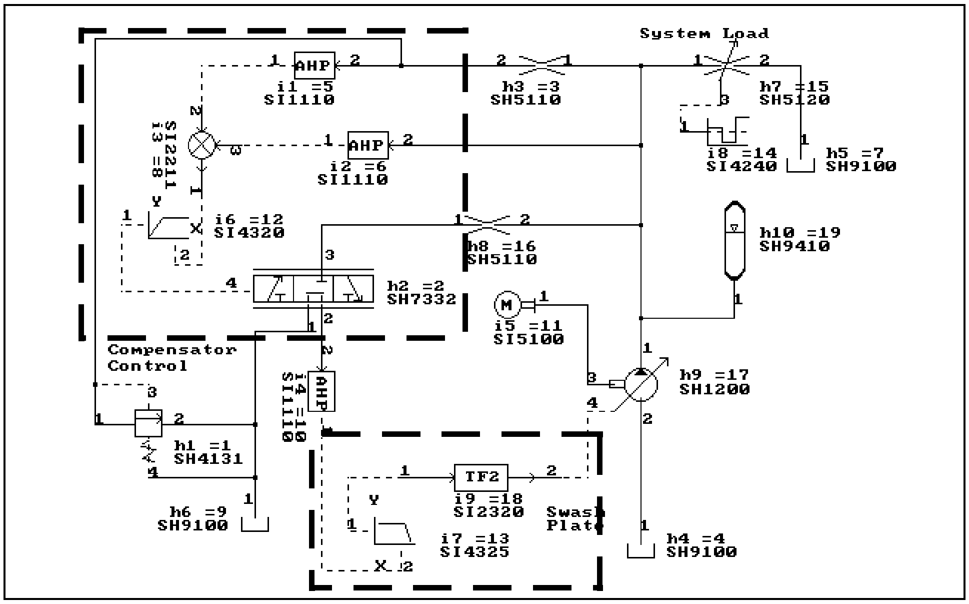


Figure 2c
Pressure Compensated Pump
Simulation Results

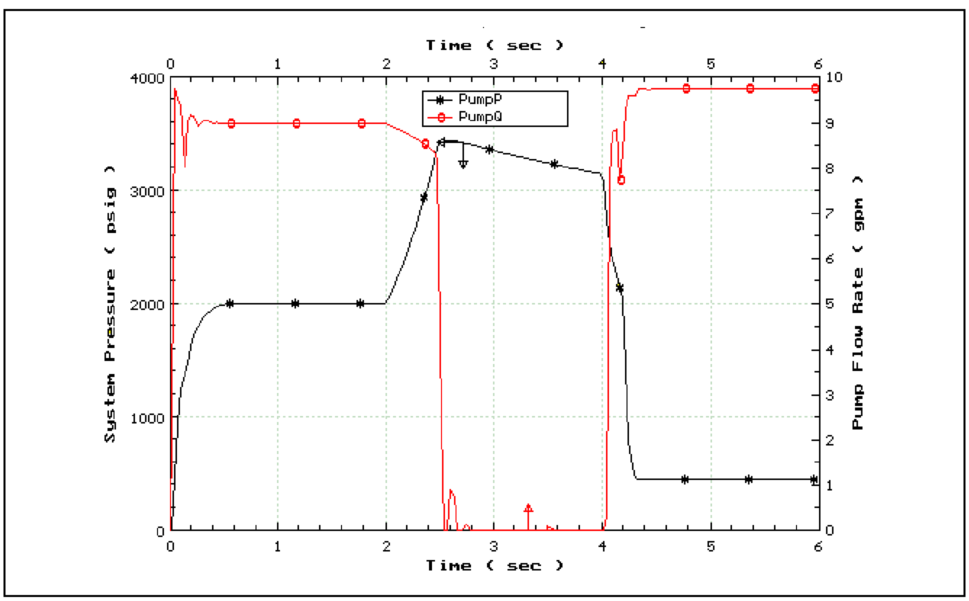


Figure 3a
PWM Control
System Schematic

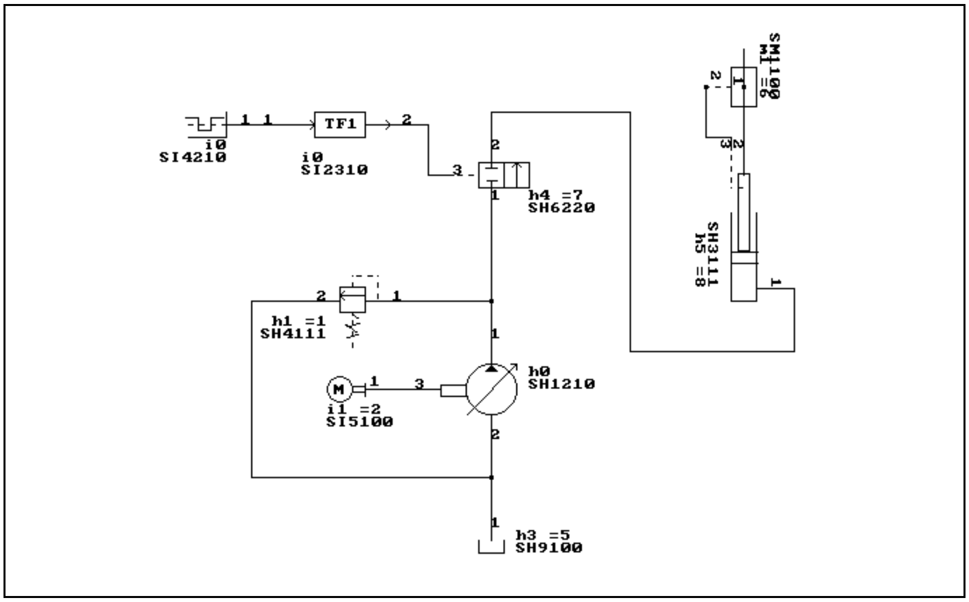


Figure 3b
PWM Controlled Hydraulic
System Analysis

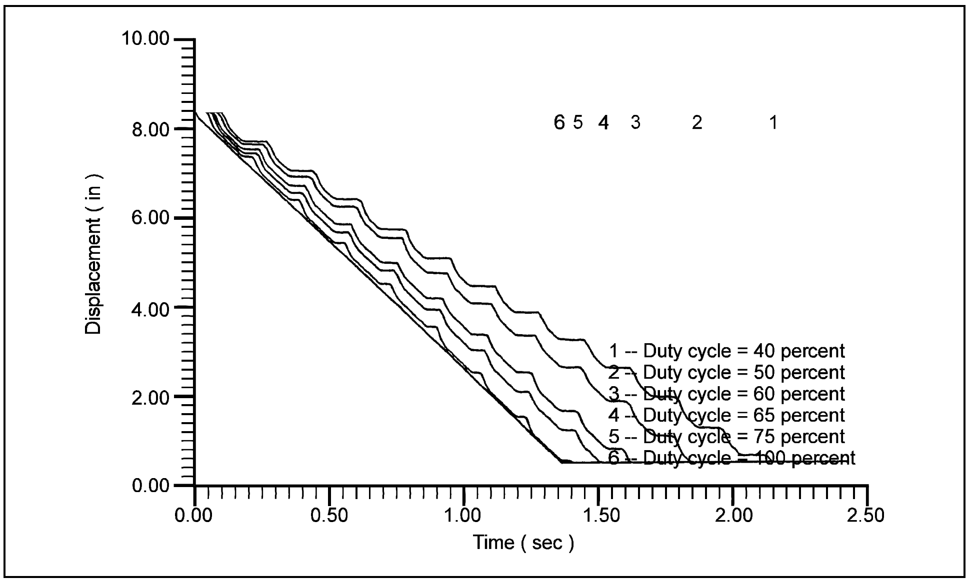
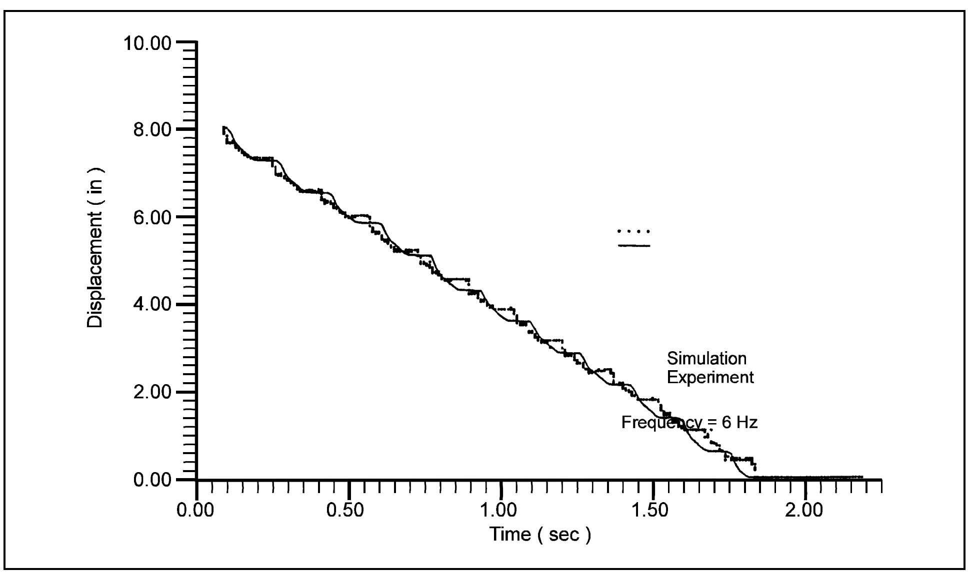


Figure 3c
Comparison of Simulation and
Experimental Data for the PWM
Controlled Hydraulic System



CASE STUDY NO. 3

This case study will illustrate the unified approach in the analysis and simulation of a complex feedback type of engineered system. A radar tracking control system as shown schematically in Fig. 4a is used here as an example of a feedback control system. It should be noted that this system incorporates hydraulic components, mechanical components, and electronic instrumentation type feedback. The dynamic response of the system was simulated for the case where the target moved from an initial condition of zero radian to a +1 radian at zero time, and to a -1 radian an the two second time. The curves of the radar receiver position and the feedback control signal are shown in Fig. 4b for illustration purposes.

Figure 4a
Radar Tracking Control System Schematic

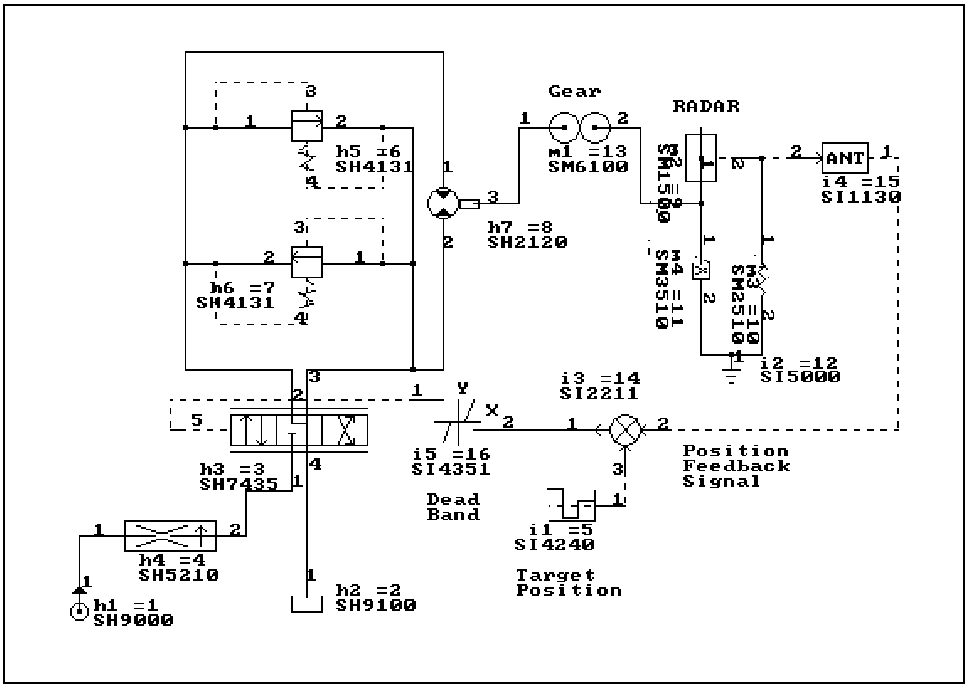
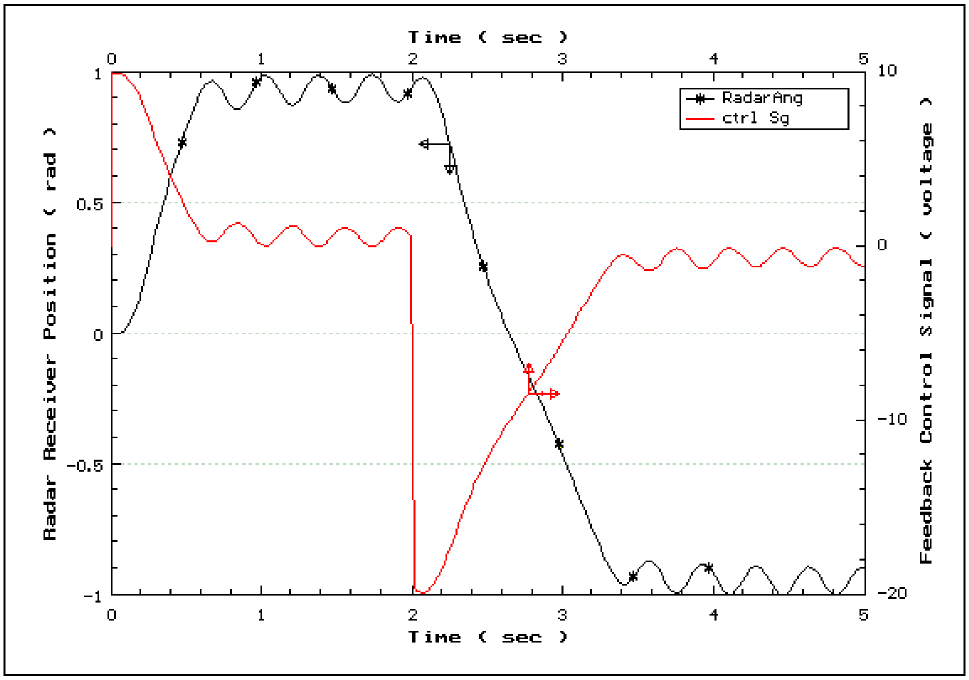


Figure 4b
Radar Tracking Control System Analysis



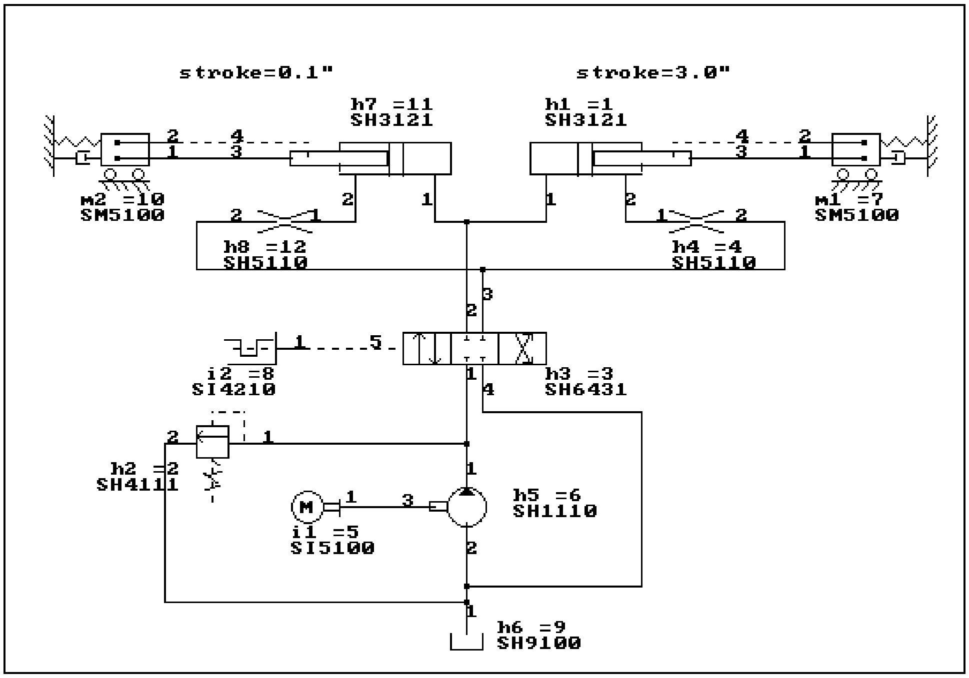
CASE STUDY NO. 4

As any user knows, hydraulic cylinders will encounter the end-of-stroke limitation in their displacement many times during the operation of most hydraulic systems. In fact, the hydraulic system may incorporate several cylinders and some of these cylinders will encounter end-of-stroke while other cylinders in the system are still moving. Therefore, it is very important that any analysis approach and software be capable of simulating hydraulic system operation when one or more cylinders reach end-of-stroke during the evaluation period.

Fig. 5a shows a schematic of a typical hydraulic system which incorporates two hydraulic cylinders. These cylinders are identical in every way except the cylinder on the left has a stroke of 0.254 cm, while the cylinder on the right has a stroke of 7.62 cm. Obviously, when the control valve (SH6431) is actuated by the control signal (SI4210), the cylinder on the left will reach end-of-stroke much faster than the cylinder on the right. To illustrate this operation, the cylinder displacement of both cylinders are plotted versus time after the control valve is opened as shown in Fig. 5b.

In addition, the cylinder inlet pressure versus time is given in Fig. 5c. It should be noted from these figures that while the left hand side reached end-of-stroke at about the 0.075 second point in the simulation, the program continued to simulate system operation without interruption.

Figure 5a
Schematic of Typical
Multi-Cylinder Hydraulic System
to Demonstrate End-of-Stroke



CASE STUDY NO. 5

One of the systems which is often used to illustrate the value of frequency analysis is the automobile suspension system which utilized a fluid shock absorber. Since in a conventional suspension system each wheel incorporates the same control system, only one wheel must be evaluated (quarter car suspension system). To illustrate the frequency analysis capability of a unified engineering approach using the HyPneu program, the quarter car suspension, as shown in Fig. 6a, was analyzed.

As can be seen in the schematic in Fig. 6a, the automobile body, the shock absorber, the spring, and the tire are all included.

Figure 5b
Cylinder Displacement Curves

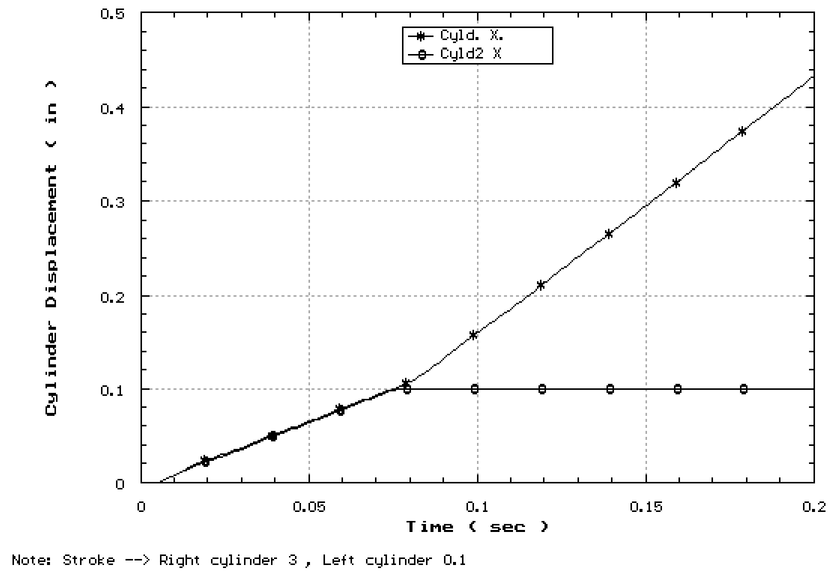
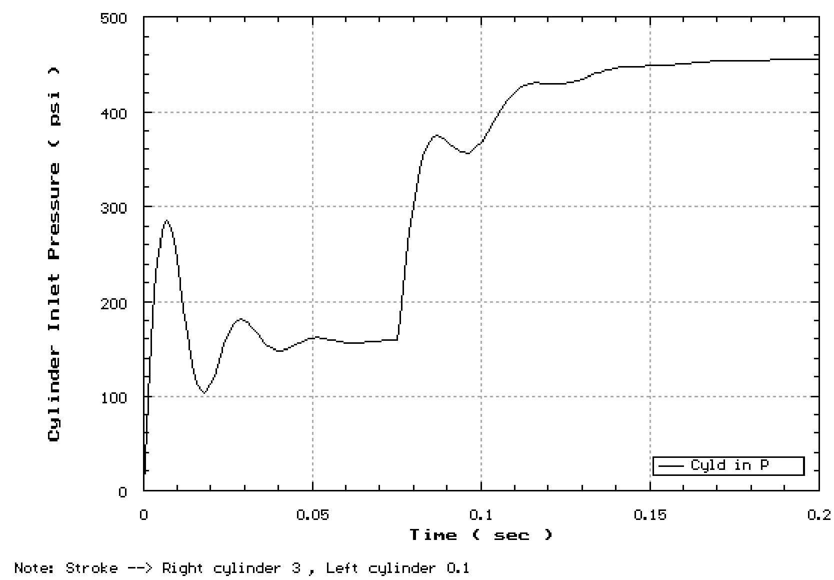


Figure 5c
Cylinder Inlet Pressure



The Bode type graph for this system is given in Fig. 6b, where the amplitude ratio is the body displacement divided by the road profile. The data shown in Fig. 6b assumes the following parameter values:

¼ Car Weight	=	555 kgf
Tire Weight	=	41 kgf
Viscous Coefficient (body to tire)	=	2.15 kgf-sec/cm
Mechanical Spring Stiffness	=	23.26 kgf/cm
Tire Stiffness	=	196.85 kgf/cm

It must be noted that the HyPneu software permits the user to select up to nine (plus time) outputs which can be displayed for each input. Therefore, several amplitude ratios could be plotted in the Bode format for each simulation.

Figure 6a
Quarter Car Suspension System Schematic

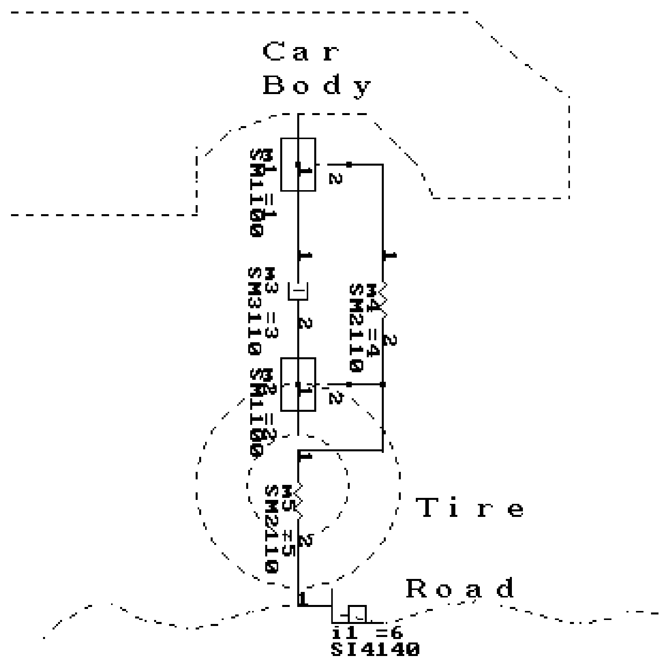


Figure 6b
Quarter Car Suspension System Analysis Displacement vs Road Disturbances

CONCLUSION

This paper has discussed unified engineering approach to the design and analysis of systems. It is very plain that one engineering discipline does not encompass the technology normally used today in engineered systems. Hydraulic, electronic, electrical, pneumatic, and mechanical components are all incorporated in the same system. In the unified approach, these components are all treated the same. That is, a hydraulic capacitance is not different from an electronic one from the standpoint of physics.

In addition to discussing the unified approach, this paper has introduced a new computer program which will operate on a PC—called HyPneu. This software relies upon the unified approach in its basic and fundamental philosophy. It has also been shown that this new computer program is versatile and simple. It is capable of evaluating unified systems, and providing several types of evaluation (steady state, dynamic, and frequency). Much of the HyPneu discussion was accomplished through the use of case studies. It was felt that the application of the software would provide the reader with a better perception than a detailed discussion of its features.

References

1. Shearer, J.L., T.M. Arthur, H.H. Richarson, "Introduction to System Dynamics", Addison-Wesley Publishing Co., 1967.
2. Karnopp, D.C., D.L. Margolis, R.C. Rosenberg, "System Dynamics: A Unified Approach", John Wiley & Sons, Inc., 1990.
3. Shearer, J.L., B.T. Kalassskoswki, "Dynamic Modelling and Control of Engineering System", MacMillan Publishing Co., 1990.
4. Hong, I.T., R.K. Tessmann, P.J. Fitch, "HyPneu Application Notes", BarDyne, Inc., 1993.

