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Computerized Fluid Power Design of Vehicle Chassis Systems

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Abstract

Fluid power is the backbone of a motor vehicle chassis system. The design of the fluid power system determines whether the ride quality and maneuverability of the vehicle are acceptable. One of the most difficult problems in chassis design analysis is to resolve the interfacing equations between the mechanical structure and the fluid power system. The complexity of the design analysis becomes even greater if there is any chassis control strategy involved.

This paper presents an innovative modeling technique for interfacing the mechanical dynamics of the chassis with the fluid power system. The technique used here is called "Interfacial Modeling" or "Visual Modeling." In this modeling approach, fluid power components and mechanical structural elements are iconized to incorporate the necessary mathematical models needed to represent the system. These character instilled icons become the building blocks to formulate a chassis system. Implementing these icons with the system integrating algorithms results in an effortless analysis and design task. This paper reveals the interfacial modeling principle and illustrates the benefit of this technique with practical design examples related to vehicle chassis systems.

Introduction

Ride environment and maneuver quality are many times the first impressions when people judge the design and manufacture integrity of a vehicle. These two factors are essentially determined by the design quality of the chassis system. However, people's perception on "quality" is very subjective. This situation underlies the difficulties in designing a chassis system that will satisfy everyone's conception of quality. Therefore, modular and adaptive design approaches have become the trend to accomplish a versatile chassis environment. The ultimate goal is to have a chassis system that can be "tuned" to provide the performance demanded by the driver and/or passengers under any operating condition and/or environmental exposure. Nevertheless, physically, a vehicle chassis system is composed of many interconnected subsystems. The performances of these

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subsytems are dynamic. This means that they are usually changing with time. The subsystem reacts dynamically not only to other subsytems but also with its own internal components. This dynamic interactive characteristic greatly increases the complexity of designing a quality chassis system using ordinary engineering approaches.

Fluid power is the backbone of a motor vehicle chassis system. A look at a few chassis subsystems, such as suspension, power brake, power steering, effectively reveals just where and how fluid power (hydraulic and/or pneumatic) components are being utilized to provide and satisfy the chassis function. The design of the fluid power system determines whether the ride quality and maneuverability of the vehicle are acceptable. To achieve a desired chassis environment, a number of fluid power variables must be controlled in the subsystems—such as the damping orifice size in the suspension system and the power steering pressure. Nearly all of these variables are dynamically interactive and highly nonlinear. Therefore, the design of these subsystems becomes almost impossible without using a computer to process such complicated dynamic and nonlinear characteristics. Unfortunately, the computer cannot be used without having proper modeling and design algorithms.

In the early days of using a computer as a design tool, the designer not only was required to be intimately familiar with fluid power components and system, but also be a mathematical whiz and a computer expert. Obviously, such a combination of talent is very unique. However, the advent of the personal computer and the development of computer aided design and analysis software has given engineering design a new dimension. Today, it is recognized that an effective computer aided design and analysis procedure literally makes available the brains of the experts that created the package. With such a package, those without an engineering background in system design and numerical analysis can implement their new machine system with sophisticated hardware. The designer can quickly try all types of candidate components and control strategies for a proposed system and immediately see whether the response, controllability and functionality they produce satisfy the desired specification.

In essence, a vehicle chassis system involves a diverse technical discipline. This results from the complexity in modeling a component and implementing system solving algorithms. One of the most difficult problems in chassis design analysis is to resolve the interfacing relationship between the mechanical elements and the fluid power components. Moreover, the complexity of the design analysis becomes even greater if there is any chassis control strategy involved in a situation, which is a very common practice in today's automobile design. This makes the computer aided design analysis of a chassis system very challenging.

This paper presents a modeling technique, called Interfacial Modeling, for interfacing the mechanical dynamics of the chassis with the characteristics of the fluid power system. This technique will unify the various technical disciplines and seamlessly formulate system dynamic equations based on the topographical information of the system. The benefit of the interfacial modeling technique will be demonstrated using practical design examples related to vehicle chassis systems.

The Interfacial Modeling Technique [1,2,3,4]

Design analysis requires a model of the physical system. The model may be derived analytically (mathematical model), empirically (physical model) or semi-empirically. However, in any case the model is just a simplification of the reality that can approximately describe the characteristics of a physical system. Additionally, no matter which way the model is derived, it is likely to be useless unless the model can be converted into a form that is suitable for computer manipulation. It should be noted that modeling is not an addition to the design process because the designer has at least already formulated a conceptual model, a schematic model most likely, and/or a mathematical model perhaps prior to the design and manufacturing activities.

At the theoretical development level, modeling is a way of formalizing the thought process so as to make the characteristics of even the most complicated system tractable. In general, a model can be considered as a set of equations. Mathematically speaking, equations relate unknown quantities to known quantities, and the values of the unknown quantities can be determined in terms of the known quantities using the equations. They can also be manipulated so that what was formerly an unknown quantity becomes now a known quantity and vice-versa. In other words, a model is to transform a set of known quantities (inputs) to obtain a set of quantities (outputs) that were originally unknown. The repetition of this input/output transformation process with the consideration of the time effect characterizes the dynamic performance of a physical system. In this regard, the object of modeling is to derive a set of equations that can be used to portray the behavior of the system according to a set of known quantities.

The behavior of a real physical system is controlled by the flow, storage and interchange of various forms of energy. Therefore, system performance can be explored analytically if the energetic actions and interaction in a given system can be described mathematically. Depending upon the manner in which system elements handle the flow of power and energy transfer, system elements can be classified as energy storage or dissipation elements. Energy storage elements can be further separated into the type of parameters that are critical—across type (A-type) or through type (T-type). The A-type variables act across the elements such as pressure, velocity, and voltage; while the T-type variables pass energy through the elements such as flow, force and current. The energy dissipation elements are called D-type elements such as orifice, friction, and resistors. Since the elements can always be represented as an A-type, a T-type or a D-type regardless of the engineering disciplines (hydraulic, mechanical, electric etc.) employed, the possibility exits of unifying all engineering system models. This unique parameter unification approach lays the foundation for the computer to process the interfacing between different engineering models.

A system is a composition of many interacting components. The interaction takes place by the exchange of energy. System modeling is to handle the interaction characteristic between components. Unlike component modeling, which it tends to be subjective in dealing with a component alone, system modeling is more objective in that it considers the synergistic effects among components as well as their interaction with the surrounding environment. For the convenience of modeling a system, it is more appropriate to consider a component to have a set of well defined power ports through which all energy transfers are accomplished. Since all physical systems obey the law of conservation of energy, this property can be used to establish a relationship between the energy transactions at the various ports of a system. In order to account for the dynamic effects, it is a common practice to use the rate of energy (power) transfer at each component port. The use of power variables has a great advantage in system modeling due to the fact that the power at each port is the product of two dynamically meaningful quantities—the A-type and the T-type variables. For example, it is the pressure and flow rate for hydraulic power, the velocity and force for translational mechanical power and the voltage and current for electric power. Consequently, the A-type and T-type energy variables are the communication flag among components. This power port approach dramatically simplifies the component model structure because internally the only variable required for formulating the component model is the D-type variable. This allows the possibility of iconizing each component with its mathematical model.

Interfacial modeling consists essentially of both component modeling and system modeling. At the component modeling level, it iconizes each engineering component of interest by setting the A-type variables as the state variable and the T-variables as the derived variables. The D-type variable is the model equation to derive the T-type variables from their related A-type variables at each power port. For example, an orifice has two ports. The orifice flow (T-type) at each port can be calculated from the orifice coefficients (D-type) and the square root of the pressure drop (A-type) across the orifice. Then an icon representing the component will be established and bears this A-D-T structure to form the building blocks for the system.

At the system modeling level, when a system is completely and correctly connected, the interfacial technique not only extracts the A-D-T equations from the component, but also employs three important conditions to form the system model. These three conditions are called compatibility, continuity and constraints as described below:

> **Compatibility Condition**—This is sometimes referred to as the path law and results in a relationship among the various across variables. Stated in very simple terms, the compatibility condition provides that the summation of the A-type variable around any closed path must equal zero. On the other hand, compatibility requires equal (compatible) A-type quantities at the points where the power ports are connected.
>
> **Continuity Condition**—This is sometimes referred to as the vertex law and results in a relation among the various T-type variables. In simple terms, the continuity condition states that the sum of the T-type variables at any node (point of port connection) must be zero in the steady state. There are as many node equations as there are nodes in the system. By considering the capacitance effect, these node equations form the system dynamic model.
>
> **Constraint Condition**—This deals with the geometric constraints and physical boundary conditions. It is the constraints that are imposed on the motions of the elements. Normally, the constraint condition is a combination of a set of non-linear algebraic equations and some known boundary values. In the mechanical system, if the displacement is assumed as an A-type variable, then the constraint condition is equivalent to the compatibility condition. However, for the convenience of analysis, the interfacial modeling treats the compatibility condition and constraint condition separately.

Obviously, from the above statements, the component interaction is handled at the system modeling level and the power variables are unified. This allows the interfacial modeling algorithm to be implemented on a computer and to be manipulated using any mixed engineering systems. Because a system model is represented visually by a component icon that carries a component performance mathematical model, interfacial modeling is also called "Visual Modeling." To demonstrate the concept of interfacial modeling, the modeling procedures stated above are linked with a system circuit drawing routines so that the iconized components can be accessed to form system models. This unification results in a complete software package called "HyPneu." HyPneu is used to illustrate the advantages of using interfacial modeling techniques with two major chassis subsystems—the suspension system and the power steering system.

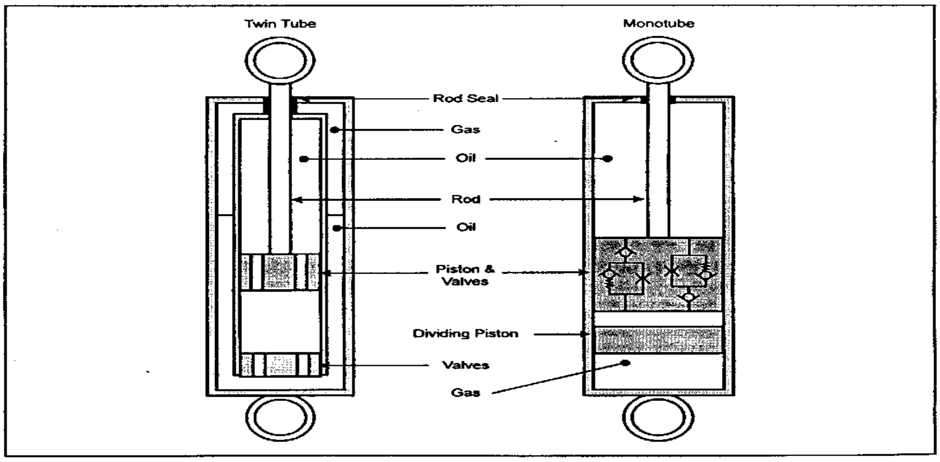
Case Studies

Case 1—The Suspension System [5,6]

A vehicle is a dynamic system. It can be excited by many sources such as road roughness, engine vibration, wind speed and direction, etc. For years, vehicle engineers have tried many possible means to minimize the disturbance that may be transmitted to the passengers. One such means is the control of suspension damping force which is primarily accomplished by the use of hydraulic shock absorbers. In structure, a shock absorber is fundamentally a hydraulic device that relies upon various valving designs to control pressure and to dissipate the energy of the suspension that absorbs the shock from the excitation. Tuning the hydraulic system to provide a desired shock absorption condition has been an art. A low damping ratio may not be able to provide enough flow restriction to dissipate the shock energy while too high a damping ratio may lose good tire-to-road contact resulting in a safety concern. Therefore, there is a need to tailor the shock absorber to achieve optimum performance.

In practice, there are two types of fluid power shock absorbers used in most automotive suspension systems. These are the twin tube and the gas-pressurized monotube as illustrated in Fig. 1. Each has its own advantage, but functionally they are similar. During compression and extension, the piston moves through the fluid in its bore. Valves in the piston restrict the flow of fluid through the piston creating the damping force. Normally piston valves consist of a bleed orifice, a blow-off valve and a reverse flow check valve. The shock absorber is tuned to provide an optimum damping of the motion of the sprung and unsprung masses by adjusting the parameters of these three control valves. What is important in the performance of a shock absorber is its characteristic curves of absorber's reaction force to the velocity and to the displacement due to the excitation. Obviously, neither the valving curves nor the force-velocity-displacement curves are linear. This creates complexity in the tuning process without the use of techniques such as the interfacial modeling method presented in this paper.

Figure 1
Twin Tube and Gas-Pressurized
Monotube Shock Absorbers



In this study, a gas-pressurized monotube shock absorber is used to demonstrate the design analysis using interfacial modeling. The schematic as shown in Fig. 2 is produced by selecting the appropriate icons from the HyPneu library for a monotube shock absorber as shown in Fig. 1. Note that each icon has a well defined set of power ports to represent its related component function. Internally, the icon also carries the A-D-T type component model. The circuit is designed to mimic a Gabriel type test system to evaluate the performance of a shock absorber. In the test, the absorber is held vertically and the excitation is a sinusoidal velocity which generates a sinusoidal displacement to simulate the road roughness. It can be seen from Fig. 2 that the shock absorber is represented by a double acting, single rod hydraulic cylinder. Both the rebound and compression valving are modeled by a flow restrictor for a bleed orifice, a relief valve for a blow-off valve and a check valve. The pressurized gas chamber is represented by an accumulator.

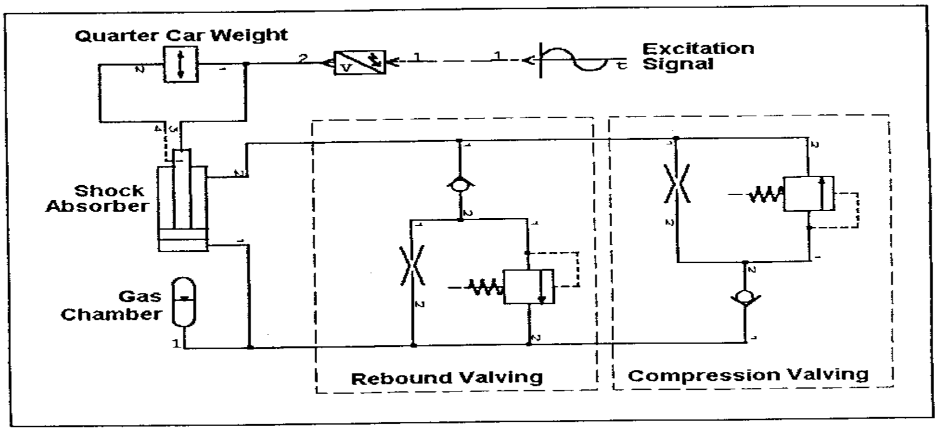


Figure 2
HyPneu Schematic of Passive Shock Absorber System

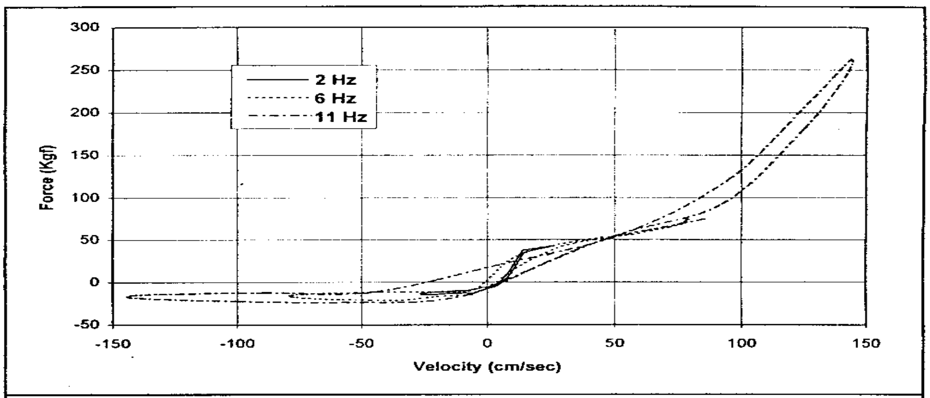
To run the analysis, each icon must contain design parameter values. The design data for the major components used in the simulation are as follows.

Shock Absorber:	piston diameter 3.2 cm, rod diameter 2.2 cm, stroke 25 cm
Bleed Orifice:	flow area 0.02 cm^2, valve coefficient 0.61
Blow-off Valve:	blow-off pressure setting 10 bar, maximum pressure override 5 bar
Quarter Car Weight:	400 Kgf

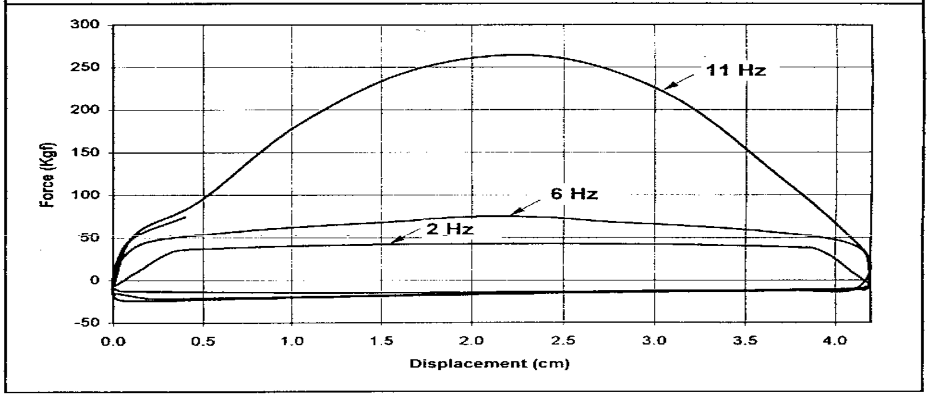
The excitation displacement for each has an amplitude of 2.1 cm (4.2 cm peak to peak) with frequencies of 2 Hz, 6 Hz, and 11 Hz, respectively. The simulation results are shown in Fig.3. Fig3(a) shows the characteristic of the absorber's reaction force to the excitation velocity while Fig3(b) shows the force to the excitation displacement. The curves certainly provide valuable information for the shock absorber designer to tune their system for optimum performance.

Although the example shown in Fig. 2 is a typical passive shock absorber, the analysis procedure used in this study can be directly applied to model any shock absorber system such as active or semi-active. For instance, the additional icons required for the active shock absorber system are the control icons, that account for feedback signals, and the related control algorithms. Also, the active suspension system requires adjustable metering valves instead of using fixed orifice valves.

Figure 3
Suspension System Simulation Results



(a)
Absorber Reaction Force vs. Velocity



(b)
Wheel Angle vs. Cylinder Displacement

Case 2—The Power Steering System [7,8,9,10]

The function of a steering system is to steer the vehicle according to driver command inputs to provide overall directional control. The design of the steering system has a direct influence on the maneuverability of a vehicle. Today the need for static torque is becoming greater and greater because of the vast use of radial tires, the tendency toward front wheel drive, and more concentration of weight at the front of the car. This trend motivates the ever increasing use of power assisted steering systems in passenger cars. In practice, the actual steering angle achieved is modified by the geometry of the suspension system to gain a mechanical advantage. The power transfer from the steering wheel to the vehicle wheel is accomplished by a series of hydraulic components and mechanical linkages. Although there are a variety of power steering designs, they are functionally similar. Fig.4 shows a typical power steering system. It consists of a steering wheel connected directly to the spool of a rotary steering valve. The steering wheel is also connected to the feedback rack of the steering cylinder through a torsion tube. The output of the rotary steering valve is connected to a steering cylinder which in turn is connected to the wheels through a mechanical linkage. The hydraulic steering cylinder displacement is used as a feedback to the rotary valve via a rack type connection. Apparently, it is a designer's nightmare to analyze the dynamic performance of such a complex power steering system. However, the analysis will be very straightforward using the interfacial modeling approach because the analysis procedure apply equally to either a simple system or a very complicated system as long as all appropriate icons are available.

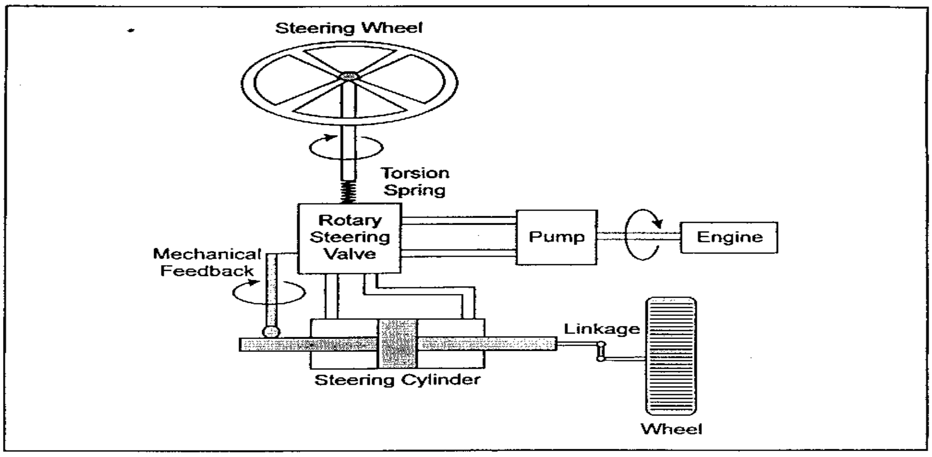


Figure 4
Schematic of Power Steering System

In the design stage, it is in the engineer's interest to know the proportionality of power assistance to the steering wheel torque. Normally, the power assistance gain is characterized by the static pressure drop across the rotary steering valve versus the opening area (restriction) of the valve. The pressure gain curve can be tuned to provide the optimum assistance needed for any driving condition.

As mentioned previously, a vehicle is a dynamic system and all power steering systems are feedback systems. This unique combination causes the power steering systems to be stability sensitive. Therefore, in addition to the pressure gain characteristic, the overall steering system performance to the operation duty cannot be overlooked. Fig.5 shows an iconized power steering system to evaluate the pressure gain and overall steering system performance. The system is powered by a hydraulic pump with a relief valve and a flow control valve. For simplicity, the rotary steering valve is represented by a white-stone bridge equivalent circuit. The restrictions of the orifices are controlled by the angular difference between the spool and the sleeve of the rotary steering valve. The design data for major components used in the analysis are as follows:

Pump:	9.5 liter/min at 1000 rpm
Steering Cylinder:	piston diameter 4.0 cm, rod diameter 1.25 cm, stroke 40 cm
Rotary Steering Valve:	the combined flow area is assumed to be linear to valve displacement Xv as 0.065 + 0.01Xv for opening, and 0.065 - 0.01Xv for closing.

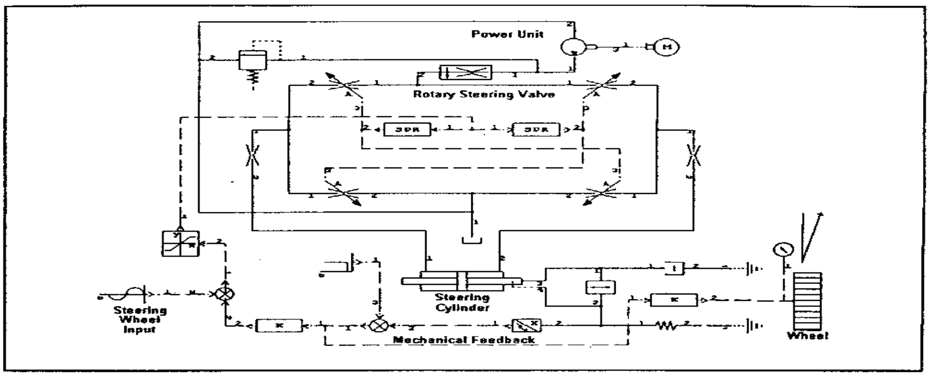


Figure 5
HyPneu Schematic of Power
Steering System

In the pressure gain analysis, the valve ports to the steering cylinder are blocked. The steering wheel angle varies from 0 to 6 degrees in one direction. The simulated pressure gain curve is as shown in Fig.6(a). In the operation performance analysis, the steering wheel is turned to 180 degrees to the right in 1 second and in the next second the wheel is turned back and forth at a magnitude of 100 degrees at 2 Hz. The result of the steering wheel angle and the cylinder displacement is shown in Fig.6(b). Increasing the wheel oscillation may cause instability of the system.

Conclusion

The design process has changed significantly since the advent of computers and effective software. The days when a design engineer develops a system through trial-and-error or over-simplified techniques are rapidly coming to an end. The interfacial modeling technique presented in this paper fills a serious void in today's design analysis and provides engineers with an effective tool to conquer the challenges of rapid advancements in technology. The use of iconized models for building engineering sytem models makes the dream of "simulation before fabrication" a reality.

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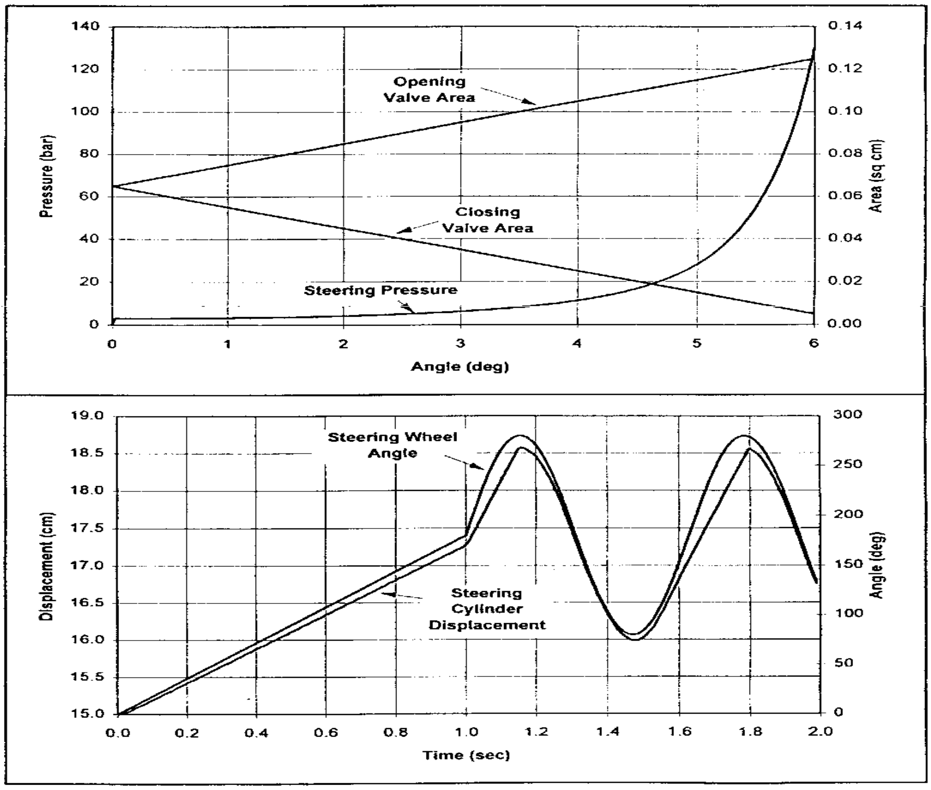
Figure 6. Power Steering Model Simulation Results



(a)
Pressure Gain Curve

(b)
Wheel Angle and Cylinder Displacement vs. Time