Int. J. Engng Ed. Vol. 11, Nos 4 and 5, pp. 358–368, 1995
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Fluid Power and Control: An Introduction through Laboratory Exercises

R. J. SMITH*
A. AKERS†
M. P. GASSMAN‡
**Agricultural Engineering, †Aerospace Engineering and Engineering Mechanics and ‡Mechanical Engineering, Iowa State University, Ames, IA 50011, USA*

Until recently, most fluid power devices operated in an open-loop mode. If the load cycle details were known, then sizing components and determination of pressures followed routine procedures. Now, however, the availability of solenoid-operated servo valves incorporating spool position feedback elements enable sophisticated closed-loop devices to be implemented economically. Design of such automatic-control devices uses coursework taken elsewhere in the curriculum, but few four-year programs offer hands-on laboratory exercises in fluid power control. Laboratory exercises are described that have been developed to bridge the gap between theory and practice.

EDUCATIONAL SUMMARY

1. The paper describes new training tools or laboratory concepts/instrumentation/experiments in fluid power systems and control.
2. The paper describes new equipment useful in courses on fluid power and control theory.
3. The students involved in the use of the equipment are seniors at a four-year college.
4. This is the first time presentation of experimental aspects of control of a fluid-power system.
5. The material presented is incorporated in engineering teaching during 16 afternoon laboratory periods.
6. The text accompanying the presented materials is H. E. Merritt, *Hydraulic Control Systems* (1967), as well as various class notes and laboratory notes.
7. The concepts presented have been tested in the classroom. There has been moderately good agreement of experiment with theory in all tests; excellent agreement in some.
8. It is rare for a four-year school to have experimental work to support fluid-power courses.

INTRODUCTION

DURING THE past ten years, Iowa State University (ISU) faculty involved in fluid-power teaching and research have made many visits to Sauer-Sundstrand (Ames, IA), Sundstrand (Rockford, IL), John Deere (Waterloo, IA), Caterpillar (Peoria, IL) and Sun Hydraulics (Sarasota, FL). After enquiring as to suitable classroom and laboratory experiences for graduates, there was, without exception, a clear indication that the majority of four-year engineering programs were not perceived as providing even a basic knowledge of fluid-power technology and control. Although the ISU was offering lecture courses, the laboratory offerings were regarded as woefully inadequate. This paper will describe the laboratory exercises that have been developed to remedy the deficiencies perceived by industry. Funds were provided by the NSF-ILI program and matching funds from the ISU.

When fluid-power engineering is taught in four-year schools in the United States, a number of barriers must be overcome. The problems include the diffuse nature of fluid-power instruction, correct technical preparation and the diverse disciplines on which the subject draws. Difficulties in teaching the subject have been outlined [1]. As a result of these difficulties, and due to the perceived elementary nature of the subject, academic recognition by senior university administrators is seldom achieved.

It is true that when the finished product, the fluid-power device, is used in open-loop systems, then the degree of analytical expertise needed for design is often minimal. There are, however, many very sophisticated applications that simply would not work unless the designer had a comprehensive knowledge of mathematical control theory. One example is the hydrostatic transmission that couples an aircraft engine to the electrical generator. The speed of the engine will vary over a wide range, as will the load on the generator. During these fluctuations, the speed of the generator must remain essentially constant. The design of such a transmission is not trivial, a fact that may be recognized by observing that virtually all civilian aircraft built in the western world use a transmission from one company (Sundstrand Avionics). Although proprietary, this device is mentioned because it can only be realized economically by using fluid-power technology. Another example would be the control of machine tools by fluid power. The slide on a mill or lathe must move under the control of a machining program, yet there must be no overshoot or oscillation. Such machine-tool operation is routinely achieved by fluid power because this offers the best combination of speed, rigidity and small component size currently available.

When the average student is first confronted with a course in control theory that lacks laboratory exercises, that student is sometimes overwhelmed by the abstract mathematics that do not seem to relate to reality. In many respects, however, we perceive the mathematics of 'pure' control theory to be easier for a student to grasp on a rote-learning basis than are the approximations and simplifications that must be made when a real component is being modelled mathematically. The laboratory course which serves agricultural engineering and mechanical engineering majors is AE/ME 413, and is described in this paper. We believe that the course will have a major impact on the integration of seemingly abstruse theory and practical applications.

A semester at ISU contains 16 laboratory periods. The laboratory exercises reinforce the main topics in the two lecture courses on fluid power control systems, ME 414 (three credits) and AE 447 (two credits). These courses follow the pattern that is taken in fluid power control texts [2–4]. These courses have some overlap, but are by no means identical. Mechanical engineering students will have taken a course in automatic controls before registering for ME 414. On the other hand, agricultural engineering students do not have this background. Thus ME 414 places more emphasis on modelling components using programmes like HYSAN [5] and CSMP [6]. In AE 447 about one-third of the course is a brief introduction to control theory. The students are then shown how to develop transfer functions for a valve-controlled pump and valve-controlled motor, and these components are then used in simple feedback circuits. Both classes, however, go through the basic modelling of valves, pumps and motors covered by Merritt [3].

The objective of the laboratory is to introduce the following broad topics:

- Fluid properties
- Head loss in pipes and fittings
- Valve characteristics
- Motor characteristics
- Measurement of open-loop transfer function for a valve-controlled cylinder
- Measurement of open-loop transfer function for a valve-controlled motor
- Feedback control of the position of a linear actuator
- Feedback control of angular velocity
- Computer simulation of fluid power devices to study their dynamic behavior

LABORATORY EXERCISES

1. Density and viscosity of common fluids used in fluid-power systems (current)

Outline. Several different compositions of hydraulic fluids are examined, including a sample of the fluid currently in use in the test stand. Viscosity is measured with a rotating bob viscometer with digital readout (Brookfield LVT) and density with a hydrometer. Measurements are made at three different temperatures.

Object. These properties are important in fluid power, in particular viscosity variation with temperature has a profound effect on system performance.

2. Inspection of partly disassembled fluid-power equipment; disassembly and reassembly of a small hydrostatic transmission (current)

Outline. Several pieces of equipment that are no longer serviceable but can be disassembled for student examination have been accumulated. Some commercially sectioned equipment is also available. The students are also able to disassemble and reassemble a Sauer-Sundstrand Series 15 integral transmission.

Object. Students need the opportunity to examine real equipment; drawings in texts seldom display the three-dimensional relationships adequately.

3. Examination of standard connections used in fluid-power systems and the development of a schedule of hoses, tube and fittings for a specified circuit (current)

Outline. Determination of the schedule of fittings required to assemble a circuit of any appreciable complexity is not trivial. The students use the existing plumbing on the main test stand as a guide when they develop their own schedule for the given circuit. A library of proprietary equipment catalogs is available.

Object. Design is a recognized part of engineering education. Selecting fittings is not an academic exercise, but it is an essential part of designing a fluid-power system.

4. *Instrumentation for measuring the characteristics of fluid-power systems (current)*

Outline. The basic equipment for measurements of pressure, flow and displacement is demonstrated. Interfacing of sensors with microcomputers is discussed in the context of signal conditioning, bandwidth and software. Sensor technology is also discussed. Examples of computerized datalogging used by industry (e.g. Sauer-Sundstrand, John Deere) is presented. The students are introduced to the problem of sampling frequency by an experiment that records samples from a sine wave generated by a signal generator. Currently the software being used on the PC-based datalogger samples at 2500 Hz. Signal generator frequencies from 1 to 5000 Hz are used and the students attempt to recover the original signal from the samples using least-squares curve fitting. They are able to observe aliasing when the Nyquist sampling criterion is violated.

Object. Computer datalogging is replacing recording oscilloscopes or pen recorders. Students need exposure to the modern datalogging technology that they will encounter in industry. The students also need to recognize that sampling frequency must be adequate to capture transients that occur during dynamic testing.

5. *Calibration of pressure transducer using a deadweight tester (current)*

Outline. A pressure transducer is connected to a deadweight tester. A sequence of pressures from 1.5 to 17.5 MPa can be developed. Because these pressures are caused by a known mass acting on a known area the pressures are both precise and accurate.

Object. The primary objective of this test is to verify the calibration of the transducer under test. An interesting secondary feature of the test is the demonstration of quantization error. An analog-to-digital converter can only present output in discrete steps, e.g. a 10-bit converter can only generate $2^{10} = 1024$ values. There is some electrical noise in the datalogging system so the students are easily able to observe that the digital readings only appear on plateaux. The students calculate the relative error in the reading as the weights are applied in sequence, and they quickly notice that it is not advisable to use a transducer at the low end of its range.

6. *Head losses in tube, hose and fittings (current)*

Outline.

The main stand with its variable-displacement pump and flowmeter is used as a source of temperature-controlled oil (Fig. 1). The pressure drop across sections of tube, hose or fittings is measured with differential pressure sensors. Viscosity results obtained in the first laboratory exercise (see above) are used to generate friction factor vs. Reynolds number graphs for the pipe flow tests.

Object. Pressure drops in systems affect performance; students need a basic laboratory on this topic.

7. *Effect of bulk modulus on system natural frequency (current)*

Outline. Oil is aerated at atmospheric pressure. A portion of this oil is pumped into the rod side of a vertical cylinder in the device shown in Fig. 2. The aerated oil is retained by closing valves. The oil pressure may be changed by altering the number of weights that are attached to the rod end. The system is set into oscillation by allowing the frame supporting the top of the cylinder to drop 6 mm until the frame encounters the frame of the device. The pressure history of the oil is recorded using a strain gauge pressure transducer that is read using the datalogger described in the exercise on instrumentation (see above). It may be shown that the oil pressure in the system should obey the relationship

$$p(t) = \omega_n^2 \frac{a}{A} \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin\left(\sqrt{1-\zeta^2}\,\omega_n t\right) \quad (1)$$

where

$$\omega_n = \sqrt{\frac{A\beta_e}{lm}} \quad (2)$$

The unknown variables in this relationship (a the impulse magnitude, ω_n the system natural frequency, and ζ the system damping coefficient) are determined by a least-squares procedure using MINPACK [7]. The effective bulk modulus can be determined from ω_n and the geometry of the trapped oil column (A = column cross-sectional area, l = column length, m = mass in vibration).

Object. This laboratory exercise does not claim to be an accurate method of measuring effective bulk modulus, but it does demonstrate quite clearly that oil is compressible and can act as a spring. Such compressibility is a new concept to students who have only been exposed to conventional fluid mechanics courses in which liquids are usually treated as incompressible. Bulk modulus is a key parameter in modelling many fluid-power components. An assumption of complete fluid incompressibility would lead to prediction of infinite pressure rises.

8. *Assembly and test of simple circuits using the Vickers trainer (current)*

Outline. The students assemble simple circuits incorporating cylinders, motors, directional valves, relief valves and flow-control valves.

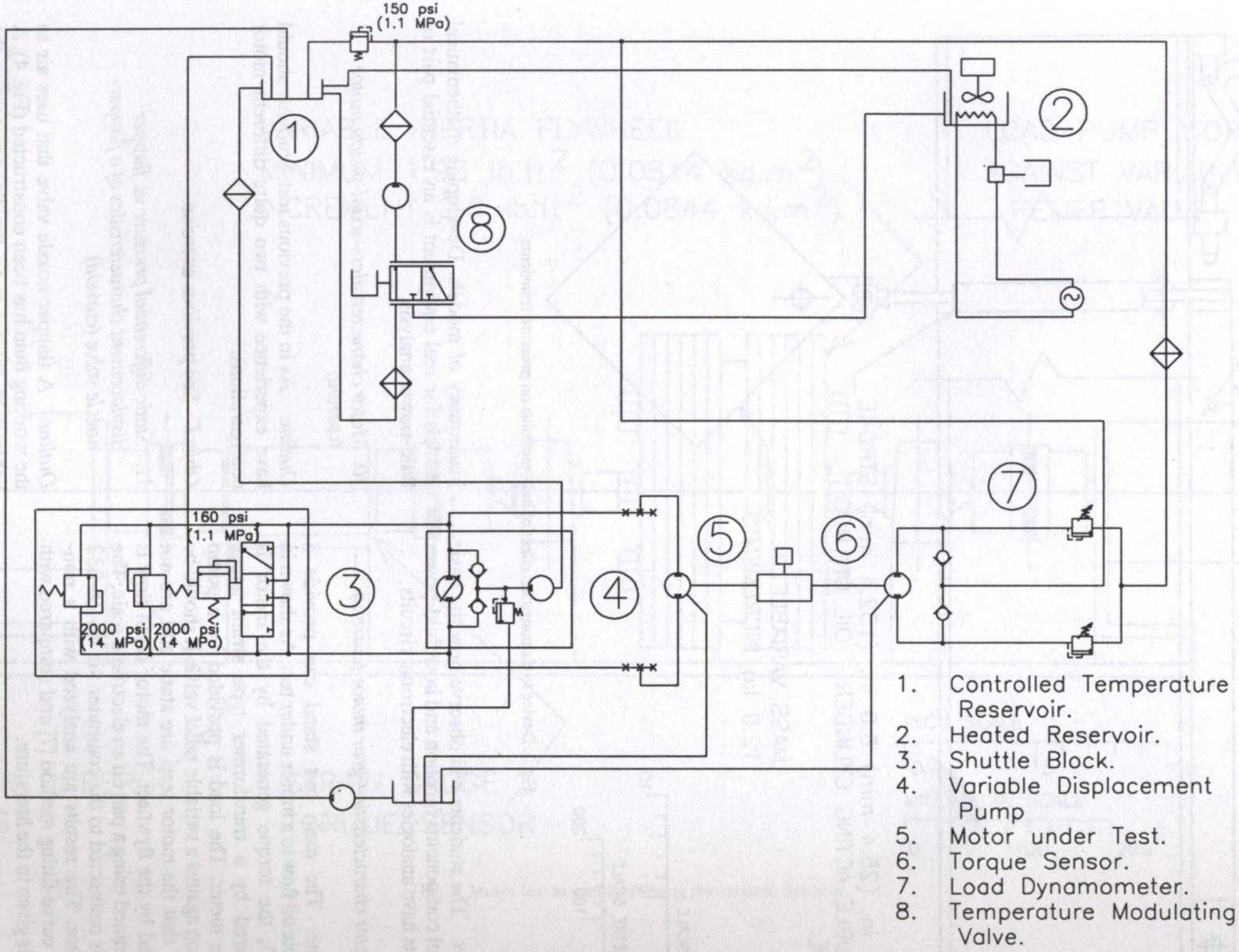

Fig. 1. Main test stand schematic.

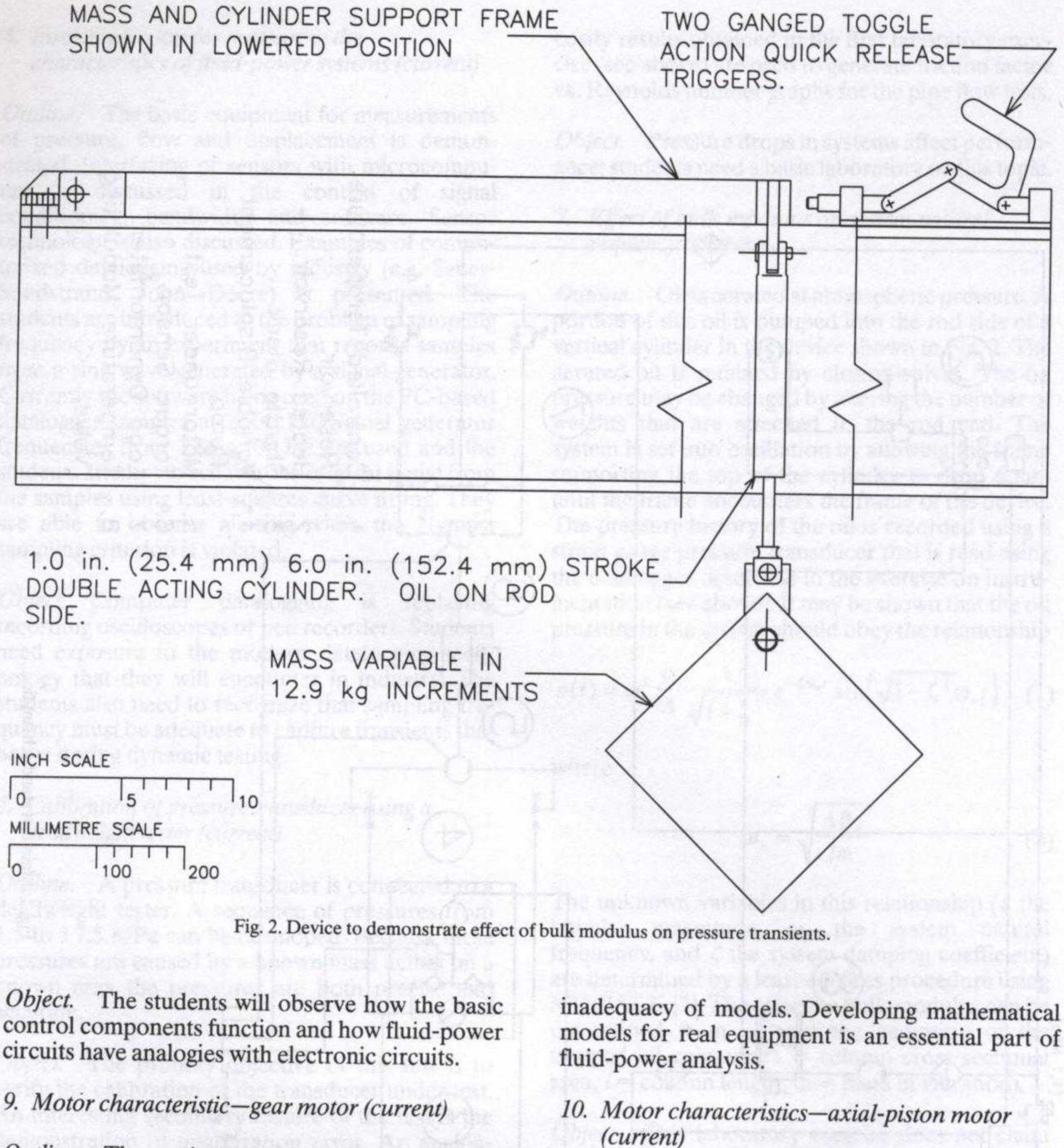

Fig. 2. Device to demonstrate effect of bulk modulus on pressure transients.

Object. The students will observe how the basic control components function and how fluid-power circuits have analogies with electronic circuits.

9. Motor characteristic—gear motor (current)

Outline. The main test stand can provide a variable oil flow to a motor under test. As shown in Fig. 3, the torque generated by the motor is measured by a transformer type strain gauge torque meter. The load is provided by a pump working against a variable relief valve. It should be noted that the motor tests are static and are not affected by the flywheel. The motor drain flow is determined using a pan on an electronic scale. The scale is connected to the computer via an RS-232 interface. The results are analyzed with a non-linear curve-fitting method [7] and compared with models given in the literature.

Object. Real motors can be approximated by mathematical models that account for leakage, Coulomb friction and viscous drag. Comparing experimental results with mathematical models will give the students information on the validity or inadequacy of models. Developing mathematical models for real equipment is an essential part of fluid-power analysis.

10. Motor characteristics—axial-piston motor (current)

Outline. As in the previous test. Students should have experience with two quite different motor configurations.

Object. See previous exercise.

11. Static differential pressure vs. flapper displacement characteristics of a flapper-nozzle valve (current)

Outline. A flapper-nozzle valve that uses air as the working fluid has been constructed (Fig. 4). A lightweight extension to the flapper carries the armature of an LVDT. The supply pressure to the unit is measured with a Bourdon gauge and the differential pressure across the flapper is measured by a diaphragm gauge with digital readout. The dimensions of the upstream orifices, the flapper

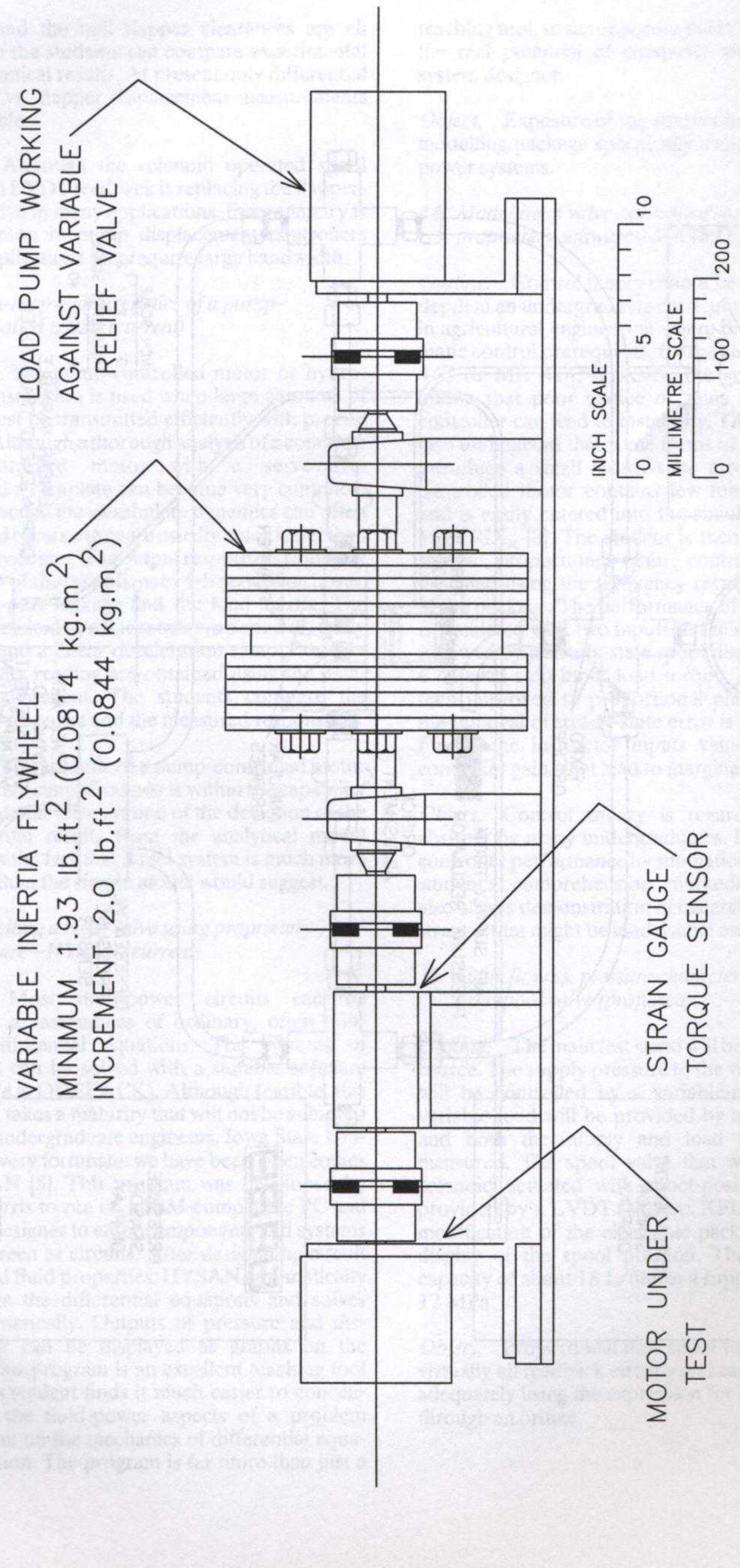

Fig. 3. Motor test assembly showing the variable flywheel.

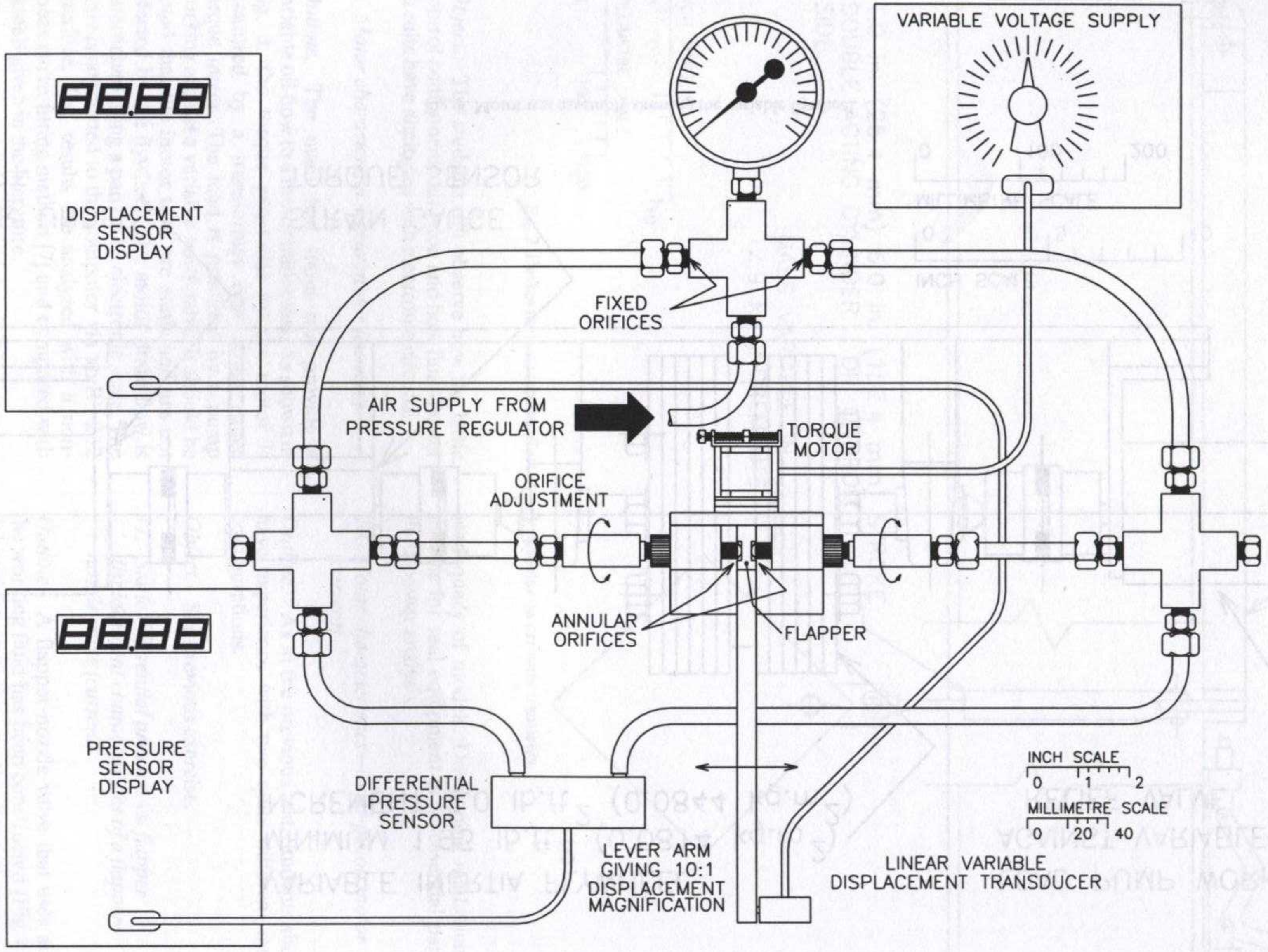

Fig. 4. Flapper nozzle valve using air as the working fluid (not to scale).

orifices and the null flapper clearances are all known so the students can compare experimental and theoretical results. At present only differential pressure vs. flapper displacement measurements are possible.

Object. Although the solenoid operated spool valve with LVDT feedback is replacing the flapper-nozzle valve in many applications, this geometry is still common in pump displacement controllers and in applications that require large bandwidth.

12. Open-loop characteristics of a pump-controlled motor (current)

Outline. The pump-controlled motor or hydrostatic transmission is used when large amounts of power must be transmitted efficiently with precise control. Although a thorough analysis of a complete pump-controlled motor with a servovalve-controlled swashplate can become very complicated, in practice the swashplate dynamics can often be ignored because they are usually much faster than the load dynamics. The output response is primarily a function of the compliance of the coupling hoses, the cross-port leakage and the load inertia. The system is excited by a linear ramp, a period of steady velocity, and a linear deceleration ramp. Pressure and velocity reading are obtained using the data-logging equipment. The students compare the analytical response and the measured response.

Object. The analysis of a pump-controlled motor given certain simplifications is within the capability of the students. Observation of the deviation of the experimental results from the analytical model reinforces the fact that a real system is much more complex than the simple model would suggest.

13. Modelling a relief valve using proprietary software—HYSAN (current)

Outline. Most fluid-power circuits can be modelled as assemblies of ordinary, often non-linear, differential equations. The systems of equations can be solved with a suitable software package (e.g. ODEPACK). Although feasible, this approach takes a maturity that will not be achieved by most undergraduate engineers. Iowa State University is very fortunate: we have been given copies of HYSAN [5]. This program was developed by Hugh Morris to run on a IBM-compatible PC and allows a designer to enter components and systems on the screen as circuits. After designating circuit values and fluid properties, HYSAN automatically formulates the differential equations and solves these numerically. Outputs of pressure and displacement can be displayed as graphs on the screen. This program is an excellent teaching tool because a student finds it much easier to concentrate on the fluid-power aspects of a problem rather than on the mechanics of differential equation solution. The program is far more than just a teaching tool, so the exposure to HYSAN indicates the real potential of computer modelling for a system designer.

Object. Exposure of the student to a commercial modelling package specifically designed for fluid-power systems.

14. Modelling a valve-controlled motor using proprietary software—MATRIX$_X$ (current)

Outline. Control theory cannot be approached in depth in an undergraduate curriculum, particularly in agricultural engineering where there is no automatic control prerequisite. By the end of either AE 447 or ME 414, however, the student at least knows that poor choice of gains in a feedback controller can lead to instability. The student may also understand that some forms of controller can introduce a small steady-state error. The valve-controlled motor contains few functional blocks and is easily entered into the simulation package MATRIX$_X$ [8]. The student is then shown how a simple proportional gain controller can be designed using the frequency response capability of the package. The performance of this controller is simulated with two inputs to the system: a ramp followed by a steady-state spool displacement and a delayed step input load torque. The control is then improved to proportional plus integral and the removal of steady-state error is demonstrated. Finally the instructor inputs values of the two controller gains that lead to marginal instability.

Object. Control theory is regarded as rather abstract by many undergraduates. Demonstrating controller performance by simulation improves the student's comprehension markedly. Simulation also allows demonstration of instability—a demonstration that might be inadvisable on a real system.

15. Static flow vs. pressure characteristics of a four-way spool valve (proposed)

Outline. The main test stand will be used as the oil source. The supply pressure to the valve under test will be controlled by a variable-relief valve. A variable load will be provided by a needle valve, and both the supply and load flows will be measured. The spool valve that will be used is solenoid actuated with spool-position feedback provided by a LVDT (Vickers KFDG4V). Minor modification of the electronic package will allow display of the spool position. The valve has a capacity of about 18 L/min at a supply pressure of 12 MPa.

Object. Proportional flow spool valves appear in virtually all feedback circuits and can be modelled adequately using the expression for turbulent flow through an orifice.

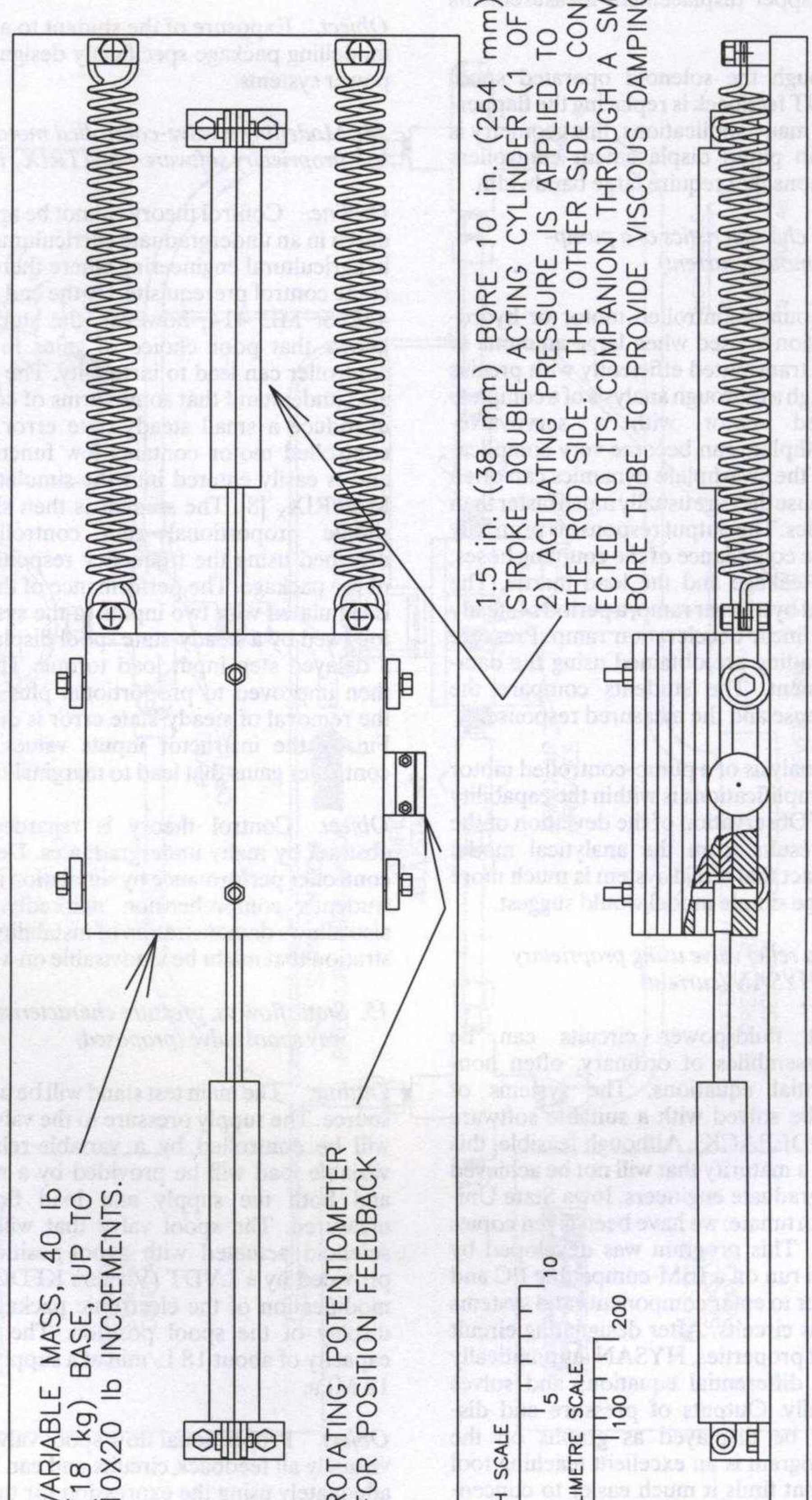

Fig. 5. Linear actuator with position sensor for feedback

16. Open-loop characteristics of a spool-valve controlled linear actuator (proposed)

Outline. A cylinder will be connected to a mass, spring and a capillary damper (Fig. 5). Actuator displacement will be measured with a potentiometer so that displacements up to 150 mm may be achieved. The actuator will be controlled by the proportional spool valve that had its characteristics determined in an earlier exercise. A variety of input signals, e.g. step, ramp, sinusoidal, will be investigated and the students will compare the measured transfer functions with the linearized models given in standard fluid power texts.

Object. Demonstration that linearized models are often adequate for small displacements will be possible, but large displacements cause nonlinearity.

17. Closed-loop characteristics of a spool-valve-controlled linear actuator(proposed)

Outline. The open-loop equipment used in the previous exercise will be supplemented by a PID controller. This unit will be implemented digitally using a combined A/D and D/A card (Analog Devices RTI-820). Digital control has been selected to allow the students to have full control over the controller gains.

Object. Experience with altering the gains of a controller on a real system so that response speed and stability can actually be observed is considered an essential part of a student's training.

18. Closed-loop characteristics of a spool-valve-controlled angular-velocity system (proposed)

Outline. This exercise will replace the linear-actuator system by a motor with an variable inertia load (Fig. 3). Angular velocity will be measured with a DC tachometer. The motor will also drive the dynamometer pump on the main test stand so that the effect of external disturbing torques on a speed control system may be demonstrated.

Object. See exercise 17.

19. Measuring the characteristics of a relief valve (proposed)

Outline. A cartridge-type relief valve will be modified to allow measurement of the sleeve displacement. The students will excite this valve with a step change in pressure. Pressure, flow and displacement will be recorded by the datalogger.

Object. The valve used in this test will have been analyzed by HYSAN so the students will have another opportunity of comparing simulation with experimental results.

20. Efficacy of a commercial filtration element (proposed)

Outline. A hydraulic power pack consisting of a pump, flow meter, filter and temperature-controlled reservoir will be filled with a contaminated oil, probably from an agricultural-tractor transmission. Oil will be circulated through the system for about 2 hr. Small samples will be bled at intervals and filtered through a membrane filter. The mass of the debris retained on the membrane filter will be determined by weighing the dry membrane filter after washing with solvent.

Object. Clearances in fluid-power devices are very small; emphasis on fluid cleanliness is essential [9].

SUMMARY AND CONCLUDING REMARKS

Fluid power has been and remains the primary choice when power transmission systems have to be compact, accurate and efficient. Although an engineer graduating with a BS in mechanical or agricultural engineering has the basic tools for fluid power design, his or her utility to an employer can be enhanced significantly if that engineer has received some specialized instruction in analyzing fluid-power devices and in applying these devices to feedback control systems. The combination of lecture and laboratory courses offered at ISU fill a void in the instruction of undergraduate engineers. Thus, after taking ME 414 or AE 447 and AE/ME 413, the students will have combined their theoretical knowledge of fluid mechanics, dynamics and controls into a comprehensive package of skills with which they can analyze real physical devices.

We also hope that the graduates from these classes will have gained a healthy respect for the complexity of fluid-power systems with feedback. The reason for this is that designing the guidance system for an off-road vehicle system will require just as much mathematical expertise as that required to design guidance for a missile. In the past, sophisticated controls were not applied to off-road vehicles, but this is changing because servo-control valves are becoming less expensive. It is tempting to conclude that graduates of the fluid power courses offered at ISU will also take their skills and apply fluid-power control technology in many new areas.

Acknowledgements—The laboratory exercises described in this paper could not have been developed without contributions from many sources. The authors would like to thank the National Science Foundation for supplying funds through NSF-ILI grant EID 9051835, Iowa State University for matching the NSF funds, and the Agricultural and Biosystems Engineering Department which has provided the space for the laboratory and also found funds for some of the datalogging equipment. Ongoing thanks are also due to all the industrial organizations who have supplied us with equipment, advice and encouragement to continue the project. Among the many contributors are

Aeroquip, John Deere, Delavan, Eaton, Fluid Dynamics International, Hydrasoft, Iowa Industrial Hydraulics, Moog Valves, Natchi, Sauer-Sundstrand and Sun Hydraulics. A major vote of thanks is due to Mr Loren Steenhoek, a graduate student in agricultural engineering: most of the exercises now labelled as current were assembled through his endeavours.

REFERENCES

1. A. Akers, Prospects of a fluid power engineering curriculum, *Int. J. Appl. Engng Ed.*, **4** (2), 97–102 (1988).
2. D. McCloy and H. R. Martin, *Control of Fluid Power*, 2nd edn, Ellis Horwood, Chichester (1980).
3. H. E. Merritt, *Hydraulic Control Systems*, Wiley, New York (1967).
4. J. Watton, *Fluid Power Systems Modelling, Simulation, Analog and Microcomputer Control*, Prentice Hall, Englewood Cliffs, NJ (1989).
5. *HYSAN software for hydraulic system analysis*, Hydrasoft Corporation, Kankakee, IL, ver. 3.50 (1995).
6. F. H. Speckhart and W. L. Green, *A Guide to Using CSMP—The Continuous System Modelling Program*, Prentice Hall, Englewood Cliffs, NJ (1976).
7. J. J.Moré, B. S. Garbow and K. E. Hillstrom, User guide for MINPACK-1, Argonne National Labs Report ANL-80-74 (1980).
8. *SystemBuild/PC core module user's guide*, Intergrated System Inc., Santa Clara, CA, ver. 7 (1990).
9. L. E.Bensch, E. C. Fitch and R. K. Tessman, Contamination control for the fluid power industry, Pacific Scientific HIAC Instruments Division (1978).

Richard Smith graduated with a B.Sc. in mechanical engineering from King's College London and obtained an MS and a Ph.D. in agricultural engineering at Iowa State University. After spending 15 years in animal waste management, he saw the light at the end of the sewer and moved into automatic control for field machinery. After being asked to teach a class in fluid-power controls he became intrigued by this subject. For the past 12 years he had been a professor in the Agricultural Engineering Department at Iowa State University. He now divides his time between teaching and research in fluid power and field machinery guidance and in his 'spare' time manages the ever-expanding departmental microcomputer network.

Arthur Akers is registered in the State of Iowa to practice mechanical engineering and is a British Chartered Engineer. He holds a doctorate in mechanical engineering, a master's degree in aerospace engineering, and a baccalaureate degree in physics and mathematics. He is an international authority in fluid power and in tribology and has over 100 publications in those areas plus areas of fluid flow, compressible flow, materials, dynamics and engineering education. For the last 18 years, he has been on the faculty of Iowa State University and is currently professor of Aerospace Engineering and Engineering Mechanics.

Max Gassman is an adjunct assistant professor of mechanical engineering at Iowa State University. He has a BS in mechanical engineering and an MS in engineering. He worked for John Deere for 28 years before taking his present position. He is a registered professional engineer in the State of Iowa. Most of his industrial experience was on fluid-power systems. He has published numerous papers on fluid power at national and international conferences and holds several patents. He currently supervises some of the senior design classes in mechanical engineering and is responsible for organizing short courses offered by Engineering Extension.