a single ended vacuum input is approximately one-fifth the gain for a positive pressure input.

Amplifier A_3 is used to boost the resulting low level output from the summing junction to a level sufficient to drive the pneumo-hydraulic power amplifier. Pump displacement is controlled directly by the rotary actuator.

In general, the fluidic devices in the circuit of Fig. 7 were matched by selecting the supply pressures for successive stages such that the maximum expected output of one stage would just saturate the following stage.

Laboratory Evaluation. A photograph of the laboratory apparatus and instrumentation used in the controller evaluation is shown in Fig. 9. The engine is a 2 cylinder, 4 cycle, 13.5 hp military engine (Army model A042). The hydrostatic transmission is a commercially available unit rated for 18 hp and with D_p = 0.84 in.^{3}/rev. This transmission is typically used in garden tractor applications. A hydraulic gear pump and needle valve serve as a dynamometer to simulate typical loading conditions. Torque and speed sensors allow measurement of engine and load speeds and torques.

The static control characteristics of the system are shown in Fig. 10. The solid curve was determined by measuring the steady-state values of the engine power and speed after the controller responded to a change in loading. The dashed line represents the maximum band of operation for slowly changing loads. This band was determined by slowly changing the loading from some steady-state operating point. The engine will overspeed or underspeed to some threshold before the controller increases or decreases the speed ratio. Thus for slowly changing loads, engine operation within these limits is assured.

After a change in loading and the controller readjusts the speed ratio, the steady-state speed returns to within about 2 percent of its previous value. That is, static repeatability is within about ±2 percent of the solid curve. Actually, the variation is unmeasurable at the lower engine speed since the sensitivity is high. The high speed operation is of course not so sensitive; however, the static repeatability is within the limits of ±2 percent even though the operating band is broader. These results are valid for any loading condition within the capability of the engine and transmission and for any throttle position.

The fluidic control system was fabricated from off-the-shelf components considering only static operation; no consideration was given to optimum dynamic operation. Surprisingly, the dynamic behavior of the prototype system is reasonably good. Fig. 11 shows dynamic responses for various step inputs at moderate engine speeds. Due to factors such as varying vacuum sensitivity to speed, torque required to hold displacement stem, and inertia, the system is more responsive at low speeds than at high speeds; however, the high speed response is acceptable as shown by Fig. 12. The use of a more constant and higher hydraulic supply pressure (not possible with the transmission auxiliary pump), a smaller rotary actuator, a better matched servovalve, and position control on the power amplifier (open loop in these tests) could substantially improve the dynamic behavior of the system.

Conclusions

Fluidic control of a vehicle propulsion system incorporating a hydrostatic transmission has been demonstrated through the successful development of the prototype V-S controller. Even though the laboratory controller was composed only of off-the-shelf components, satisfactory steady-state and dynamic performance of the propulsion system was achieved. The controller was designed on a semi-quantitative basis without the benefit of a complete engine map. Consequently, no conclusions can be made on the "quality" of the actual design in terms of engine and system efficiency, dynamic responsiveness, etc. Nevertheless, technical feasibility of the V-S concept and fluidic implementation has been established. An additional and important contribution of this study is the establishment of a viable systematic procedure for automatic control concept selection and fluidic implementation.

Concepts and implementations other than the fluidic pneumo-hydraulic V-S controller concept in this paper are possible and may be more attractive in certain applications. An all-hydraulic, fluidic implementation is being explored presently which utilizes the pressurized hydraulic source available within the transmission. Electronic implementation of the V-S concept is possible, but it appears that the fluidic implementation would result in fewer total components and interfaces; reliability and maintainability should be correspondingly higher.

Acknowledgments

This work was performed under contract DAAE07-67-C-5639 with U. S. Army Tank-Automotive Command, Warren Mich. Mr. Walter Slabiak of the Propulsion Systems Laboratory, TACOM, provided technical supervision and liaison for the project. Dr. R. Gunda, OSU, contributed significantly to the experimental development of this system.

References

1 Wilson, W. E., and Lemme, C. D., "Hydrostatic Transmissions," Parts 1 through 7, *Hydraulics and Pneumatics*, Vol. 23, 1970.

2 Howard, F. W., Clark, S. J., and Turnquist, R. O., "Fluidic Control of Hydrostatic Tractor Transmissions," A.S.A.E. Paper No. 69-136, Presented at the 1969 Annual Meeting of the A.S.A.E., Purdue University.

3 Latson, D. M., Gordanier, M., Dorgan, R. J., and Rio, R. L., "A Hydromechanical Transmission Development," SAE Paper No. 670932, Presented at the Combined Fuels and Lubricants, Powerplant and Transportation Meetings, Pittsburgh, Pa., Oct. 30–Nov. 3, 1967.

4 Reid, K. N., Woods, R. L., and Gunda, R., "Application of Fluidics in the Control of Military Vehicle Propulsion Systems," Final Technical Report under Contract No. DAAE07-67-C-5639, to U. S. Army Tank-Automotive Command, Warren, Mich., Technical Report No. 11401, Apr. 1971.

5 Wilson, W. E., *Positive Displacement Pumps and Fluid Motors*, Pitman Publishing Co., N. Y., 1950.

6 Schloesser, W. M. J., "Mathematical Model for Displacement Pumps and Motors," *Hydraulic Power Transmission*, Apr. and May 1971.

7 Wilson, W. E., Schloesser, W. M. J., Firth, D., Thoma, J., and Holzbock, W. G., "Can Mathematical Models Predict Performance—A Panel Discussion," *Hydraulics and Pneumatics*, Vol. 23, No. 2, Feb. 1970.

DISCUSSION

P. H. Schweitzer[3]

This excellent paper treats the problem of programmed control of a hydrostatic transmission in a thorough, scholarly manner. It also describes an implementation by a Fluidic V-S Controller with creative imagination and encouraging experimental results. The authors explicitly ignore the adaptive control alternative, their Class III; this discussion presents a concept of control for this type of machinery of the adaptive closed-loop type.

Fig. 13 shows a block diagram of the concept. The operator controls directly the fuel (or mixture) rate, engine input. The engine drives the pump end of the hydrostatic transmission, and the motor end of the transmission drives the vehicle. Under any instantaneous load condition, and at any speed he selects, the operator is interested in negotiating the load (grade, etc.) in the most economical manner.

The efficiency of the hydrostatic transmission naturally varies with its setting of pump displacement and motor displacement. The diagram shows how both can be optimized so that the com-

[3]Vice-President Optimizer Control Corp., State College, Pa.

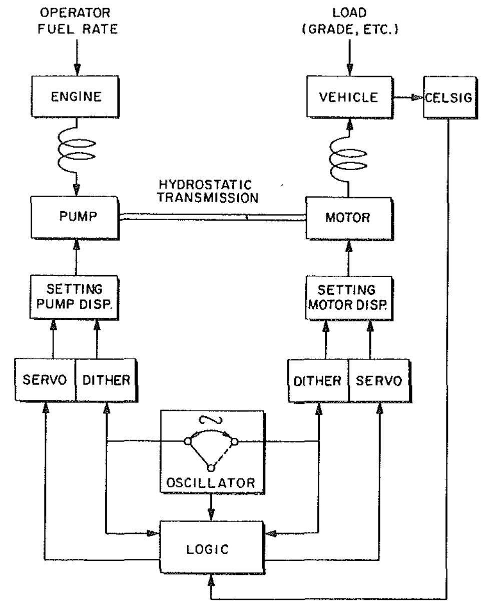

Fig. 13 Closed loop optimizer control for hydrostatic transmission

bination results in the lowest specific fuel consumption for the desired power output. Only one sensor is used which we have named "celsig" (SAE paper 660022) which is an abbreviation for acceleration and deceleration signaler. It signals whether in a particular instant the power output is increasing or decreasing. This information can be obtained by monitoring the transmission output; either shaft speed or torque is acceptable because in a vehicle both increase or decrease together.

The celsig sends a plus or minus signal to the logic depending on whether the output is increasing or decreasing at that instant.

The displacement settings of the pump and motor are dithered independently and alternatively (time sharing). The displacement setting is varied a minute amount a few times per second. Every change will cause the power output to change up or down. Therefore the power output will fluctuate.

The dither signal is fed to the logic, thereby signaling whether at the particular instant the displacement setting was increasing or decreasing. The logic compares the signals received from the dither and the celsig. Whenever the power increase and displacement increase are in phase, the logic sends a command to the servo to increase the displacement setting, and vice versa.

In one cycle the control improves the pump setting, and in the next, the motor setting. After several cycles, the transmission will have the best combination of settings which will yield the maximum power output for the set fuel rate controlled by the foot pedal of the operator.

If the operator sees that at the equilibrium reached the vehicle speed exceeds the desired speed, he slightly releases the pedal and reduces the fuel input. At the desired speed the fuel rate will be the lowest for the given conditions as the transmission will work at its best efficiency.

Thus, the operator is part of the control circuit. He sets the fuel rate while the transmission settings are continuously optimized by the closed-loop Optimizer control.

It will be noticed that no matter how many parameters influence the transmission efficiency and the power output, and the optimum transmission settings, the control has only one sensor, the celsig. Yet, it responds to all relevant variables as speed, load, fuel, environmental conditions, tuning, parts wear, etc. It contains no tailor-made cams or function generators. Neither does its proper operation depend on the judgement of the designer. The control asks questions from the machine and the machine answers. It tells which way it wants a setting to be changed to improve its performance.

Optimizer controls for spark-timing and mixture ratio for Otto engines is described in SAE paper 720254, but the field for their application is very wide.

Authors' Closure

We were very pleased to see Dr. Schweitzer's discussion since it concerned one aspect of our paper that we had to neglect for brevity. His proposed adaptive control scheme is very attractive for applications in which speed of response is not at a premium. We considered a similar system in our early work. A combination of adaptive and simple prescheduled control would be even more desirable.

As Dr. Schweitzer points out, it is mandatory that the operator input is fuel flow and not air flow or throttle position. This input assures that the maximum load power is obtained for a given fuel consumption, which, therefore, optimizes specific fuel consumption. This conclusion assumes that the engine air flow is properly controlled (either prescheduled or optimizer control) to produce maximum engine efficiency.

We performed an extensive study to determine the optimum pump and motor displacements for various transmission ratios. The results indicate the optimum power transmission always occurs when either the pump or motor displacement is at full stroke. Thus Schweitzer's optimizer circuit could be simplified by following the displacement schedule shown in Fig. 6(*c*) and not independently dithering the pump and motor displacements.

As a final note, we might point out that engine and transmission detuning from the pre-scheduled values is a likely occurrence. An optimizer circuit would be a desirable feature if precise fuel economy is important.