Discussion

R. Oldenburger.[4] In the matter of education the role of mathematics is extremely important. The same type of mathematics applies to different areas of application and as the author so aptly points out, it is the mathematics that is the unifying agent. Intelligent use of modern control theory requires an extensive knowledge of the vast body of underlying mathematics. An understanding of Dr. Nyquist's pioneering frequency-response paper alone requires a considerable background in the theory of functions of complex variables. The more mathematics a control expert knows the better able he should be to find quick and efficient methods of solving his problems and to employ analytical techniques that fit the specific problem.

These facts suggest that it is desirable for the future automatic-control expert to major in mathematics both in his undergraduate and graduate work and to minor in the physical sciences and engineering. It is unquestionably much easier for a person with an extensive mathematical background to pick up the engineering, such as the physical limitations involved in the design of equipment, than the other way. It is very important that the control expert be trained in engineering in general, and not be limited to electrical, mechanical, or other specific branches of the field. Training in the use of computers is also essential.

The various transfer functions given by the author are in common use in the design of speed governors for prime movers. They are naturally valid for rough studies and noncritical areas, but will break down in certain situations. Thus we found that the gas-turbine equations of the paper were inadequate for explaining the performance of our governors on these turbines; in fact we discovered experimentally by frequency-response runs (verified later by NACA) that we could not neglect a certain combustion lag that appeared as a dead time. This lag could be as much as $^1/_4$ or $^1/_3$ sec. In this case the denominator in Equation [22] should include a factor e^{Tp} for the dead time T. This dead time T is in addition to the delay time T_b of Equation [22] and is due to the time it takes to go from one combustion pattern to another.

The gas turbine-governor application probably was given only for purposes of illustration. In practice we would measure the speed of the gas turbine directly. In fact, it is our experience that variables to be controlled should be measured as directly and accurately as possible. The arrangement of Fig. 2 of the paper shows a measurement of pressure. It is evident that there will not be a one-to-one correspondence between pressure and speed holding at each instant during a transient.

[4] Director of Research, Woodward Governor Company, Rockford, Ill. Mem. ASME.

Author's Closure

Dr. Oldenburger is undoubtedly correct in asserting that an extensive mathematical background will be of great assistance to any control expert. Surely this applies to most fields of modern engineering. The study of mathematics must form the basis of all higher technology. Nevertheless, the author believes it is important to distinguish between the control experts, the designers or researchers, and the far larger number of engineers who use or buy automatic instrumentation and machinery. It is valuable for them also to have a working knowledge of the theory of feedback systems, for which no very extensive mathematical equipment is required beyond an acquaintance with the properties of complex numbers and the ability to solve linear differential equations with constant coefficients. The author has attempted to show in his introductory article to the symposium publication that this much is all that is indispensable.

Undoubtedly a finite delay or dead time will occur in the loop of many control systems; fortunately it is not necessary to resort to approximate analysis when this happens, for exact methods are available to take account of this type of linear delay, using the transfer function given by Dr. Oldenburger. In reference (22) of the paper a method is given for approximating the transfer function of many processes by means of a combination of finite and exponential delays. Charts computed on this basis, to assist in the setting of process controllers, also might be used by the designers of governors, provided that suitable nondimensional scales have been used.

It is always important to measure the controlled variable of any servosystem as accurately as possible, and it is best to compare the actual value of the controlled variable as directly as possible with the desired value. Whether the output of the measuring device is to be a mechanical displacement or a change of electrical potential, some delay inevitably is involved in obtaining it, if its physical nature differs from that of the quantity measured. An exact one-to-one correspondence between turbine speed and the quantity representing the measurement is therefore never possible. It is no more direct to use a mechanical centrifugal governor than to use a measurement of centrifugal pressure, although in practice the time delay involved in the former certainly might be made much the shorter.