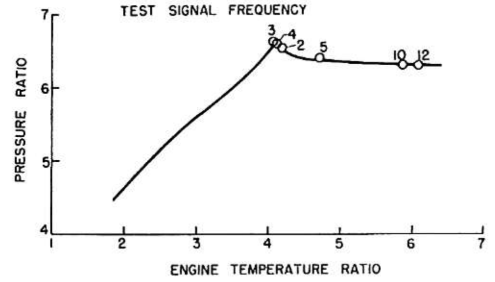

Fig. 11 Steady-State Performance of Control for Various Test-Signal Frequencies

(Test signal amplitude $A_0 = 1.41$ volts; control gain, $K = 0.05$; integrator time constant, $\tau = 0.1$ sec; relative Mach nun.ber = 1.052.)

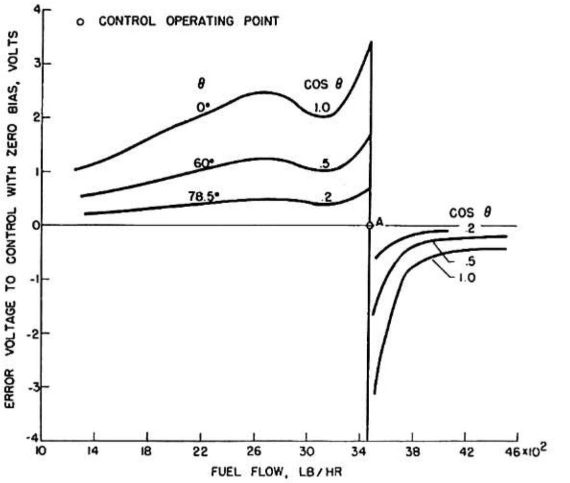

Fig. 12 Effect of Phase Shift on Error Voltage

(Test-signal amplitude, $A_0 = 1.41$ volts; relative Mach number = 1.052.)

nal frequencies would permit higher filter cutoff frequencies and hence, faster response, data were taken to determine the performance of the system under such conditions.

The steady-state behavior of the system at several test-signal frequencies is shown in Fig. 11. No attempt had been made to correct for the phase shift due to the fuel servo and engine at these higher frequencies. Nevertheless, the system operated satisfactorily in steady state for frequencies up to 4 cps.

The error voltage to the control for these frequencies is indicated in Fig. 12. As the phase shift increases from 0 to 90 deg, the error voltage to the control $(A_0A_1/2)$ cos θ is reduced, and for 90-deg phase shift becomes zero. Operation at 90-deg phase shift therefore is impossible. For frequencies which produce less than 90-deg phase shift, the control operates at point A, which corresponds to operation at peak pressure.

When the frequency was changed from 4 to 5 cps, the operating point suddenly shifted from the peak to a point well to the right of the peak as indicated in Fig. 11. This sudden change in operating point occurred because the phase shift increased beyond 90 deg. For phase shifts greater than 90 deg (and less than 270 deg), cos θ is negative. When cos θ is negative, the control is unstable (runs away) at the peaks.

The conditions under which the system can operate stably far to the right of the peaks are illustrated in Fig. 13, where the error voltage to the control $(A_0A_1/2)$ cos θ is shown again. In this case, however, the curves are inverted because cos θ is negative. Stable operation at high fuel flows is possible if a small amount of d-c bias exists (caused for example by drift in the multiplier).

The operating point shown in Fig. 11 for a test-signal frequency of 5 cps corresponds to operation at point A in Fig. 13. Increasing the test-signal frequency from 5 to 12 cps caused the phase shift to increase further. As the phase angle increased, cos θ increased in magnitude. The increase in error voltage to the control as a function of cos θ caused the operating point to shift as illustrated by points A and B in Fig. 13 and as shown in Fig.11 for frequencies from 5 to 12 cps.

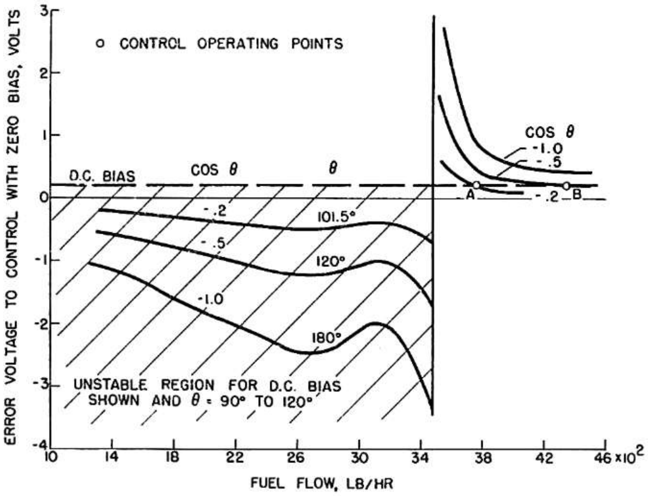

Fig. 13 Effect of Phase Shift on Engine Operating Point for Abnormal Operating Conditions

The effect of component dynamics on A_1 in the term $(A_0A_1/2)$ cos θ must of course also be considered. In this case, however, variations in A_1 are small compared to variations in cos θ.

To alleviate the difficulties encountered here, and possibly permit operation at even higher test-signal frequencies, the test signal fed to the multiplier should be shifted in phase to compensate for the phase shift through the fuel servo, engine, and other components in the loop.

Conclusions

The experimental data indicated that the continuous test-signal optimalizer control, applied to the control of compressor-output pressure in a flight-propulsion system, gave very nearly maximum output pressure over a range of flight conditions.

For a test-signal frequency of 2 cps and with a large amount of filtering in the system, response times of less than 2 sec were obtained with only a small amount of overshoot. These response times can be shortened considerably by increasing the test-signal frequency and decreasing the amount of filtering.

The type of response varied greatly over the range of Mach numbers owing to the variation in the shape of the engine static characteristics from one Mach number to another.

The data indicated that good filtering was not required. The system could therefore be made to operate faster by removing part or all of the filtering.

The minimum test-signal amplitude was found to be dictated not by the signal to noise ratio, but by imperfections or minor peaks in the engine static characteristics. For very small test-signal amplitudes, the control would hang up on a minor peak.

Discussion

Y. T. Li.[3] The author is to be congratulated on this excellent paper. The presentation of the problem is well done and the experimental coverage is quite complete. An optimalizing system,

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like any control system, must prove its practicability by being subjected to the disturbance environment the system is likely to encounter. The extensive study of the noise effects upon the operation of the tested system fulfills this requirement quite well. The author also has established the response speeds of the system at different operating conditions. To be more inquisitive, the writer would like to ask this question: How does this response speed compare with the actual drift speed of the operating condition of the engine under flight conditions?

In so far as the basic purpose of the control system is concerned, the use of the engine pressure ratio as the output, and the fuel flow rate as the controlled input, indicates that the goal is to maintain a maximum delivery of thrust without the consideration of fuel consumption. Clearly, if the economical use of fuel is the primary purpose, then the output might have been the ratio of the pressure ratio divided by the fuel rate.

To get an optimum operation we usually have two possible schemes; i.e., program-type control and an optimalizing control. The final choice between the two depends upon the relative complexity of the system. The writer wishes to know whether the author has considered the possibility of getting similar control performance with a programmed-type controller, and whether it is more complicated to attempt this?

In so far as an optimalizing controller is concerned, a continuous test signal is a neat system and has a lot of appeal to electronic systems operating at many thousands of cycles per second. For mechanical systems with hunting periods down to the order of a second, it is the opinion of the writer that a peak-holding type might be considerably more simple and flexible.

AUTHOR'S CLOSURE

The author appreciates the complimentary remarks and excellent discussion offered by Dr. Li. It is a privilege to have one of the inventors of optimalizing controls discuss this paper.

Dr. Li asks several rather interesting questions. In his first question he asks how the response speeds of the system, as investigated, compare with the actual drift speed of the operating condition of the engine under flight conditions.

The answer to this question will depend upon the particular application of the engine. For certain vehicles and missions, the response times given are adequate. For others, the speed of response is not so fast as desired. The response speeds shown, however, are for the system with a large amount of filtering. It was shown that the system would operate with all of the filtering removed. Since the response time would improve considerably as the filtering is reduced, it is the author's opinion that response times could be obtained with an optimalizing control system which would approach the best that can be obtained with standard nonoptimalizing control systems. Once the filtering has been removed, the author feels that the basic limitations on speed of response of the two types of systems are the same. (Actually, it is not suggested that all of the filtering be removed. How much filtering exists, either intentional or unavoidable, will again depend upon the specific application and on the hardware employed. Nevertheless, it is felt that the response times shown can be considerably improved.)

The second question involves the variable being optimalized. Apparently, the author's use of pressure ratio was confusing. The quantity actually sensed, as shown in Fig. 2, was an engine pressure, P_x. The plots, however, were made in terms of pressure ratio for convenience.

The economical use of fuel was not discussed in the paper and Dr. Li's observations in this regard are well made. It turns out, however, that minimum specific fuel consumption occurs at or near maximum pressure and therefore use of the ratio of pressure to fuel flow as the output is not necessary in this case.

Programmed-type controllers have been used successfully in many applications. A program-type control depends upon the calibration of the engine to get the required program. As the number of variables (Mach number, altitude, angle of attack, etc.) which affect engine operation increases and as the range of these variables increases, the calibration becomes more difficult to obtain and also less reliable. In addition, changes occur in the engine after the calibration has been made.

It is the author's opinion that an optimalizing control could be made which is less complicated and more reliable than many of the existing engine controls. Operations such as filtering, multiplication, and signal generation can be performed by relatively simple devices which can be mechanical, electrical, electronic, acoustic, or other types. Utilizing such devices, simple continuous test-signal optimalizing controllers can be designed to operate over a wide range of frequencies. Although the peak-holding type might be more simple and flexible, it would very likely not be so insensitive to noise as the continuous test-signal type.