CORNELL AERONAUTICAL LABORATORY, INC.
PRESENTATION

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I. INTRODUCTION

Adaptive control systems were first studied at Cornell Aeronautical Laboratory by Graham Campbell. The usefulness of such devices was rapidly becoming apparent in the fields of automatic flight control and also stability augmentation. In June of 1955, the Flight Research Department of C.A.L. submitted a proposal to the Flight Control Laboratory of WADC to investigate servo control loops which could adapt themselves to produce a desired effect, regardless of changing characteristics of the controlled element. This proposal grew out of Campbell's work, which was continued and eventually published as a Master of Science thesis at the University of Buffalo and also as a C.A.L. report. In this report, Campbell investigated the fundamental technique of continuous adaptive control by comparing outputs of the actual system and a dynamic model of desired dynamics.

In March of 1957, a study was initiated under the sponsorship of the Flight Control Laboratory to determine the feasibility of using this servo technique to minimize the variations in the dynamic and static characteristics of high performance aircraft. It is this study which will be of primary concern in this paper.

II. BASIC SERVO LOOP

The basic servo loop, described briefly above, is shown in Figure 1. The input is fed simultaneously to both the controlled element and the model, and the error fed back directly. (There are other ways in which the error could be used, for example to simply adjust the feedback gain of a single loop system).

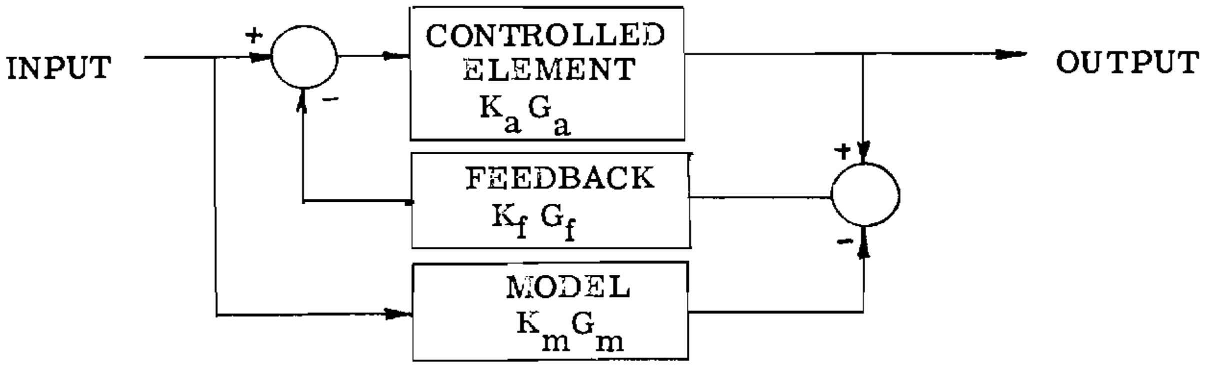

Figure 1

The transfer function of this loop is

$$\frac{\text{Output}}{\text{Input}} = \frac{K_aG_a + K_fK_aK_mG_aG_mG_f}{1 + K_fK_aG_aG_f} = K_a'G_a'$$

If K_f is made moderately large, the influence of K_aG_a on the closed loop behavior is reduced. In the limit, the overall transfer function approaches K_mG_m exactly. One can see, then, that although K_aG_a may vary, $K_a'G_a'$ can be restricted to an area around K_mG_m.

The particular advantages of this loop in aircraft control application are the following:

(1) No unproven sensing, computing, or actuating techniques are required. This system is very close to the normal stability augmentation loop found in many aircraft and missiles today.

(2) With the model responding only to the selected input, the device becomes a disturbance alleviator as well as an adaptive servo.

III. CHOICE OF LOOP COMPONENTS

It was desired to apply this technique to the problem of control of high performance aircraft by human pilots. Consideration of the characteristics of the human controller and the necessity for simplicity and reliability of implementation were the prime factors which determined choice of the loop components. Both longitudinal and lateral modes of motion were studied, although this discussion will be restricted to the longitudinal short period mode because of its primary importance in control of the aircraft.

Within the framework of the basic loop, choices had to be made of model static and dynamics, the flight variable to compare with the model output, and the feedback gain and transfer function.

(1) Model Characteristics - The model was chosen giving a steady state output for a steady stick force or position input and having a second order characteristic equation. This made the model quite similar, in first approximation, to the normal aircraft in the short period frequency range. The model steady state gain was fixed at the median value of the aircraft gain so that the steady state error between the two would be minimized. The model natural frequency was set at .5 cps and the damping at .7 of critical. This dynamic behavior has been found to lie close to the optimum for human controllers as determined from pilot opinion data gathered in variable stability airplanes.

Choosing the model in this way would result in the most desirable closed loop behavior, providing the feedback gain can be made high enough to force the aircraft to closely follow the model. However, if the aircraft does not closely follow the model, these model dynamics might not produce optimum closed loop response, and minor changes should be made to optimize the system.

(2) Aircraft Output Variable - Considering aircraft variables which might be compared with the model output, we have normal acceleration (n_z), angle of attack (α), or pitch rate ($\dot{\theta}$), all of which reach a steady value in the short period mode following stick force or motion input. To decide among these, the transfer functions n_z/δ_e, α/δ_e, and $\dot{\theta}/\delta_e$ were examined for the F-101, the F-102 and the F-104 over their entire flight ranges. Pitch rate was chosen for the following reasons. First, it is the most advantageous to measure, requiring nothing external to the aircraft as does measurement of angle of attack and being less susceptible to high frequency noise than an acceleration measurement. Second, its response to elevator motion had the least amount of phase lag at high frequencies. Third, it had less variation (although slightly more than angle of attack). An objection might legitimately be raised here that the pilot flies by stick force and it would be desirable to keep the stick force per "g" constant over the flight envelope. Given a flight control system which produces stick force and elevator deflection proportional to stick position and a servo loop which forces pitch rate per elevator deflection to be constant, the stick force per pitch rate would be constant and stick force per "g" inversely proportional to velocity. One can see, however, that with the slight complication of making the stick force per elevator deflection directly proportional to airspeed, the stick force per "g" is also made constant.

(3) Feedback Gain and Transfer Function - The feedback gain is, of course, limited in any realistic servo loop. The limitation in the adaptive servo loop should be of the same order as that in the conventional stability augmentation loop. This has been shown by manipulation of the block diagram as in Figure 2.

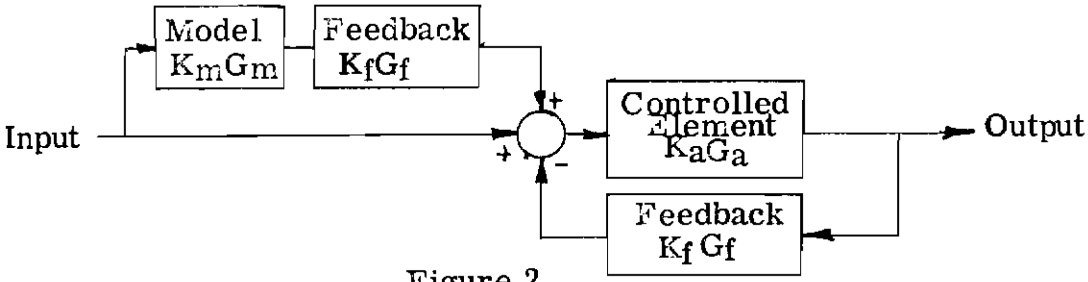

Figure 2

Therefore, it was decided that adaptive servo performance should be determined using loop gains ($K_a K_f$) no higher than the maximum which has been attained in flight or a reasonable extrapolation of present stability augmentation practice. Based on experience at C.A.L. with variable stability aircraft, a maximum loop gain of five was chosen.

The feedback transfer function used was $(1 + \tau s)$. The lead was necessary to prevent the normal instability at some value of feedback gain when a loop is closed around a third order system (second order short period mode and first order power control lag). The value of τ was .2.

V. PERFORMANCE IN ANALOG F-101, F-102 AND F-104 AIRCRAFT

In Campbell's earlier work, simple second order systems were used for both controlled element and model. Moderate variations in the characteristics of the controlled element were made. Natural frequency varied from .25 to .75 cps, damping ratio from .3 to 1.0, and static gain from .5 to 1.5. With moderate feedback gain, these variations were almost completely nullified. In the recent study, actual aircraft data were used covering the entire flight ranges of the F-101, the F-102, and the F-104. The variations were much wider, especially those of static gain. Natural frequency varied from .2 to 1.7 cps, damping ratio from .06 to .53 and static gain by a factor of 60 to 1. Since the feedback gain had to be set so that the loop gain at maximum forward gain was equal to 5, this meant that the loop gain could get as low as .08.

At this point, it was realized that a desirable complication to the basic loop would be some method of making the feedback automatically variable. But investigation of the performance with constant feedback gain showed that the system, even in this form, has promise. In seven extreme flight conditions, the variations in natural frequency and damping ratio were considerably reduced. The steady state pitch rate per elevator deflection varied considerably, since the low loop gain in some conditions permitted a large steady state error between the model and the aircraft. However, it is felt that this will not cause major difficulty in achieving constant stick force per "g" in view of recent advances in the design of feel systems which produce stick forces by directly sensing the aircraft motion.

VI CONCLUSION

Although this study has not been extensive enough to make firm conclusions, the results are definitely encouraging, especially in view of the possible operational simplicity of an adaptive flight control system of this type.