SIMULATORS AS AN AID TO FLIGHT RESEARCH

presented by

Flight Research Branch

We like to use the opportunity that these inspections present not only to discuss particular research problems of current interest but also to keep you informed on the "state of the art" - the new techniques that significantly increase the fruitfulness and the safety of much of our work. One of the most significant of the recent developments is the extensive use of analog computers or simulators as a basic flight research tool. This afternoon we want to show you how we use this equipment and tell you why it is so useful.

First of all, what is an analog computer? The dynamic behavior of an airplane or any of its parts can be expressed by some mathematical equation; for instance, we can set up an equation which expresses the motion of an airplane as a function of a movement of the control stick by the pilot. An analog computer is simply an electrical or mechanical analogy, a computing device which is set up to solve that particular equation and therefore computes for us the same response to a control movement that the airplane we wish to study would have in flight.

Let's look at an illustration, using for our example the rotation in pitch of a complete airplane in response to an elevator movement by the pilot. This chart (chart #1) shows us the variation with time of the elevator angle which the pilot imposed on this (YF-86D) airplane in a particular flight-test run. Next we see the pitch attitude of the airplane as it responded to the elevator movement. In other words, as the pilot did this with the elevator, the airplane responded like this. There are two response curves shown; the green one is the actual response of the airplane measured in the flight test, the tan curve is the response of an analog computer set up to solve the equations which govern the airplane motion. Note that the two curves agree very well. It is apparent that if we wished to study this motion we could obtain it with equal success either by flying the airplane or using the simulator.

In order to appreciate more clearly what the simulator is doing for us, let's look at the equations it is solving. This next chart (chart #2) shows, at the top, the two general equations of motion which describe the pitching behavior of an airplane. If a mathematician had to compute the airplane response by hand he would have to solve these two equations simultaneously for a number of steps or points corresponding to successive intervals of time. This means that at each time he would have to get a specific numerical solution for an equation similar to this very formidable one shown on the bottom of the chart. The airplane attitude is the product of the stick movement times all this. To get reasonable approximation to the response curve you saw on the last chart would take a mathematician using a desk calculating machine about two days. You will shortly watch an analog simulator computing the response as rapidly as the control surface is moved by the pilot.

While we have these equations in front of us is a good time to consider the question of accuracy. The simulation can only be accurate if the equations used are adequate. This is why our flight tests and the use of the simulators are so very closely tied together and why, in fact, the same scientist usually runs both jobs. A large part of our flight research effort is devoted to tests which determine the necessary form of these equations and continually check whether the answers we are getting from the simulators are right.

In order to show how this work fits in with our other flight research programs, it is interesting to trace the systematic growth of the need for this equipment through past inspections. In the 1946 inspection we talked about flight tests of one particular production airplane. There was a lot of information we could get from such tests, but there were two very important limitations. First, the area of research was limited; we could look only at the characteristics of airplanes that already were in production so that time-wise we were well behind the designer in facing the problems of future airplanes. Second, in order to generalize our results (say, the pilots' opinion of the amount of directional stability a fighter airplane should have), we needed to test a large number of different airplanes carefully selected so that we could isolate the one characteristic we wished to study, an expensive procedure with many practical difficulties. By the 1950 inspection we had taken a large step forward by taking one airplane and inserting variable-stability gear, in effect imitating many different airplanes with just one. We could isolate one particular design feature such as the directional stability and in a short time test it over a considerable range, including values corresponding to future designs, get opinions from a number of pilots, and provide a much sounder basis for selecting quantitative design values. But still the amount of research we could do was limited; devising this equipment for just one characteristic was quite a job and the amount that we could change the airplane's behavior in flight safely was relatively small. The effort to increase our capacity and flexibility has therefore led one step further to the use of analog computers and ground simulator studies as a supplement to the flight tests.

We have planned two demonstrations of simulators to bring out the factors that make them useful. As you watch the demonstrations, bear in mind the versatility, the speed, and the safety. The use of simulators as a safety measure is particularly well illustrated by the first demonstration which will be explained by Mr. _______.

In the past few years several fighter aircraft using power controls have broken up in the air as a result of violent oscillations that increased until the wings failed under the load. This is believed to be due to an instability of the complete system including the pilot, control system, and the airplane dynamics. Most modern fighters with power controls exhibit a tendency toward this condition. In some cases the only method of recovery is for the pilot to release the control stick entirely, a practice which can be extremely undesirable in some situations. It is our purpose to demonstrate how the analog computer is used to predict the possibility of such an occurrence in a specific airplane with an experimental control system.

We are installing in this airplane an experimental control system to study methods of improving power controls. The airplane, like most modern aircraft, requires a hydraulic jack to move the stabilizer against the air loads in flight. In the original airplane the valve controlling the flow of oil to the jack was connected directly to the control stick by a system of pushrods, bellcranks, and cables. Such systems have very poor dynamic response due to cable stretch, friction, and backlash. We have replaced this mechanical link with an electrical link — a "fly-by-wire" system as it is sometimes called. A device in the stick grip produces an electrical signal proportional to the force applied by the pilot. This signal is fed through several boxes of miscellaneous vacuum tubes, resistors, and condensers, and opens a valve controlling oil to the hydraulic jack.

On the surface this looks as if it should work out quite well — no friction, no backlash, and almost instant control response to stick force. But what are the possibilities of getting into those violent oscillations that so many fighters with power controls have experienced? Before we ask a pilot to go out and risk his neck it is well to give the system a second look strictly from that standpoint. One of the best ways to do this is to break out the analog computer and run our flight-test program right here in the hangar.

There is the computer. It is set up to simulate the motions of the airplane in response to the stabilizer movement as was shown on the first chart. Since we are looking for an instability involving the pilot response as well as the airplane and control system, we will have to put a pilot in the plane to work the controls in response to some signal. One of the best problems to give the pilot is the problem of tracking where the pilot tries to keep his gunsight on the target by maneuvering his own airplane. We will present to the pilot a picture of a target and of his gunsight as he tries to put the sight on the target. This will be done on an oscilloscope similar to this one mounted near the cockpit. An oscilloscope is an electrical measuring instrument using a screen, as you see here, similar to those found on TV sets. The circle will represent the gunsight and the line will be the target. The pilot will try to keep the sight on the target by applying forces to the control stick.

Let's go back to the chart again and see if we can follow what is going on. The pilot compares his sight with the target and applies a stick force to bring the sight to the target. A gimmick in the stick changes this force to an electrical signal which is fed through the electronic equipment and opens the valve controlling the flow of oil to the hydraulic jack, thus moving the stabilizer. Another device measures the stabilizer movement and tells the computer how much the stabilizer has moved. The computer determines the airplane response and controls the movement of the sight on the oscilloscope. Notice, we are not simulating the experimental equipment to be used in flight. The pilot uses the control system and all of its related equipment exactly as he will use it in flight. We merely simulate the airplane's response to the resulting stabilizer movement and present to the pilot a picture of his sight in relation to the target.

Let's move the target around a bit and have the pilot try to follow it.

(A tracking run is made and the pilot does a reasonable job.)

There doesn't seem to be any real problem here. The pilot was able to keep the sight on or near the target a reasonable amount of the time. There could undoubtedly be a lot of improvement, but it doesn't look as if the pilot will get into anything dangerous.

Now why do some planes with power controls get into trouble in similar situations? Are we simulating everything properly? From some of the planes that get into violent oscillations it is known that the only way to stop the oscillation is for the pilot to take his hands off the stick — the oscillation then stops immediately. If the pilot tries to hold the stick fixed, however, the oscillation continues. This suggests that the violent motions of the airplane are throwing the pilot around the cockpit to such an extent that he is inadvertently moving the stick in such a manner as to sustain the oscillation. If this is the case there must be a stick force proportional to the airplane pitching acceleration applied to the control system. Our airplane is sitting on the deck here and is not bouncing the pilot around so we are not getting the extra stick force.

Let's assume that this force proportional to pitching acceleration is possibly the cause of the sustained oscillation and put such a force into our control system and see what happens. Since the airplane is not moving, we will have to go to the computer to get a pitching acceleration signal to feed into our control system. This is a very simple adjustment to make. Now we will try it again.

(A tracking run takes place. The circle representing the sight oscillates rapidly.)

The pilot is doing his best to control the plane. That's enough. Let's turn it off.

Well, we got into trouble all right! At low altitudes we would have lost the wings well before the oscillation built up to the extent you just saw. Since this stick force proportional to pitching acceleration is one that we are likely to encounter in flight we must find some way to make the system work with this extra stick force present. There seems to be at least two possible ways to accomplish this: (1) to change the sensitivity of the control system so that much larger forces are required to move the stabilizer, or (2) to fix the system so that small forces will not move the stabilizer at all, but under large forces the stabilizer will move at its normal rate. Let's try the latter approach. Our electronic experts have included in the system a device which makes it necessary to apply a predetermined amount of force before the signal will go through the system calling for stabilizer movement. This breakout force can be set at any value from 0 to 20 pounds. Let's use a breakout force of one pound. That is, there will be no stabilizer movement until the pilot pulls more than one pound on the stick. Now let's repeat the tracking run.

(The tracking run is repeated.
There is no oscillation.)

The addition of a breakout force to the control system seems to have been effective in eliminating the oscillation. The safety aspects over the full operating range of the airplane will be thoroughly checked by similar tests before the airplane will be cleared for flight. The computer will be used as well to establish the settings of the electronic equipment most likely to yield useful data to minimize the amount of flight time required in the investigation.

You have seen how the analog computer is used to check the safety aspects of experimental aircraft. Mr.________ will now discuss the use of the computer to study the dynamic properties of the airframe itself. Mr.________.

It has been observed during extensive flight tests that some swept-wing airplanes have a tendency to pitch up uncontrollably when maneuvered above their normal operating range of lift coefficient at high speeds. This pitch-up is attributable primarily to an unstable variation of pitching moment with lift that results from a loss in lift at the wing tips. The severity of pitch-up is influenced, of course, by the degree of instability and, among other factors, by elevator or stabilizer effectiveness. From flight tests of current fighter airplanes, it was found that a given pitch-up intensity could be eliminated or alleviated by various changes to the wing and tail; however, because of the complexity of the problem, it is difficult to predict whether these changes will provide satisfactory flight characteristics in any given case. This comes about because it is generally not possible to interpret wind-tunnel pitching-moment data in terms of the actual pitching behavior of an airplane controlled by a human pilot. For this reason, it appears desirable to have some means of translating pitching-moment curves obtained from wind-tunnel tests of new airplane designs into pitching motions simulating those that would be experienced by the actual airplane-pilot combination in flight.

The pitch simulator shown pictorially here in this fourth chart was designed to provide this type of simulation. As shown, the simulator comprises three main parts, including (1) the pilot - control-stick combination, (2) the analog computer, and (3) the skeleton cockpit or cab. In the operation of the simulator, the pilot introduces a signal into the computer by moving the control stick in the cockpit. The computer converts this signal into the appropriate control-surface angle and control moment, then computes the aerodynamic response to this control moment and feeds a pitch-attitude signal to the hydraulic ram which drives the cab. The operation of the simulator will now be demonstrated using the mass, inertia and aerodynamic characteristics of the elevator-controlled fighter airplane over there assumed to be operating at a Mach number of 0.90 at 35,000 feet altitude. Let's first take a look at what happens when the airplane attitude is kept within its normal operating range, that is, below the unstable region, which is identified here on this scale by the red band. The computer has already been adjusted so that we may now proceed with the first demonstration. The pilot will attempt to pull up to a pitch attitude of the cab or about 3° corresponding to a load factor of the simulated airplane of 2-1/2g. Note, as the cab reaches the desired pitch angle, the pilot can, with very little effort, maintain the desired attitude. (Any small residual oscillations that you may see are due to the relatively low damping of the actual airplane at the flight speed and altitude assumed for this simulation.) Now let's see what happens when the pilot attempts to pull up through the green stable region that represents the normal operating range of the airplane into the red region on this scale where the pitching-moment variation with lift is unstable. For this demonstration the pilot will attempt to pull up to a cab attitude of about 5° corresponding to a load factor of 4g on the simulated airplane. As the pitch angle reaches the unstable region, notice the abrupt pitch-up of the cab and the ensuing large oscillations as the pilot attempts to bring the cab under control. It is obvious that the cab is relatively uncontrollable in the unstable region, indicating that under these conditions the actual airplane could not be used for any task calling for fairly precise maneuvering. It is of interest to note that this simulation agrees with NACA flight tests with this airplane where we observe a considerable reduction in tracking performance in the pitch-up region.

It is to be emphasized that this pitch-up is a characteristic which exists to a degree on almost every current high-performance airplane and is a result of the very features that are being built into airplanes to give them their high speed capabilities. It is as real a limit to the useful operational range at high Mach numbers as is maximum lift in landing. The problem is to increase the "g" at which pitch-up occurs or decrease its severity when it occurs without sacrificing these high performance features. Generally, it may be expected for a given unstable variation in the pitching-moment curve that increasing the control effectiveness by changing from elevator control to all-moving-tail control would tend to decrease the amount of effort required by the pilot to cope with the pitch-up. To demonstrate this let's simulate this airplane here and look at its pitching behavior in the unstable region. Notice that only a few changes are necessary on the computer and we are prepared to go ahead with the demonstration. The pilot will again attempt to perform the same task as that of the previous demonstration. As the cab enters the unstable region, it starts to oscillate about the desired level; however, these oscillations are fairly small and represent much better controllability than was shown in the previous demonstration. It may be pointed out that the improved controllability of this airplane shown by this simulation agrees with our flight tests.

In this last chart (chart #5) the main features of the demonstrations you have just witnessed are shown. The yellow lines in this chart, typical of runs obtained with the elevator-controlled airplane, show the control-stick angles used by the pilots in attempting to hold the pitch attitude steady in the unstable region. It is obvious, from the large and rapid stick motions used, that the pilot tried hard, with little success, to maintain the pitch attitude at the desired level. The green lines in this chart show results, typical of runs performed with the airplane with an all-moving tail. Both the smaller stick motions and pitch-attitude oscillations for this airplane show that the controllability of the airplane with an all-moving tail in the unstable region was considerably improved over that for the elevator-controlled airplane.

Now that we have succeeded, by means of this simulator, in translating the pitching-moment curves for these two airplanes into pitching behavior in the unstable region that agrees quite well with our flight experience, we are now prepared to investigate, in a similar manner, the pitching behavior of new airplane designs. Our objective will be either to check whether a new design will have satisfactory pitch-up characteristics, or if unsatisfactory, to assist in arriving at modifications that will insure satisfactory characteristics in flight.

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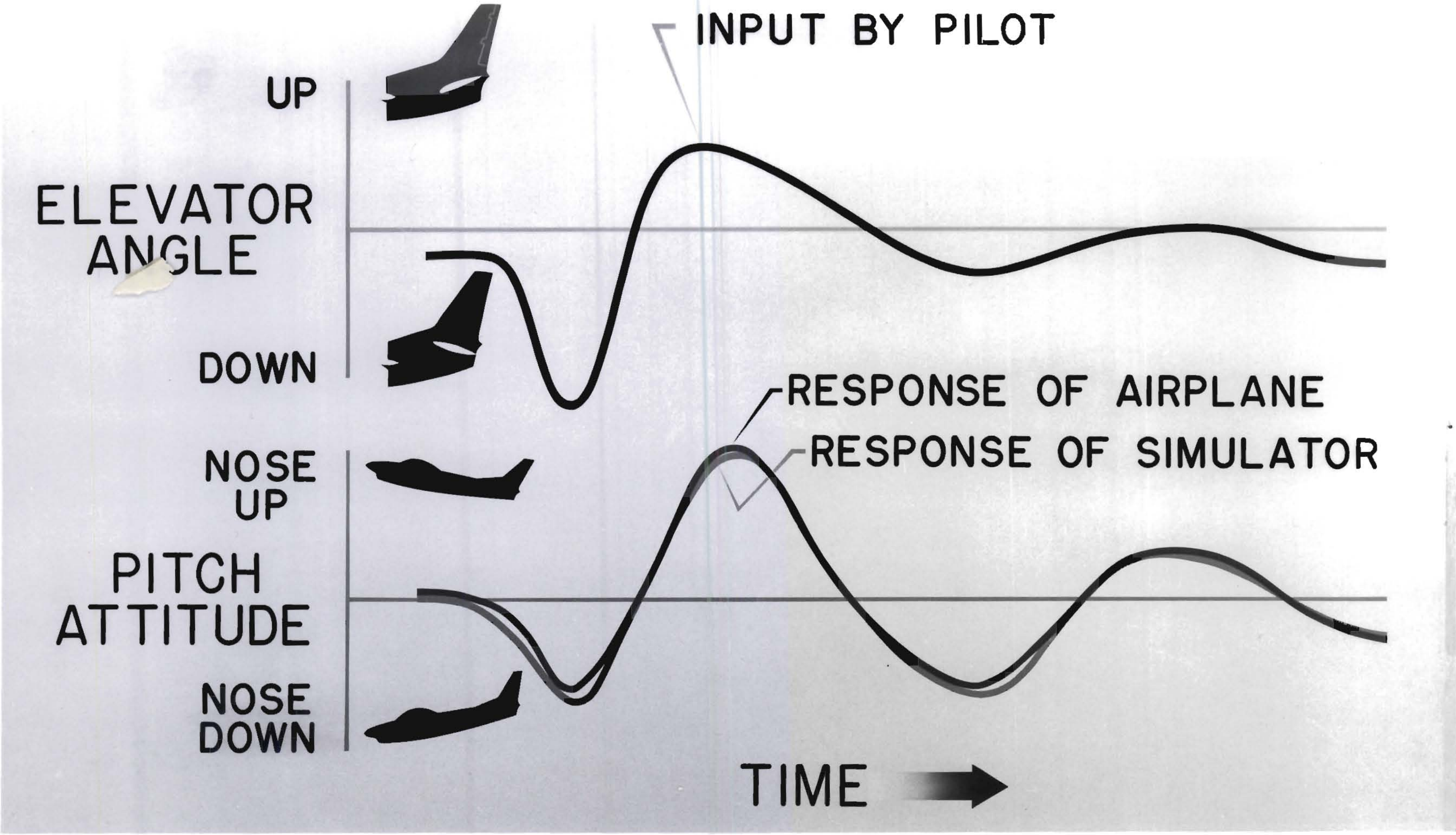
AIRPLANE MOTION SIMULATED



EQUATIONS FOR AIRPLANE PITCHING MOTIONS

TWO GENERAL EQUATIONS OF MOTION:

$$mV(\dot{\alpha} - q) = Z_{\alpha}\alpha + Z_{\delta}\delta$$

$$I_y \dot{q} = M_q q + M_{\alpha}\alpha + M_{\dot{\alpha}}\dot{\alpha} + M_{\delta}\delta$$

SOLUTION FOR PITCH ATTITUDE DUE TO ELEVATOR MOTION:

$$\text{CHANGE IN PITCH ATTITUDE} = \text{CHANGE IN ELEV. ANGLE} \times \left\{ \frac{T_{\theta}k - K_{\theta}b}{k^2} + \frac{K_{\theta}}{k}t + \frac{e^{-\frac{b}{2}}}{\omega}\left[\frac{\left(\frac{-T_{\theta}b^2\omega}{4} - T_{\theta}\omega^3 + K_{\theta}b\omega\right)\cos\omega t}{\frac{b^4}{16} + \frac{b^2\omega^2}{2}} + \frac{\left(\frac{-T_{\theta}b\omega^2}{2} - K_{\theta}\omega^2 - \frac{T_{\theta}b^2}{8} + \frac{K_{\theta}b^2}{4}\right)\sin\omega t}{\frac{b^4}{16} + \frac{b^2\omega^2}{2}} \right] \right\}$$

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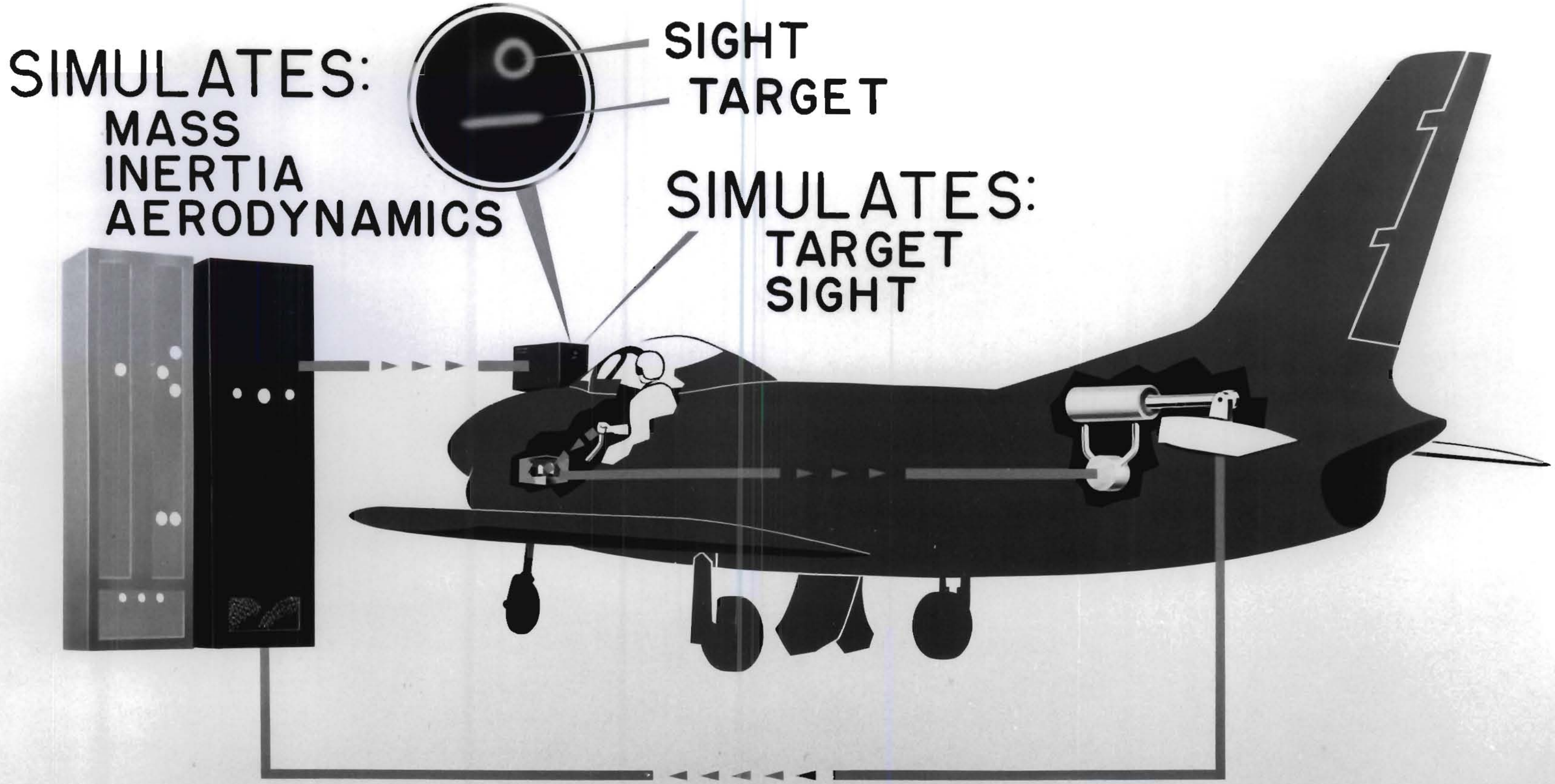
USE OF SIMULATOR FOR CONTROL RESEARCH



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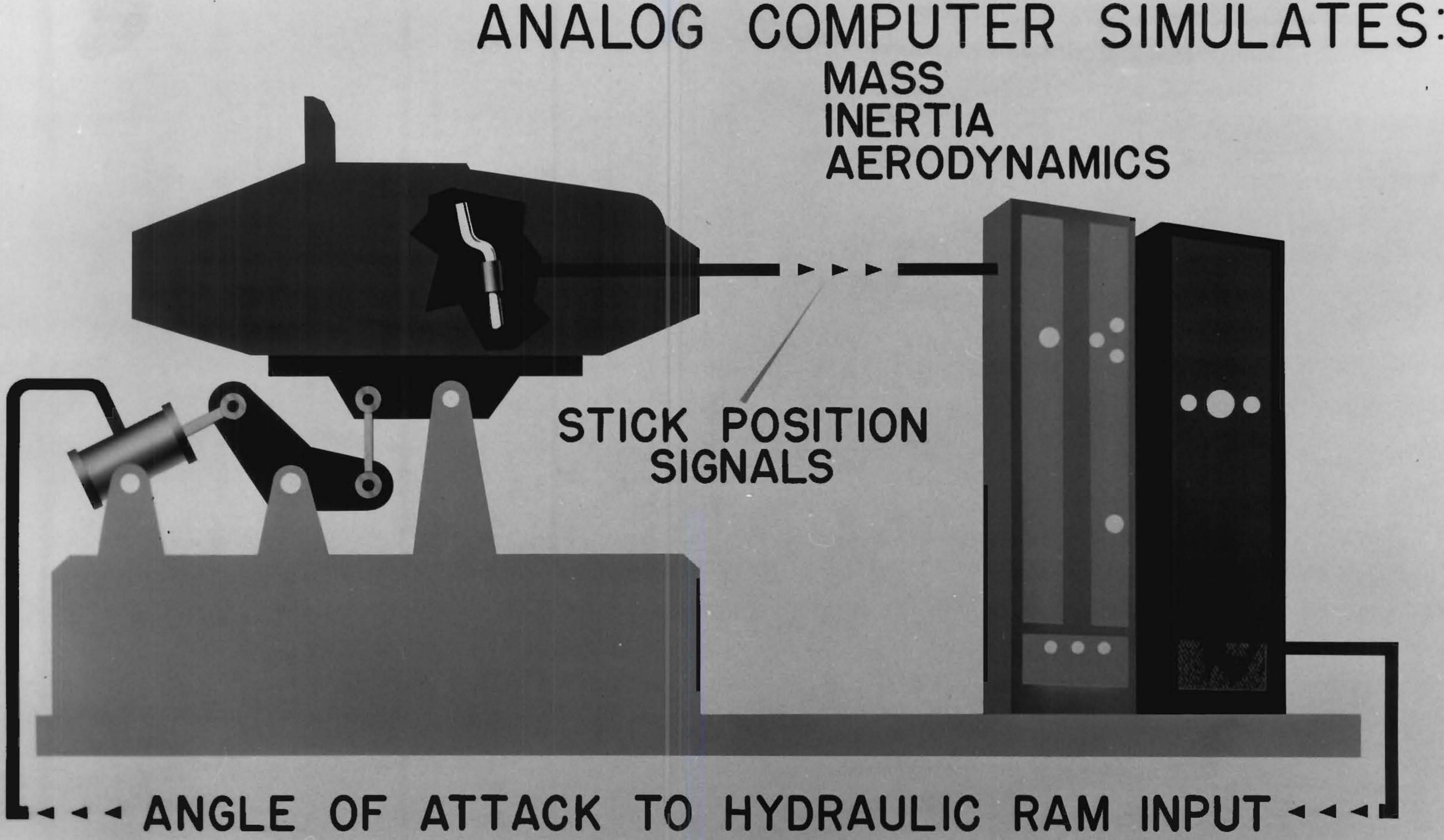
USE OF SIMULATOR FOR PITCH-UP RESEARCH



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ELEVATOR CONTROL COMPARED TO ALL-MOVING-TAIL CONTROL