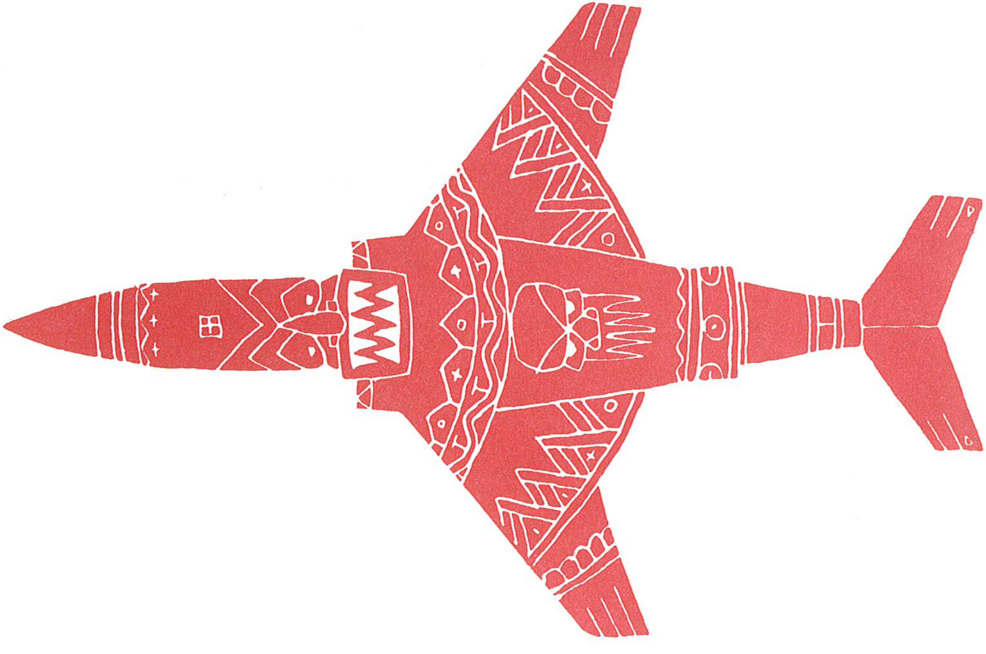
F-101 VOODOO PITCH CONTROL SYSTEM

McDONNELL Aircraft Corporation

REPORT NO. 5790

F-101 VOODOO

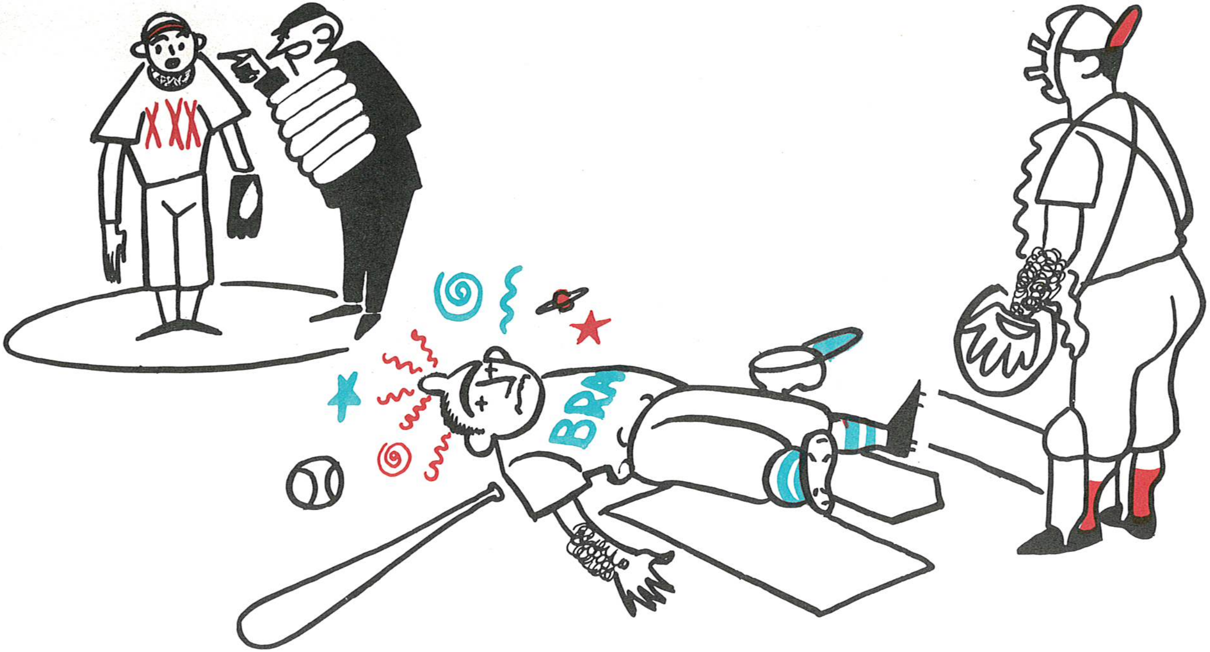


summary

Like others in this generation of high speed aircraft, the M.A.C. F-101 Voodoo can become longitudinally unstable and "Pitch-Up" at excessively high angles of attack. In order to warn the pilot of impending pitch-up, M.A.C. has designed and installed in all F-101 aircraft an automatic pitch-up warning system.

The design requirements for this system were:

1. Provide a positive warning of approach to the unstable region.
2. Provide a corrective control action far enough from the unstable region to preclude overshoot into it in case the first warning is unheeded, but close enough to maximize the useable flight envelope.
3. Provide an anticipatory function so that the system will be equally safe for slow and rapid approaches to the region of instability.
4. Maximize reliability.
5. Provide easy ground and in-flight operational checks.
6. Provide emergency malfunction cut-out switches and pilot override so that the pilot has direct control of the aircraft 100% of the time.



the pitch control system is:

a safety device that prevents the inadvertent operation of the Voodoo outside of its large combat flight envelope.

M.A.C. engineers developed the Pitch Control System to meet these requirements, and in so doing, provided the Voodoo pilot with maximum safety without compromising the Voodoo's mission capability.

The P.C.S. has been officially Air Force flight evaluated and is installed in all of the F-101 Voodoo aircraft that are being delivered for squadron service. The P.C.S. includes:

★ A horn boundary to aurally warn the pilot of approach to pitch-up.

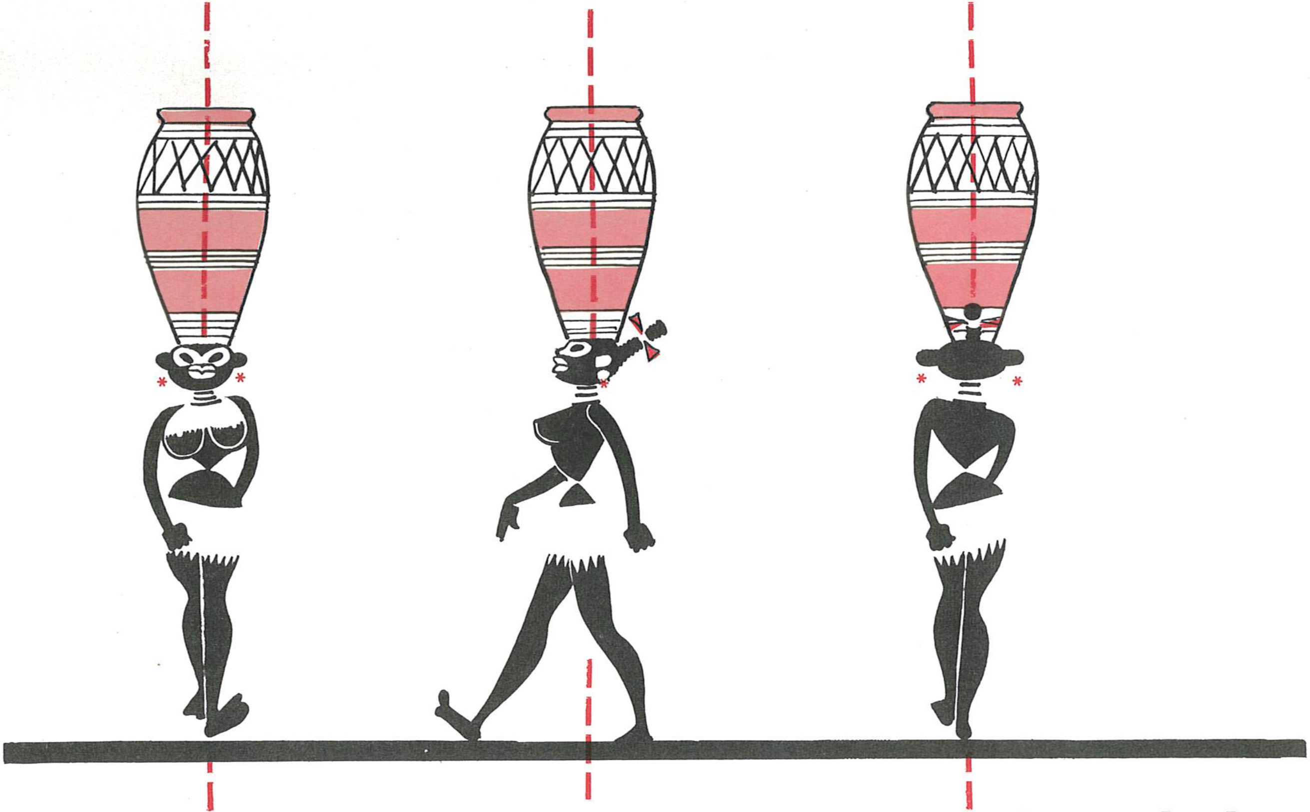
★ An independent pusher system to physically initiate corrective control prior to entering the unstable region in case the horn warning is unheeded.

★ In-flight operational checks and automatic visual warning of malfunction.

★ Extensive dual-component back-up design for maximum reliability.

This booklet describes the aerodynamic phenomena called "Pitch-Up," and the features of the P.C.S.

Remember, all of the F-101 aircraft can perform all of the modern combat missions and maneuvers for which they are designed without ever activating the P.C.S.



the VOODOO and longitudinal stability

The flight characteristics of all conventional aircraft begin to deteriorate at some point as increasing angle of attack changes the air flow over the lift and control surfaces. The characteristics of this deterioration depend primarily on aircraft configuration.

The configuration of every airplane is the result of a combination of compromises which, in the designer's opinion, gives the optimum solution to the design objectives. The F-101 Voodoo is considered by M.A.C. to be the optimum design for a versatile, long range, supersonic combat weapon system capable of rapid acceleration and maneuverability adequate for modern combat situations.

The characteristic features of this optimization in the Voodoo are:

★ Long fuselage to house fuel for long combat radii, and to house modern fire control systems and armament for all-weather attack and intercept.

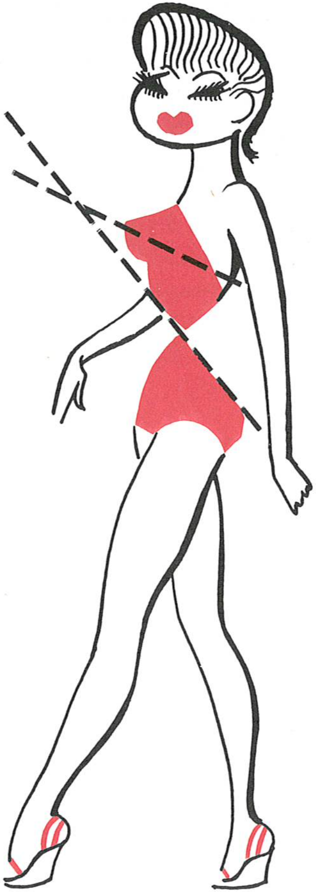
★ Large fuselage to house two engines for reliability and high thrust-to-weight ratio.

★ Thin, swept back wing to minimize drag.

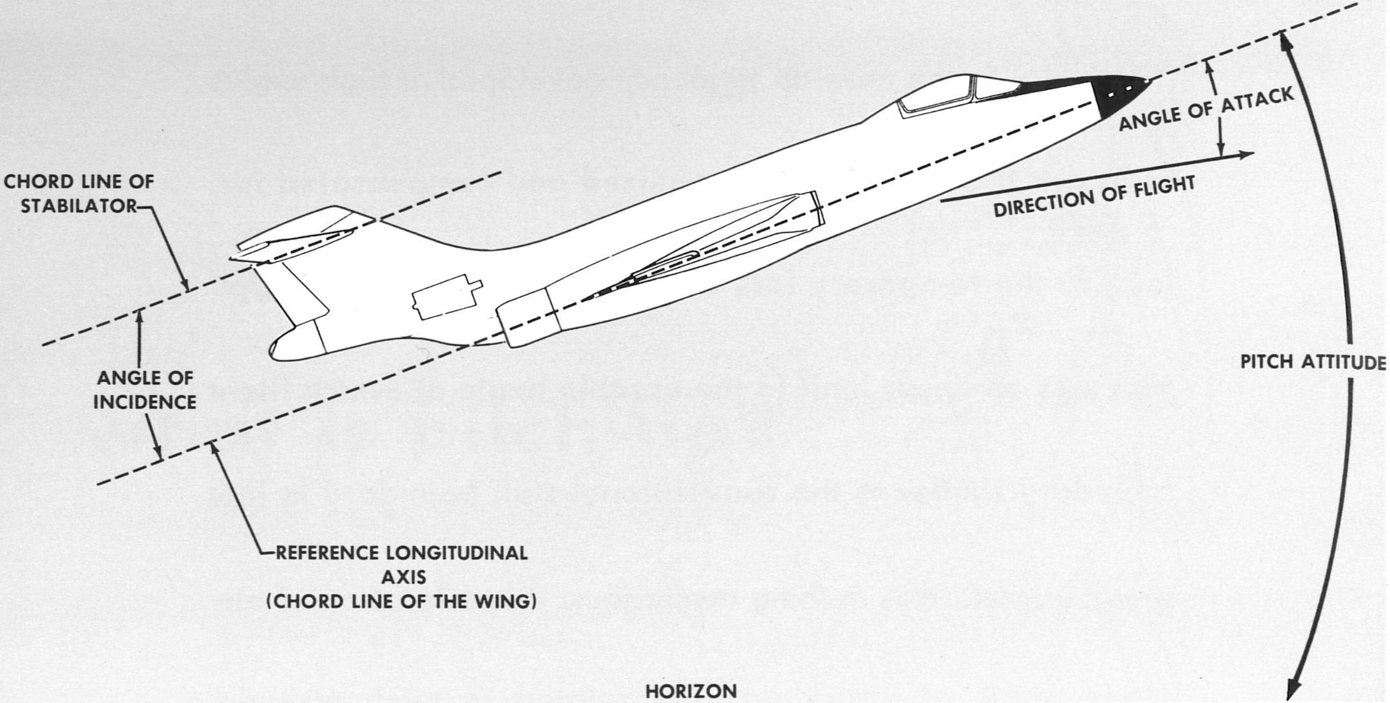
★ Low aspect ratio wing to minimize high speed structural problems.

Like others in this generation of high speed aircraft, as the Voodoo experiences a deterioration of flight characteristics at high angles of attack, it develops longitudinal instability. Pitch-up is the descriptive name that is popularly given to this phenomena.

what is pitch-up?



“Pitch-Up” is the nose-up tendency developed at high angles of attack that will, if not recognized and compensated for, lead to the temporary loss of controlled flight. “Pitch-Up” provides an upper limit to the useable angle of attack flight boundary similar to the conventional stall boundary in low speed aircraft. It is nothing mysterious. It is a function of airplane angle of attack and not related to pitch attitude.



Just as you can not fly conventional low speed aircraft at ever decreasing speeds and increasing angles of attack without stalling, you can not so abuse high speed aircraft.

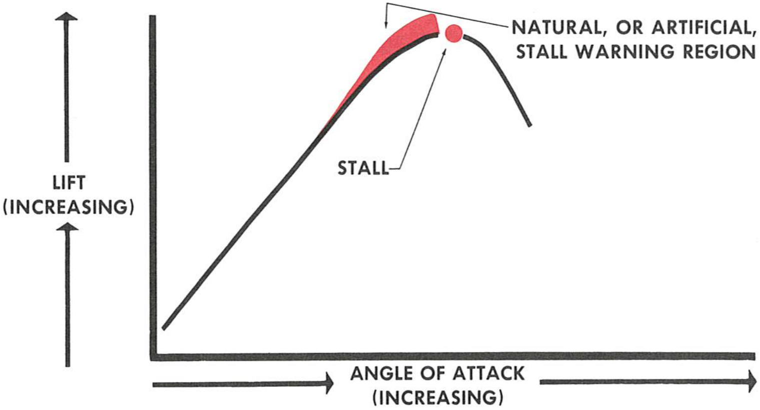
In order to better understand pitch-up, let us first examine the phenomena of the conventional stall.

An airplane is stable in the longitudinal direction if an increase in angle of attack produces an increase in nose down moment. Thus, in a longitudinally stable aircraft, if the pilot is to increase angle of attack he must apply increasing amounts of nose up elevator to counteract the increasing forces tending to push the nose down.

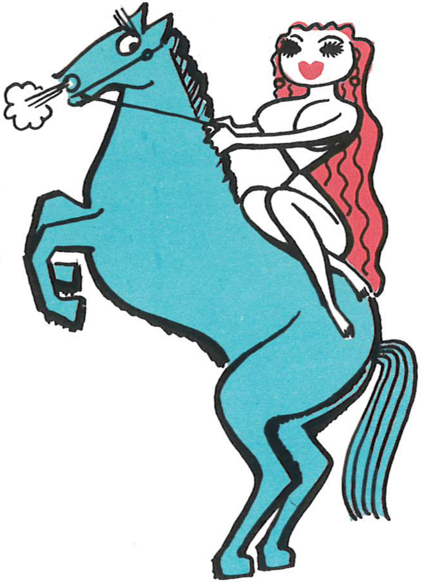
Normal stall occurs as the increase in angle of attack causes a deterioration of the lifting flow on the wing until the point is reached where lift starts to decrease with additional increases in angle of attack. The degree of longitudinal stability present establishes the amount of control stick force and travel required to bring an airplane up to this stall point.

At stall, the conventional airplane is at a high angle of attack. The wing lift starts to decrease and the nose drops. With the aid of nose down control, flying speed is regained rapidly and a normal pull up completes recovery. Artificial stall warning devices are usually installed in aircraft that do not have sufficient natural pre-stall buffet to warn of approach to the stall.

conventional airplane stall characteristics

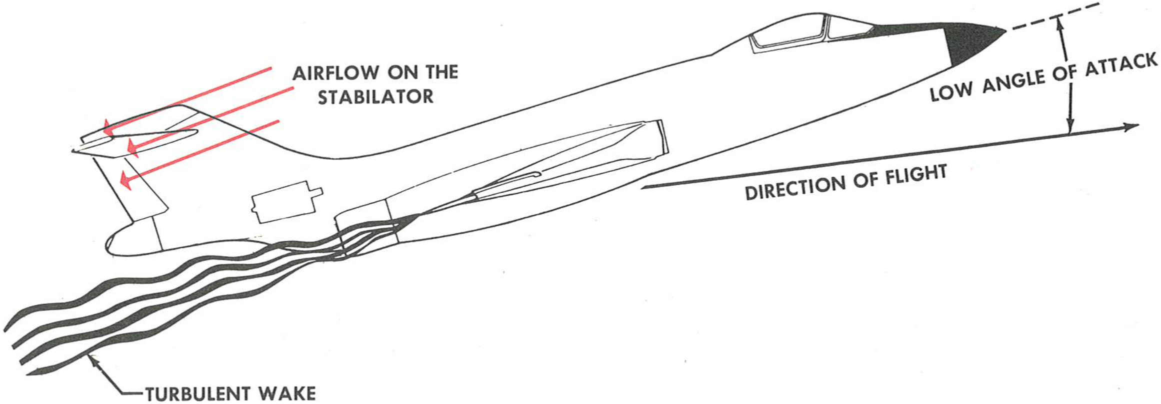


F-101 VOODOO longitudinal stability characteristics

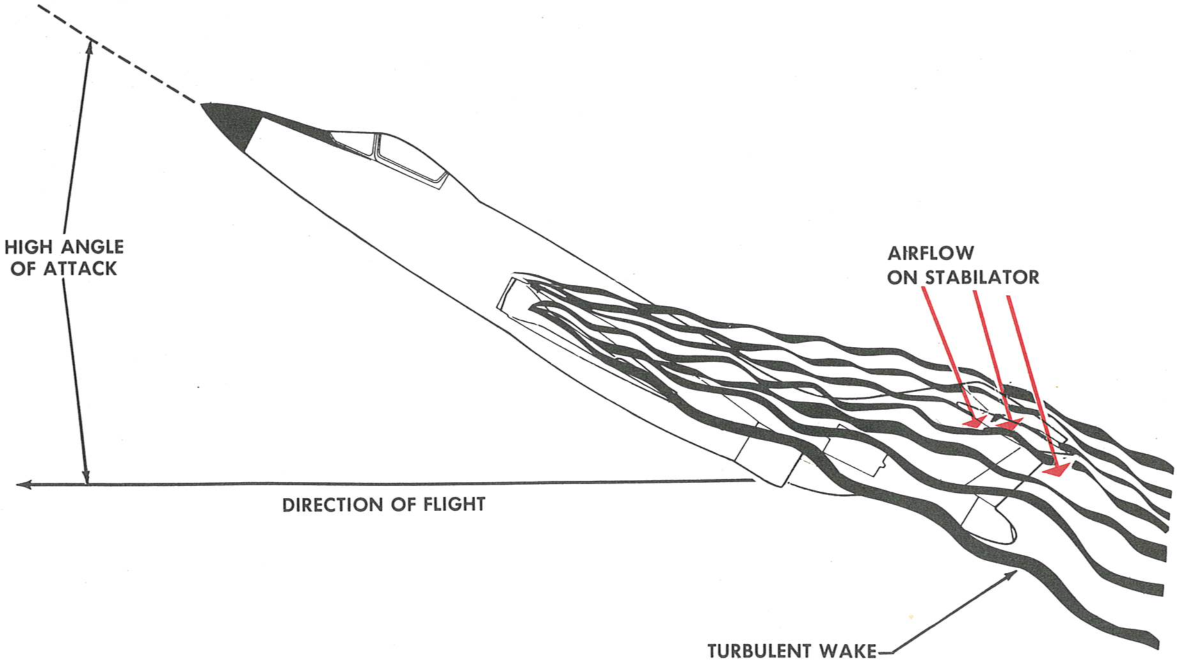


The longitudinal stability characteristics of the Voodoo and other modern, low aspect ratio, swept wing aircraft, deteriorate at high angles of attack. Trying to fly this airplane into the region of longitudinal instability is as foolish as trying to fly an older airplane past the stall limit.

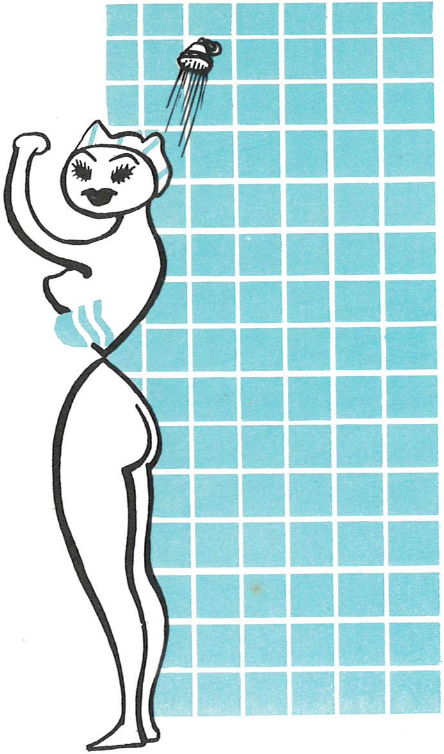
The aerodynamics of longitudinal instability are described graphically herein to give the operational pilot a background of what is happening to his steed when he rides too close to the pitch-up region.



"Pitch-up" was not experienced in the older generations of aircraft because stall limited them to much lower angles of attack than are now possible. The very high angles of attack at which modern high speed, low aspect ratio wings continue to lift accentuates the downwash effects of the wing and fuselage on the horizontal stabilizer. This intensified downwash is the primary cause of longitudinal instability.


HIGH ANGLE OF ATTACK
AIRFLOW ON STABILATOR
DIRECTION OF FLIGHT
TURBULENT WAKE

downwash is:



the downward component imparted to the flow over a wing by the trailing vortex field. The intensity of downwash is proportional to the lift generated by the wing and the distribution of this lift. Thus, the downwash angle experienced by the horizontal stabilator is greatly increased at extreme angles of attack by the concentration of wing lift on the inboard portion of a swept wing as tip stall develops. Vortices around the large engine air inlet ducts on the fuselage also contribute greatly to this downwash field on the horizontal tail. Figure (1) presents a comparison of typical airplane lift vs. angle of attack relationships between the F-101 Voodoo and an older, more conventional airplane. The regions indicated on the Voodoo curve correspond to conditions sketched in Figure (2). Notice that pitch-up occurs at angles of attack way past normal stall, and in the region of wing drop, and directional instability.

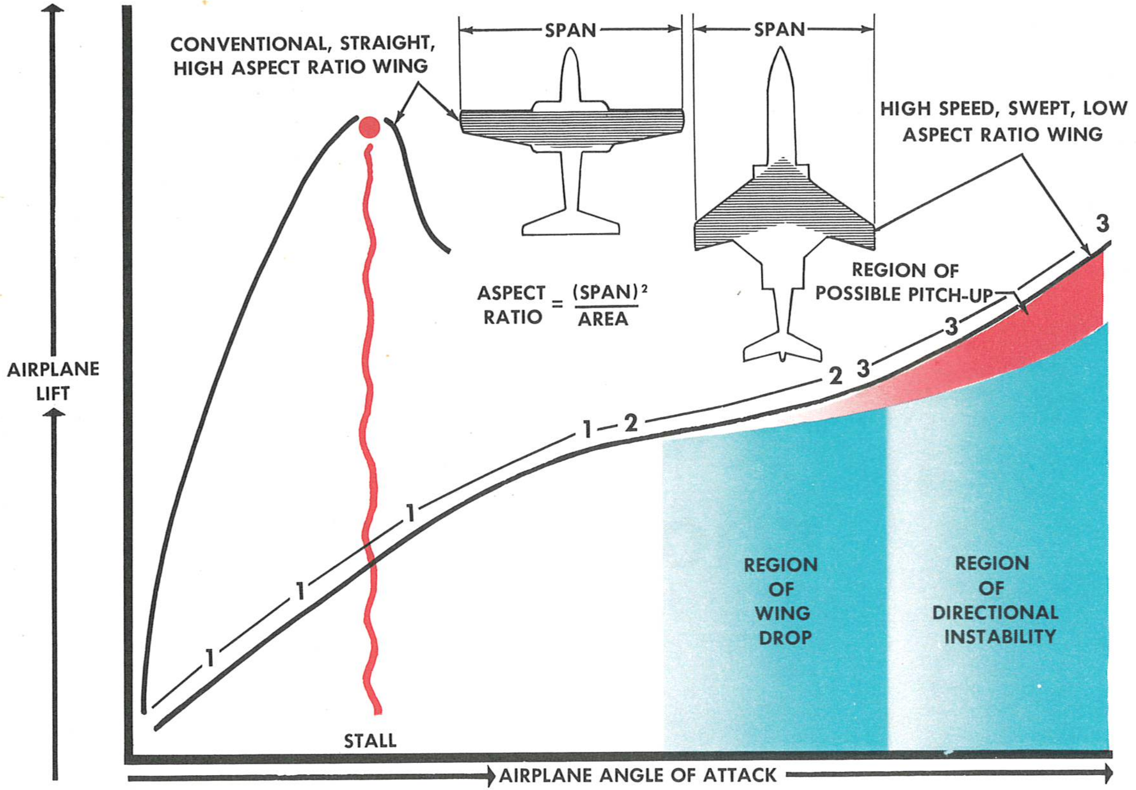
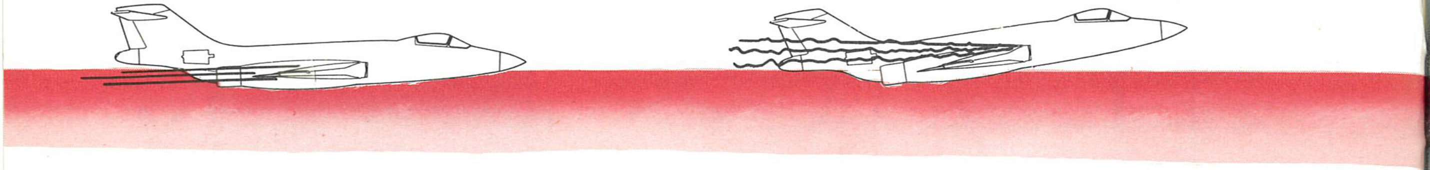
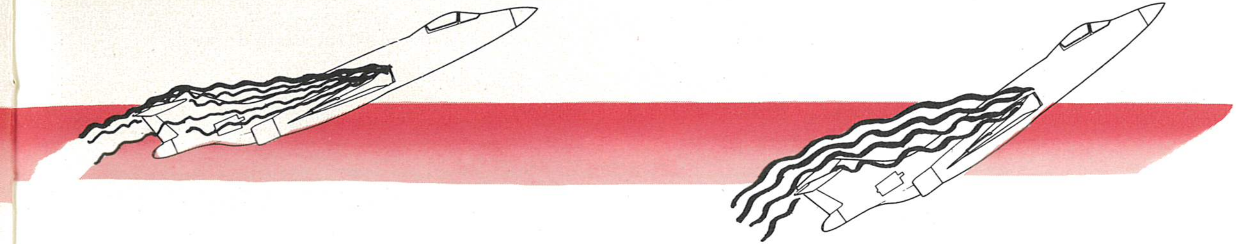


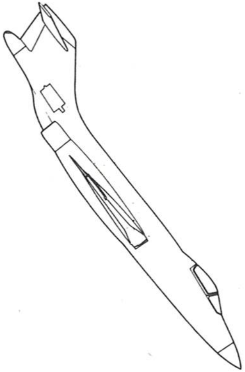
FIGURE 1 AIRPLANE LIFT VARIATION WITH ANGLE OF ATTACK



F-101 VOODOO pitch-up



characteristics



The three sketches in Figure (2) illustrate the changes of spanwise lift distribution, and the results on horizontal tail lift of the downwash developed, with increasing angle of attack. The large blue vector represents the remote free stream velocity impinging on the wing. The downwash angle is the difference between the direction of this vector and the direction of the flow vector impinging on the horizontal tail as represented by the large red vector. Sketches (2) and (3) show that downwash causes a decreasing stabilizing force (positive lift) on the tail with increasing angle of attack until finally it actually causes a downward de-stabilizing force and "pitch-up."

A secondary effect contributing to the unstable nose up moment is the forward shift of the swept wing center of pressure as the tips begin to stall. This effect is exaggerated on the sketches for descriptive purposes.

The vertical position of the tail is important because it dictates the angle of attack at which the tail enters the downwash field, and the intensity of downwash which it can experience. In general, a low tail is less stable throughout the low angle of attack region than the high tail, but never gets submerged in the downwash field to become unstable. The high tail is very stable at low angles of attack. It delays the entry into the unstable region until very high angles of attack, but greatly intensifies the instability once it is in the downwash field.

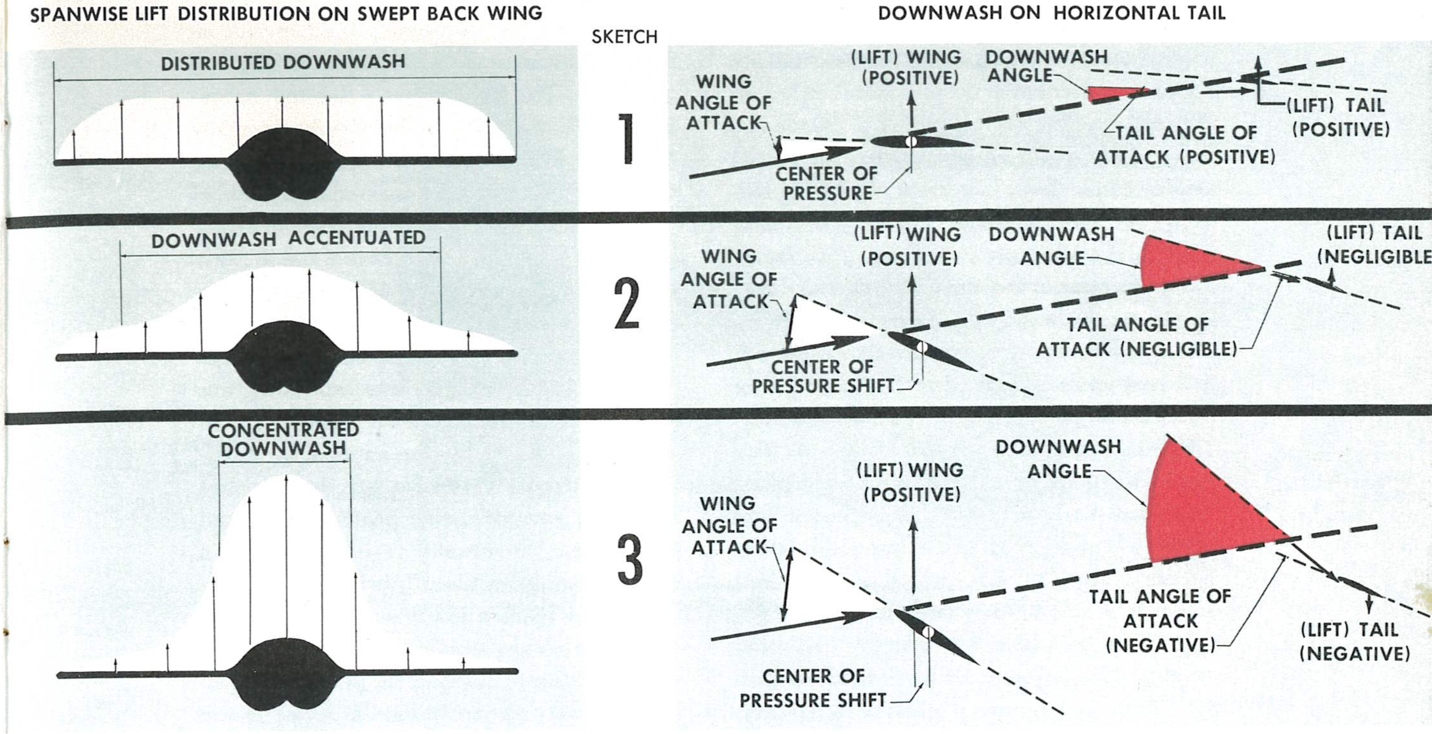


FIGURE 2 SPANWISE WING LIFT DISTRIBUTION AND DOWNWASH ON THE HORIZONTAL STABILATOR

The Voodoo pitching moment vs. airplane angle of attack curve illustrates the three stability regions represented in the previous sketches. In the stable region, corresponding to Sketch (1), an incremental increase in angle of attack (A) creates a nose down increment of pitching moment (M). This increment of moment decreases until, at the neutrally stable region, an incremental increase in angle of attack creates a negligible change in pitching moment (Sketch 2). The unstable region, Sketch 3, is shown to result in a nose up increment of pitching moment for increased angle of attack increments. The ratio "Pitching Moment Increment" divided by "Tail Angle of Attack Increment" is plotted against "Airplane Angle of Attack" to emphasize that pitch-up is not caused by the loss of tail "effectiveness." The loss of tail effectiveness at these angles of attack actually decreases the severity of pitch-up because a fully effective tail would develop more negative lift from the downwash field. The recovery control available is, however, correspondingly reduced as the tail loses its effectiveness.

The foregoing discussion of downwash on the tail has assumed a constant tail angle of incidence. The Voodoo has a slab tail, or stabilator, so that longitudinal stick control actually changes tail incidence. A careful pilot can, through judicious control, maintain longitudinal trim and increase the airplane angle of attack into the neutral and even unstable region. This will require control reversal at very high angles of attack. The rapidity with which the unstable region is approached dictates the degree of success that the pilot will have in controlling this effect. A slow approach to the unstable region permits the pilot to feel the impending "pitch-up" and to apply corrective nose down control in time to prevent further penetration. Rapid pull up near the unstable region can result in a dynamic overshoot into "pitch-up" even after the pilot has applied nose down control. Because it does not possess a sufficiently vigorous buffet warning, prior to entering the pitch-up region, it is necessary to incorporate a device in the Voodoo to warn the pilot so that he will not unwittingly fly into the unstable region.

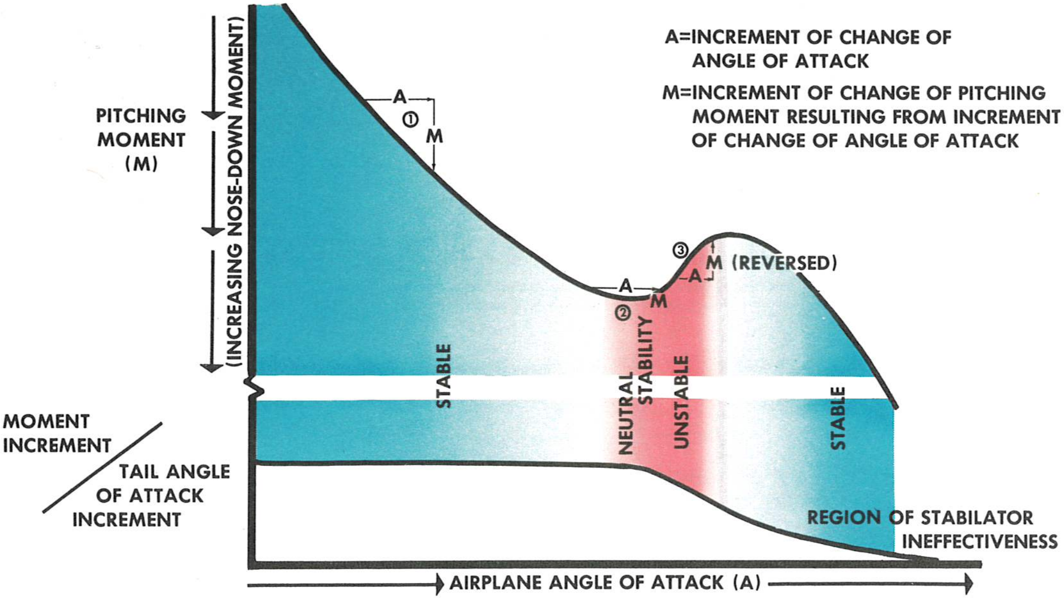
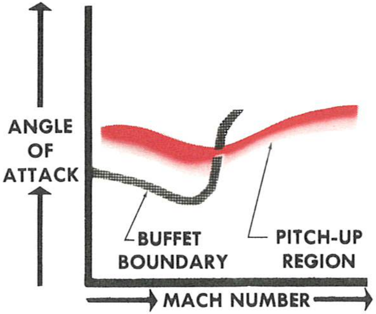
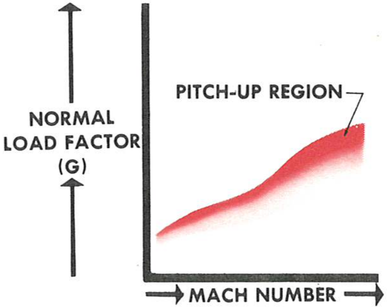


FIGURE 3 VOODOO PITCHING MOMENT vs. ANGLES OF ATTACK

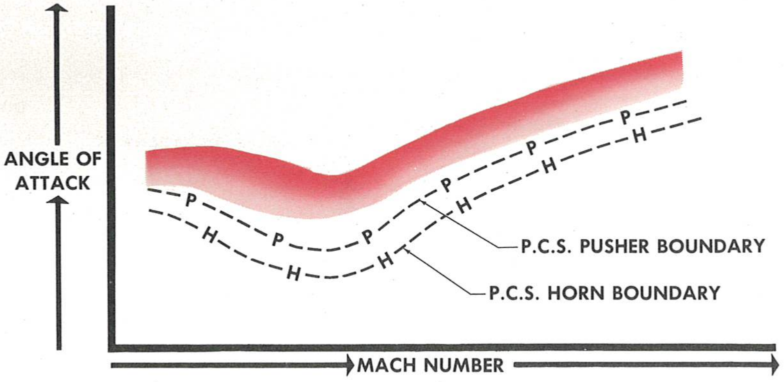
M.A.C. designed the Pitch Control System (P.C.S.) as a warning device to inform the Voodoo pilot when he was flying too close to the pitch-up region. The following curves are representative of data presented in classified reports. They are based on extensive wind tunnel and flight tests to accurately determine the angle of attack, Mach number, and normal load factor boundaries of the Voodoo pitch-up region.

the pitch control system





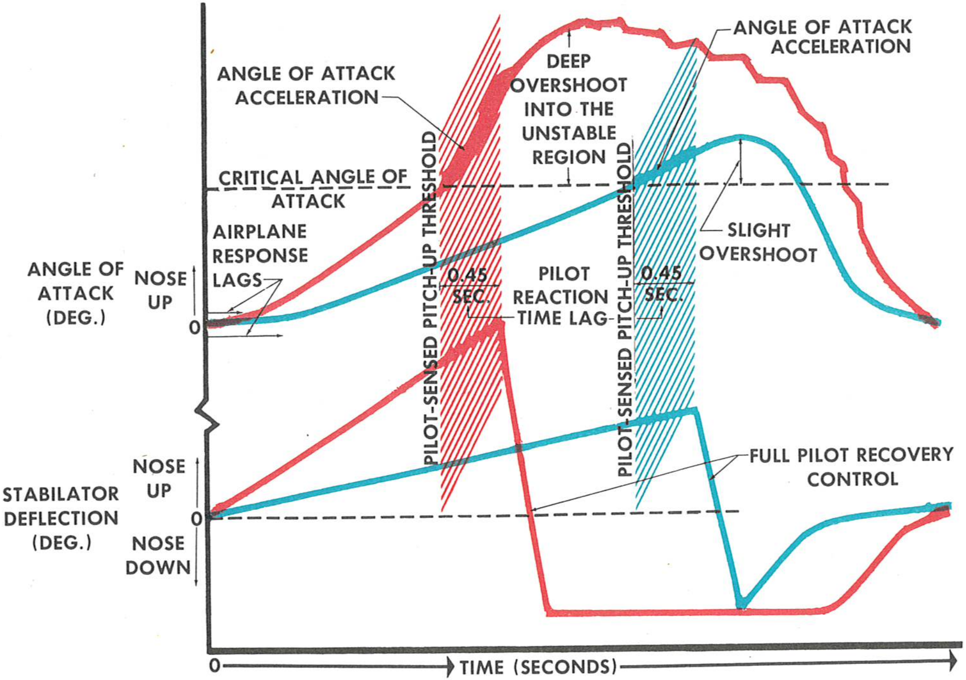
NOTE: The shading of the pitch-up region emphasizes the fact that pitch-up is defined as a region rather than a sharp boundary. Slow penetration of this region can result in controlled flight up to the dark area and even beyond.



These curves illustrate the wide variation in the pitch-up angle of attack region with Mach number. It is obvious that the boundary of a warning system must follow the actual airplane boundary very closely if the useable flight envelope is to be maximized. In order to do this, the M.A.C. Pitch Control System incorporates Mach Scheduling so that the boundary angle of attack is a function of the flight Mach number.

The P.C.S. provides the Voodoo pilot with two degrees of warning by having two independent systems with independent trigger boundaries. A horn in the head phones is excited sufficiently far away from the pitch-up region so that forward stick response by the pilot, or merely a relaxing of nose up control will keep the Voodoo from getting any closer to unstable flight. If this warning is unheeded, the P.C.S. "Stick Pusher" will be triggered at a slightly higher point. The pusher boundary is set on the fringe of the pitch-up region, and the pusher provides a fast corrective nose down stick movement to initiate positive recovery. A rapid pusher rate maximizes the useable stable flight envelope by initiating fast recovery.

BASIC AIRPLANE RELATIONS WITHOUT P.C.S.



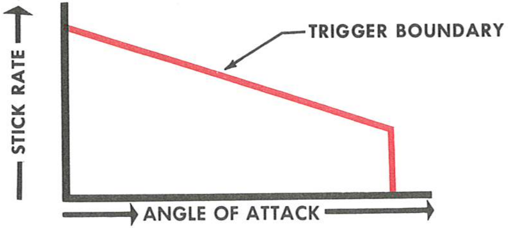
Fitting the static horn and pusher boundaries close to the pitch-up region necessitates providing an anticipatory function in the P.C.S. so that a rapid approach to the region of instability will not result in dynamic overshoot into pitch-up. The accompanying representative time-plots of Stabilator Deflection and Angle of Attack graphically shows why anticipation of the pitch-up region is necessary to avoid overshooting the critical angle of attack.

This example assumes the airplane is *not* equipped with a PCS.

M.A.C. studies indicated that the average pilot reaction time lag is approximately 0.4 second. It is obvious from the preceding curves that rapid and severe nose up control movement by the pilot can result in dynamic overshoot well into the unstable region. M.A.C., therefore, decided that sensing stabilator movement rate would provide the most positive and direct method of equipping the P.C.S. with an adequate anticipatory function because it is, as the previous figure indicates, the primary input function leading to the rapid, dynamic-type of approach to the region of instability.

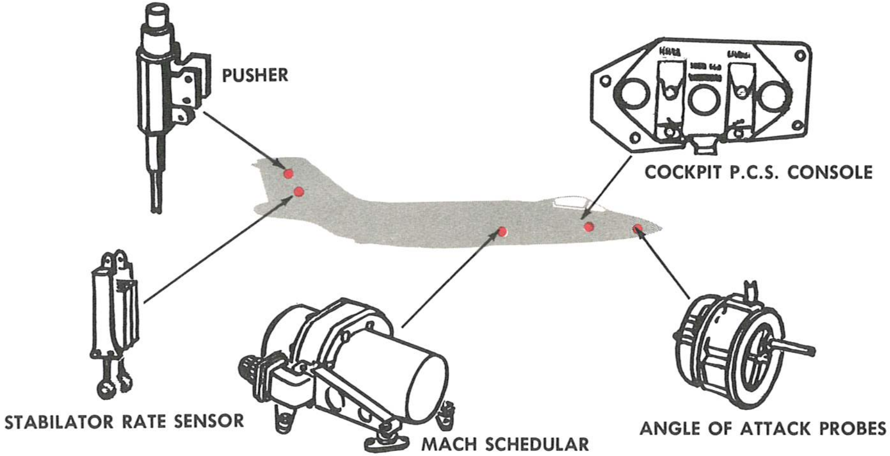
The stick rate trigger points of the P.C.S. are scheduled as a function of angle of attack so that at high angles near the pitch-up region, an early warning of too radical stick rate is provided while at low angles of attack, freedom of control is maximized.

The simplicity, and resulting reliability of the linear potentiometer stick movement sensor system are important considerations in comparing this method of anticipating approach to pitch-up with somewhat more rigorous methods which are considerably more complex.



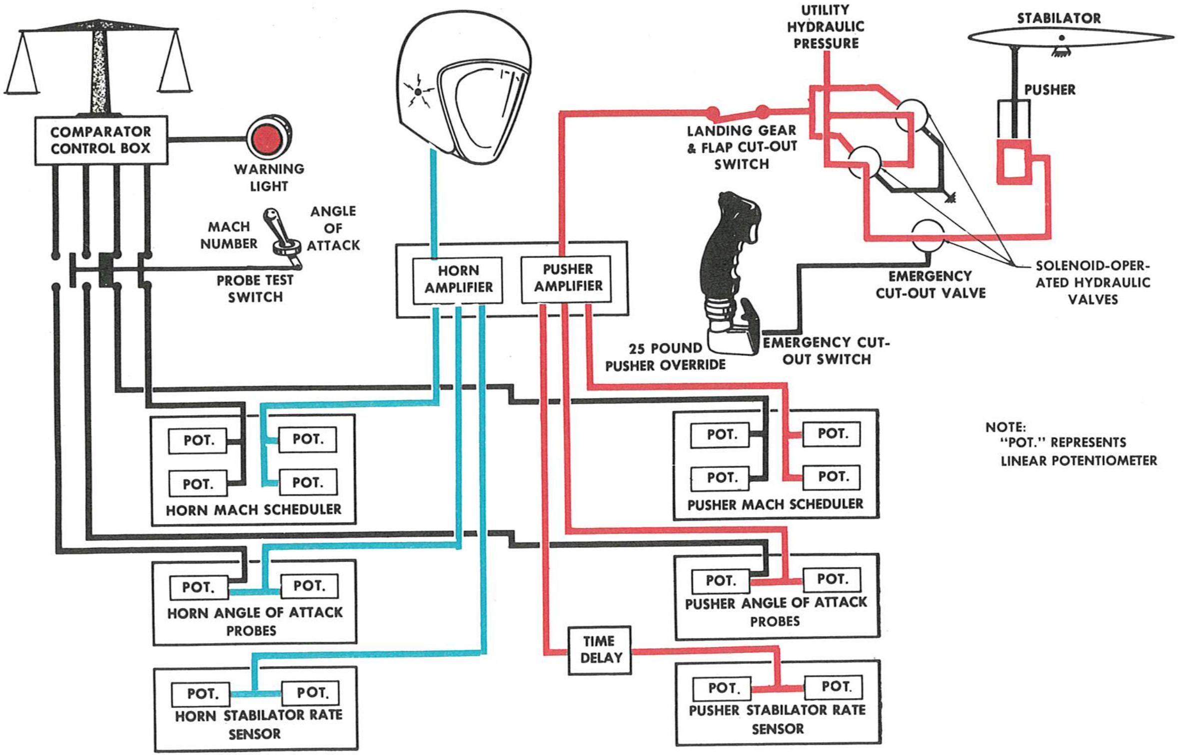
Complete duality of components is built into the P.C.S. for maximum reliability. The critical angle of attack is sensed by two independent probes, one located on the left side of the fuselage nose for the pusher system, and one located on the right side of the nose for the horn system. The signals from both of these systems are combined with the signals from their respective stabilator rate sensors (linear potentiometers on the control system) and, supplemented by independent Mach number schedular signals, are fed into independent transistorized amplifiers.

safety features of the P.C.S. design



THE SCHEMATIC DIAGRAM ON THE FOLLOWING PAGE ILLUSTRATES THIS COMPONENT DUALITY AND BACK-UP DESIGN.

PITCH CONTROL SYSTEM SCHEMATIC



NOTE:
"POT." REPRESENTS
LINEAR POTENTIOMETER

The Mach signals in the P.C.S. are constantly being compared, and by pushing a test switch the angle of attack signals can also be compared. If either sets of signals should fail to correspond, an amber warning light in the cockpit will light. Typical of the "back-up" design illustrated in the preceding schematic is the set of two parallel solenoid operated hydraulic valves which operate the pusher, further backed-up by an emergency cut-out valve. Additional safety features indicated on the schematic are the emergency P.C.S. disengage switch on the control stick grip, which permits immediate system deactivation without the pilot taking his hand from the stick, and the 25 pound override force built into the system so that the pilot can easily over control the P.C.S. in case of malfunction. These two features guarantee complete pilot control of the airplane at all times.

Because of the lack of necessity for extreme maneuvers in the landing configuration, the pusher and the stick rate anticipation functions of the P.C.S. are automatically deactivated when the landing gear and/or the flaps are extended. The P.C.S. horn and the low speed buffet boundary are still present to warn the pilot if he flys at too high an angle of attack.

Once the pusher is activated it drives the stabilator "nose down" until two conditions are satisfied; the aircraft is below the critical angle of attack, and the stabilator has traveled approximately 2.5 degrees. To preclude inadvertent premature reengagement, there is a time delay circuit in the pusher system which prevents the reactivation of the pusher by stick rate until 0.4 seconds after it has cut itself off. There are two stabilator system cutout switches that limit the stabilator push to a maximum of 1.5 degrees of nose down trim with the speed brakes in, and to 3.5 degrees with the speed brakes extended in order to prevent a malfunction from resulting in full nose down control.

The complete P.C.S. system can be operationally checked out without any special ground test equipment. Normal external hydraulic and electrical power activate the system, and manual manipulation of the probes and control stick give a complete indication of any malfunctions in the system.

pitch control system operational checks

We have explained the phenomena of pitch-up and how the Pitch Control System is designed to help the Voodoo pilot avoid flying into this region. The Voodoo is a fast and high-flying bird. She has outstanding maneuverability. The P.C.S. will help you to safely take full advantage of this speed and maneuverability.