JET TRANSPORT OPERATION IN TURBULENCE

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AIAA Paper
No. 64-353

1st AIAA Annual Meeting
Washington, D.C. June 29 – July 2, 1964

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General

During 1963 and early 1964, a series of turbulence associated upsets occurred in civil and military jet transport operations. The following factors were common to a number of the upset cases:

- Control was lost in turbulent air conditions.
- Unusually high pitch attitudes preceded a dive at high speed.
- The dives involved speeds in excess of 460K IAS at steep nose down attitudes.
- Successful recoveries were made only after visual outside reference was established.
- Recovery efforts were complicated by high elevator forces and stalling of the stabilizer drive actuator.

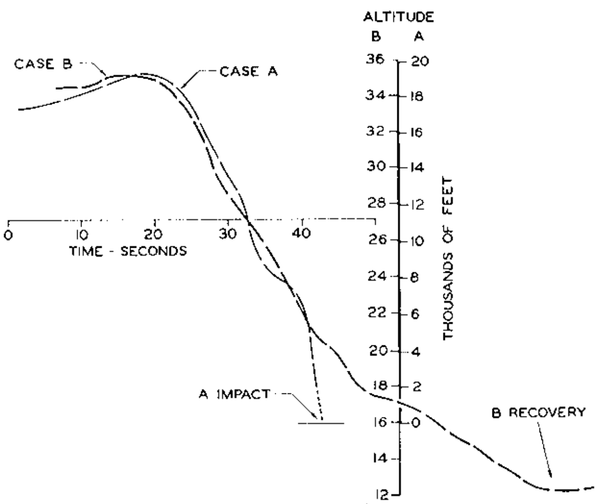


FIGURE 1 - JET TRANSPORT UPSETS

Figure 1 shows altitude versus time plots from flight recorder information in two such upset cases. In both cases, minimum and maximum speeds were nearly identical at approximately 215K and 475K IAS. In Case A structural failure occurred at low altitude seconds before impact. In Case B a successful recovery was made at approximately 12,000' and no structural damage occurred. Flight paths in both cases were nearly identical down to the point at which structural failure occurred in Case A.

Investigation Of The Problem

Intensive studies of the turbulence problem have been made, particularly of the factors involved in Cases A and B of Figure 1 above. In addition to the usual investigative activities, the studies have included analyses of flight recorder records and flight crew statements, computer simulation studies, human centrifuge tests, flight tests, and other efforts still continuing. Though these activities have not pinpointed a specific cause of the upsets, they have led to better understanding of the problems of operating jet transport airplanes in areas of turbulence. The following factors have been particularly highlighted:

- Attitude indicator readability and interpretation.
- Turbulence penetration speeds.
- Control problems.

Attitude Indicator Readability And Interpretation

Since many of the cases involved unusual attitudes, indicator readability and interpretation in unusual attitudes was reevaluated. A typical contemporary attitude indicator is shown in Figure 2.

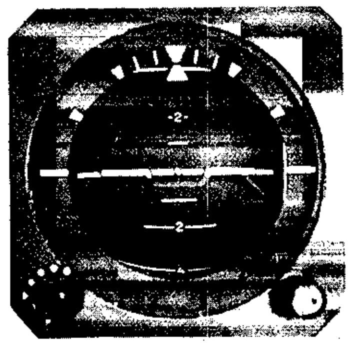


FIGURE 2 CONTEMPORARY ATTITUDE INDICATOR

The pilot maintains the airplane level in pitch and roll by keeping the symbol airplane "on" and parallel to the horizon bar. The roll reference pointer at the top of the indicator furnishes an additional roll attitude reference. This pointer always points at the sky and is thus sometimes called the "sky pointer". The lateral direction in which it points is the direction in which control input must be made to return to wings-level flight. In this usage the "sky pointer" is a command index.

As the airplane deviates from a level pitch attitude, the vertical distance between the reference airplane and the horizon bar increases, making roll attitude more difficult to visualize. At extreme pitch attitudes, the horizon bar may disappear behind its surrounding mask leaving only the "sky pointer" for roll reference. Since the horizon bar is the primary attitude reference, the picture of roll attitude becomes less clear at extreme pitch attitudes. This factor is evident in Figure 3 in which the airplane is in a wings-level climb at a 50° body attitude.

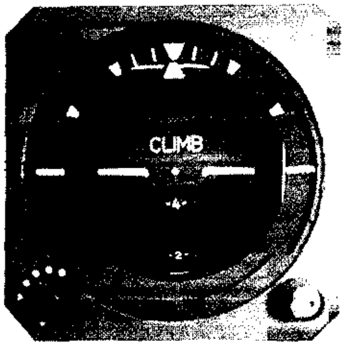


FIGURE 3 CONTEMPORARY ATTITUDE INDICATOR, STEEP CLIMB ATTITUDE

Figure 4 shows an experimentally modified indicator in the same attitude as that of Figure 3.

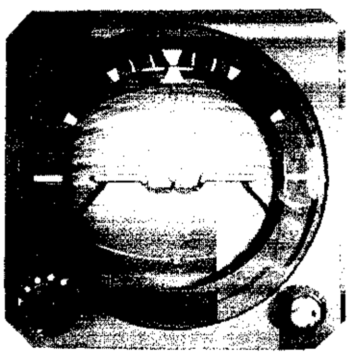


FIGURE 4 MODIFIED ATTITUDE INDICATOR, STEEP CLIMB ATTITUDE

Note that the increased span of the pitch markings improves the roll picture when the horizon bar is out of view. The command word "PUSH" indicates the proper control input required and the closely spaced horizontal lines form a warning that an unusually high pitch attitude exists. The word "PUSH" and associated warning lines do not appear until the maximum normal pitch attitudes are exceeded. A similar warning area with the word "PULL" appears when the maximum normal nose down pitch attitudes are exceeded.

In unusually nose-high and nose-low attitudes, some contemporary indicators make use of the words "CLIMB" and "DIVE". In extreme attitudes such as inverted flight, the word "CLIMB" (or "PUSH" or "UP") may not be correct and some say this is reason to avoid the use of words altogether. No single word will be entirely correct for such attitudes unless some universal one such as "HELP" is used. Use of "CLIMB" and "DIVE" or other suitable words is justified since they should clearly help the pilot prevent extreme attitudes developing. Prevention of an extreme attitude seems the preferred alternative. Further, most present day gyro/attitude indicator combinations cause the indicator to rotate 180° in roll when the airplane approaches vertical pitch attitudes so that basic indicator information will be correct when the airplane is inverted. This process inverts the words "CLIMB" and "DIVE" while the airplane is inverted. When the words are inverted they are essentially unreadable, and in this sense do not give incorrect information.

Figure 5 shows the "old" attitude indicator alongside the experimentally modified indicator in several attitudes.

fig 5
APPEARS ON PAGE 6

FIGURE 5 ORIGINAL AND MODIFIED ATTITUDE INDICATORS IN VARIOUS AIRPLANE ATTITUDES

Note in Figure 5H, for example, these features:

- The words "PULL" and the closely spaced warning lines indicate that an unusually steep nose down attitude exists.
- The word "PULL" calls for the correct recovery pitch input.
- The "sky pointer" calls for the correct recovery roll input.

In the experimental indicator, the "sky" is a bright blue while the "earth" is black with perspective lines. The perspective or "section line" presentation gives a more realistic "earth" picture. A proposed revision moves the radiating perspective "earth" lines to the 15 and 30° roll positions. This improves the perspective picture and gives a convenient bank angle reference at the normal maneuvering values.

Turbulence Penetration Speeds

Turbulence penetration speeds are a product of two main considerations. The chosen speed must be high enough to protect against a gust induced stall, yet low enough to protect against excessive structural loads. Figure 6 shows factors of significance in the choice of turbulent air penetration speeds.

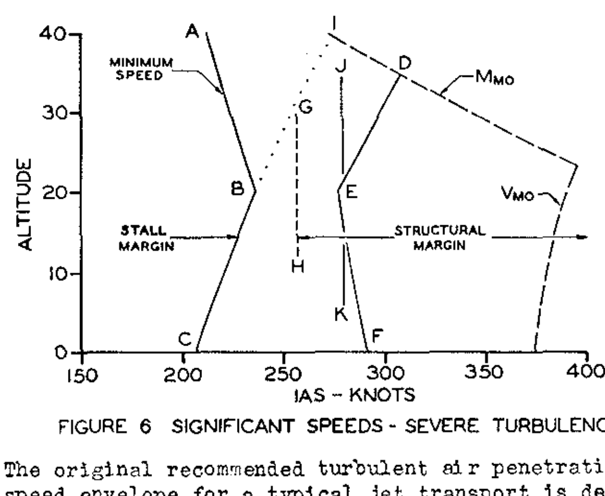


FIGURE 6 SIGNIFICANT SPEEDS - SEVERE TURBULENCE

The original recommended turbulent air penetration speed envelope for a typical jet transport is defined by the "hourglass" figure (Lines ABC, DEF) in Figure 6. Although the hourglass curve is no longer in effect, it bears discussing because of its influence on the choice of earlier turbulence penetration speeds.

The minimum speed, Line ABC, is that at which the airplane will stall if it encounters the design gust. Line CB indicates, as it should, an increase in stall speed with altitude up to 20,000'. The decrease in gust value allowed for design purposes --66 fps MSL to 20,000' decreasing linearly to 38 fps at 50,000'--accounts for the apparent wrong way bend in Line ABC at 20,000'. Stall speed in gusts would continue to increase as shown by Line BI if the design gust value was not reduced above 20,000'.

Use of speeds to the left of Line ABC would obviously be unwise since a stall and loss of control would be a certainty if the design gust was encountered. And the stall, of course, is not the only consideration near the low speed end of the range.

Line DEF, the right side of the hourglass curve, defines the speed at which the design limit load factor would be reached if the design gust was encountered. The airplane can withstand the design gust at speed V_{MO} and still have substantial strength margins. Since speed V_{MO} is well above that defined by Line DEF, the latter should not be thought of as the speed at which the airplane would be near structural difficulties if the design gust was encountered.

Based on the old penetration speed envelope (Lines ABC, DEF) a mid-range speed (Line GH) might seem a good choice. At speeds not far below this value, however, the airplane will be on or near the back side of the thrust required curve. Corrective thrust and longitudinal trim adjustments in this range will be relatively large and the airplane will be more difficult to control. At high altitude, if the airplane is allowed to get very far to the left of the bottom of the thrust required curve, a large loss in altitude may be inevitable if adequate speed and control are to be regained even in perfectly smooth air.

The airplane's response to gusts will be greatest at the lower speeds and this will also complicate control. Choice of the mid-range speed (GH) becomes even less appealing at the higher altitudes. Since gusts often do not decrease in intensity above 20,000', Line BI represents a more realistic minimum speed value at the higher altitudes. These factors, plus the fact that strength margins exist beyond V_{MO} for encounters with the design gust, suggest use of a speed near the high speed line of the hourglass envelope. The speed defined by Line JK will provide adequate stall and control margins while still preserving large strength margins.

While a constant indicated airspeed is used at low and intermediate altitudes, a constant Mach number should be used at the higher altitudes. The changeover from IAS to Mach will occur at about 34,000' for most contemporary jet transports. The specific changeover altitude depends on the shape of the buffet boundary curve for the airplane involved. As load factor and/or weight increase, the buffet boundary curves pull down along a constant Mach line as in Figure 7. The Mach number that goes through the peak of the curves is the one speed that gives the greatest margin to both low and high speed buffet onset.

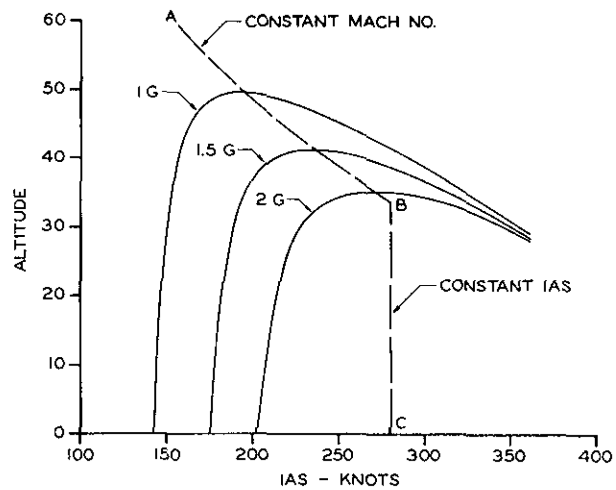


FIGURE 7 BUFFET BOUNDARY - ONE WEIGHT

The recommended turbulent air penetration speed is a constant indicated airspeed from sea level up to the intersection of the constant Mach number line. Above this altitude, the Mach number line that goes through the peak of the buffet boundary curves is used. It is important to note that these are recommended and not limiting speeds. And as between the two, it is perhaps better to be on the high side than on the low.

Control Problems

Elevator Forces

In Case B of Figure 1 above, the flight crew reported that, in the high speed dive, they pulled as hard as they could, and though the elevator column moved somewhat, there was no corresponding response of the airplane. Unusually heavy forces are characteristic of flight at such extreme speeds, and column movement without airplane response was no doubt due to cable stretch and aerolasticity effects. Inasmuch as these effects cannot be demonstrated in training, it is no wonder they are surprising to the pilot who may experience them only once in a lifetime. Such effects can complicate recovery efforts when upsets do occur.

Stabilizer Drive Stall

If sufficient mistrim exists, it is possible for resulting aerodynamic loads to exceed the drive capability of the stabilizer actuator. Mistrim will occur in event of a trim runaway although a runaway is an unlikely possibility. Mistrim is more probable if trimming is attempted in severe turbulence. Proper trim is normally established by trimming to a zero stick force reference. In the rapidly changing conditions of severe turbulence, no stable stick force reference is available and trimming attempts are likely to result in mistrim.

Once mistrim exists, some of the elevator's pitching moment contribution must go to oppose the pitching moment developed by the mistrimmed stabilizer. This will have several adverse effects. First, some of the available elevator capability goes to oppose the mistrimmed stabilizer and less is left to counter any adverse gust-induced pitching motions. Second, elevator forces will be increased and may complicate recovery from a high speed dive. Third, and perhaps most significant, whenever the elevator opposes the stabilizer, the aerodynamic load on the stabilizer may reach a level that is impossible for the trim actuator to overcome.

If, for example, nose down trim is used to counter the airplane's pitch up response to a vertical draft, the airplane will pitch down more sharply when the draft reverses in direction. Elevator will be used to counter the pitch down motion, and the resulting aerodynamic load may be sufficient to stall the stabilizer actuator. As speed increases, the adverse effects increase, and the elevator may have insufficient effect to counter the nose down forces of the draft and the mistrimmed stabilizer. It is obvious that tuck effects may also complicate the picture, and it is significant that tuck effects cannot be countered by a Mach trim system that is unable to move the stabilizer. <u>But a stabilizer trim system that is mechanically normal will drive out of such an adverse trim situation if the pilot applied elevator column forces are reduced</u>. A happy circumstance.

An increase in actuator drive power seems a good thing at first look but is not necessarily feasible A system powerful enough to drive regardless of aerodynamic loads may well have the capability of imposing destructive stresses if a trim runaway should occur at high speeds. The power of the drive system, like so many other things, must be a compromise.

<u>Control Cues</u>

To fly the airplane properly in severe turbulence, keep it level. The best way to keep it level? <u>Fly the attitude indicator</u>. Obvious? Of course. Simple? By no means. Many things complicate the task.

To fly straight and level the pilot must control roll, pitch and yaw. A wings-level airplane resists turning, and "straight and level" becomes essentially a two, rather than three, element task--the control of roll and pitch. Of the two, pitch control problems predominate in severe turbulence. Upsets in the pitching plane, both small and large, are more common than upsets in roll, especially on instruments. It is interesting to speculate why.

Only one instrument furnishes roll attitude information. And it tells the truth. When the airplane rolls, the attitude indicator pictures it faithfully and essentially without error. Not so the pilot's pitch references.

Pitch references? The trouble may be that he has too many! Five cockpit indications respond to airplane pitch changes and are interpreted directly or indirectly as pitch indicators. Pitch clues come to the pilot from:

- The attitude indicator.
- The altimeter.
- The vertical speed indicator.
- The airspeed indicator. *
- Load factor changes.

Of these, only the attitude indicator tells the pitch story truthfully in turbulence.

Jump now from turbulence to smooth air. In nearly all flight regimes, the above "pitch indicators" respond to airplane pitch changes as indicated in TABLE I.

TABLE I here

The pilot spends thousands of hours consciously and unconsciously seeing and using the indications of TABLE I. Since all respond to pitch changes they tell him something about his pitch attitude.

A normal flight usually involves a constant airspeed climb, a constant altitude cruise segment, and a constant airspeed descent. In each of these segments, an indicator that is not truly a pitch indicator is used as the basis for pitch control inputs.

In the normal climb, the desired aerodynamic and other requirements are satisfied by a constant airspeed. Since the climb is also normally made with an essentially fixed thrust lever setting, the resulting pitch attitude changes with altitude. Constant <u>airspeed</u> is the requirement and it cannot be satisfied by a constant pitch attitude. Pitch control inputs are made as a direct result of airspeed changes and the attitude indicator assumes a supporting role. The same is true of the descent. The net result over countless hours of flight experience is that the airspeed indicator becomes a powerful influence on the pilot's control of pitch. An airspeed indicator that moves rapidly toward the lower levels, for example, will call forth a strong pilot elevator input.

Constant altitude cruise puts the altimeter "in command". The present day traffic control environment makes a constant altitude mandatory. And since a constant <u>altitude</u> cannot be maintained by use of the <u>attitude</u> indicator alone, pitch control inputs are made as a result of movement of the altimeter needle. Again the attitude indicator assumes a supporting role. And again many hours spent in constant altitude cruise, plus the stringent altitude requirements of instrument flight, result in the pilot responding to "pitch" indications from the altimeter. Constant attitude cruise might well be superior to constant altitude cruise, but it does not fit today's traffic control picture.

Consider this:

1. An airplane that is pointed up will go up.
2. An airplane that is going up must be pointed up.

It seems quite right. If not aerodynamically correct, it seems it ought to be. It is a curious thing, but the concept of items 1. and 2. apparently is a strong influence on the pilot's thoughts

* In the interest of simplification--and since its pitch indicating influence is probably weak--the Machmeter is left out of this discussion.

and actions. If the airplane rises in an updraft it seems that it must be pointing up. Many pilots will insist that an airplane pitches up in an updraft and down in a downdraft, but the reverse is true.

Turbulence is not made up of vertical drafts alone. They may come at the airplane from any direction and the airplane's response depends on the direction from which the draft comes. For drafts in the XZ (pitching) plane only, the airplane responds as shown in TABLE II, and the five "pitch indicators" of TABLE I react as indicated.

TABLE II here

Assuming that the pilot's control inputs are influenced by all five of the "pitch indicators" of TABLE II, the commands each will call forth will normally be as shown in TABLE III.

TABLE III here

The attitude indicator calls for a correct control input; the other "pitch indicators" lie to the pilot in varying patterns and degrees. The heavy boxes indicate the pitch commands that are reversed. Over half tell the pilot to PULL when he should PUSH, or vice versa.

We do not know how strongly wrong way pitch clues may be influencing the pilot, and it is a difficult thing to measure. Tests conducted on "g" chairs, a human centrifuge, and in flight tend to indicate that reversed pitch control inputs are being made under conditions where severe turbulence effects are simulated. Further studies and tests are planned to learn more about the phenomenon.

For the sake of exploring further, assume that each of the five "pitch indicators" has an exactly equal influence on the pilot. For six of the eight draft directions (TABLE III, Drafts 2,3,4,6,7,8--the up and down drafts), three or more of the five "pitch indicators" tell the pilot to do the wrong thing. It is doubtless faulty to assume an equal influence for each of the five indicators; one will have more or less impact than the next. It seems that the attitude indicator should carry the most weight, but do we know that a PULL "command" from the attitude indicator will override the wrong way PUSH from two and perhaps three other indicators?

If wrong way control inputs are in fact being made as a result of the above phenomenon, what can be done about it? Although further studies and tests will better equip us to answer, two operational approaches are evident now.

1. In severe turbulence FLY THE ATTITUDE INDICATOR and ignore pitch clues from other sources.

Now this is old stuff but it has new implications. It seems a radical thing to say, but it may be wise to cover up all "pitch indicators" except the attitude indicator! No matter how much a pilot may believe he is ignoring the false pitch clues, we think they are influencing him more than he knows or intends. When the altimeter, in thousands of hours of cruising flight, tells the pilot to PUSH when it increases, can and will he ignore the same influence in the relatively few minutes he is apt to spend in severe turbulence? Under stress a normal human being reverts to habit. Covering up the altimeter, airspeed, and vertical speed indicators is too radical an approach to seriously recommend, but if the false pitch clue phenomenon is real, it just might be the lesser of two evils. And it might not be so radical at that. If thrust is set for level flight at turbulent air penetration speed (then left alone), even in severe turbulence the airspeed and altitude will remain within safe aerodynamic limits if the attitude for level flight is maintained reasonably constant. The pilot handling the controls would be insulated from the false pitch clues, while the other pilot's uncovered indicators could be monitored for gross airspeed and altitude changes.

2. In severe turbulence USE THE AUTOPILOT.

The autopilot is not fooled by false pitch clues. And it has other advantages.

The autopilot is calm and dispassionate and unaffected by stress; the human pilot is not. The autopilot does not get tired. It is as fresh and efficient at the end of a long flight as it was at the start. Not so the human pilot. Dust dislodged by negative "g" forces does not get in the autopilot's eyes. When the instrument panel shakes so the instruments are unreadable, the autopilot could care less. The autopilot is not subject to nystagmus. The autopilot is safely force limited in one fashion or another. The autopilot sees every attitude displacement and makes a corrective control input the instant it happens. The human pilot cannot. When the autopilot carries all the control load, the human pilot is free to monitor. It is far easier to monitor than it is to do everything. It is also safer. We find no case where a modern autopilot has lost control of a jet transport in turbulence. We know of several cases where the human pilot has lost control. We know of at least one case where the pilot firmly believes the airplane was saved by use of the autopilot in severe turbulence.

There are cautions of course. Some installations incorporate an automatic cutoff circuit (ACO) that responds to load factor when it increases above a certain level. With such circuit it may not be feasible to use the autopilot in severe turbulence. Only a small percentage of commercial jet autopilot installations have an ACO circuit, however, and it is possible to disconnect it. It is possible for the autopilot to mistrim the airplane in severe turbulence if the requirement for a pitch input exists for a long period. This brings perhaps the most important caution: Monitor the trim indicator during autopilot operation to be sure it does not depart far from the trim point. If it does, it can readily be disconnected. An inadvertent disconnect or failure of the autopilot in severe turbulence would be undesirable and the operation must be monitored to guard against any adverse consequences of such an occurrence. And so it is with any useful device--it must be monitored or its failure can pose difficulties.

If the autopilot is used in turbulence, it is probably best to leave the altitude hold control OFF. But even this old rule may be questioned. Some actual turbulence penetration experience suggests that it may be best to use altitude hold, and certain other things tend to support its usage. But until more is know, it is best to leave the altitude hold OFF.

The false pitch clue phenomenon is only a theory at this time. A number of things indicate that it may be an important contributor to the turbulence upset problem. Further tests are planned to prove or disprove the theory. Meanwhile it is interesting food for thought.

FIG.5

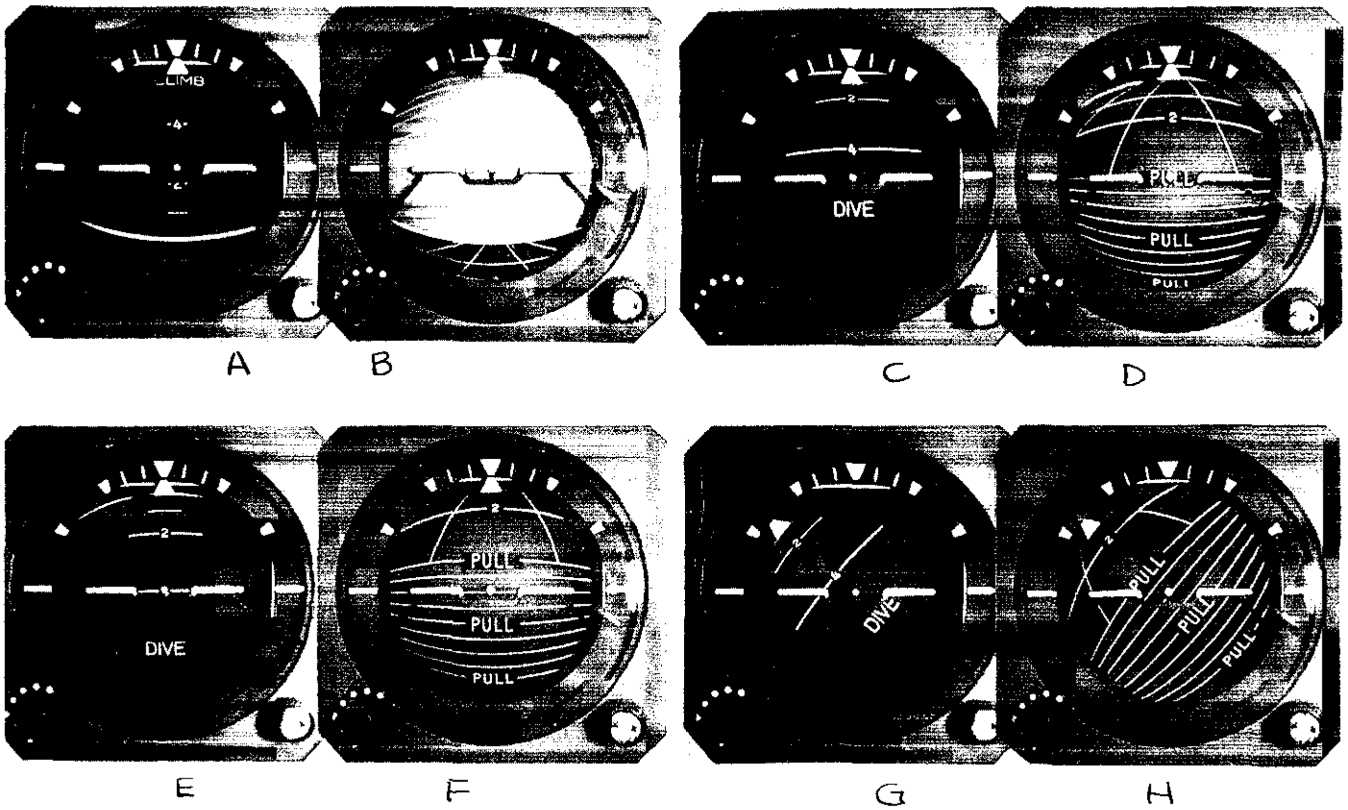
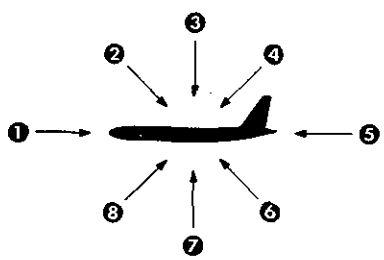


Table I Response Of Cockpit Pitch Indications To Airplane Pitch Changes

Airplane Pitch Change	Attitude Indicator	Altimeter Indication	Vertical Speed Indication	Air speed Indication	Load Factor Change
Pitches nose up	Pitches up	Increases	Climb	Decreases	Increases
Pitches nose down	Pitches down	Decreases	Descent	Increases	Decreases

Table II Airplane Response To Steady State Drafts In The Pitching Plane

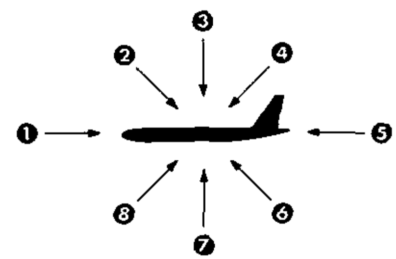


Draft Dir-ection	Airplane's Pitch Response	"Pitch Indicators" Attitude Indicator	Altimeter Indication[a]	Vertical Speed Indication[a]	Airspeed Indication[a]	Load Factor Change
1	Pitches up	Pitches up	Increases	Climb	Increases	Increases
2	Pitches up	Pitches up	Decreases	Descent	Decreases	Decreases
3	Pitches up	Pitches up	Decreases	Descent	Decreases	Decreases
4	Pitches up	Pitches up	Decreases	Descent	Decreases	Decreases
5	Pitches down	Pitches down	Decreases	Descent	Decreases	Decreases
6	Pitches down	Pitches down	Increases	Climb	Decreases[b]	Increases
7	Pitches down	Pitches down	Increases	Climb	Increases	Increases
8	Pitches down	Pitches down	Increases	Climb	Increases	Increases

[a] The response shown for the altimeter, vertical speed, and airspeed indicators assumes that pressure changes are consistent with steady state drafts, and ignores short period changes due to random pressure changes.

[b] Decreases initially, then increases.

Table III Elevator Input "Commanded" By Cockpit Pitch Indicators



Draft Dir-ection	Airplane's Pitch Response	Pitch Command Response: Attitude Indicator	Altimeter Indicator	Vertical Speed Indicator	Airspeed Indicator	Load Factor Change[a]
1	Pitches up	PUSH	PUSH	PUSH	PULL	PUSH
2	Pitches up	PUSH	PULL	PULL	PUSH	PULL
3	Pitches up	PUSH	PULL	PULL	PUSH	PULL
4	Pitches up	PUSH	PULL	PULL	PUSH	PULL
5	Pitches down	PULL	PULL	PULL	PUSH	PULL
6	Pitches down	PULL	PUSH	PUSH	PUSH	PUSH
7	Pitches down	PULL	PUSH	PUSH	PULL	PUSH
8	Pitches down	PULL	PUSH	PUSH	PULL	PUSH

[a] Assumes that changes in load factor will call forth a control input that tends to restore normal 1 "g" conditions. There are reasons to believe that, particularly under negative "g" conditions, this may not always be so.