Fig. 5 Damping effect of roll moment of wing rock control.

Fig. 6 Normal vortex position during control of wing rock.

Spanwise Camber Effects

In a previous study by Roberts and Arena[4] steady and unsteady effects of asymmetric leading-edge flap deflections on the 80-deg wing were discussed. In the present effort flaps are activated in an antisymmetric sense, proportional to roll rate. The effect of the flap deflections on the wing rock oscillation, can be seen in Fig. 4a. Several cycles of steady-state wing rock are shown prior to flap activation. Antisymmetric flap activation proportional to roll rate occurs at a nondimensional time of approximately 60 as shown in Fig. 4b, after which the motion rapidly decays. The behavior of the moment hysteresis for this time history may be seen in Fig. 5. During the cycle of the wing rock oscillation before control is turned on, the cycle still exhibits the three major hysteresis loops, indicating that the limit cycle motion has reached steady state. When control is turned on, the roll moment rapidly decreases in a counterclockwise spiral toward zero moment, indicating the significant damping contribution added by the flap activation. An explanation for the resulting damping after flap activation may be seen in Fig. 6, which is a plot of the normal vortex position during control of wing rock. The left vortex only is shown for clarity. During wing rock, the large time lag that was discussed previously is observed. After the flaps are activated, the lag is quickly eliminated. The variation of spanwise camber caused by the flaps that results in a damping of the wing rock motion should be noted. As seen in Fig. 4b, the flap on the downward-going wing is deflected downward, and vise versa on the upward going wing.

Conclusions

The goals of the present study were to assess the roles that the unsteady boundary condition and spanwise camber play in wing rock, and to apply these concepts in developing a control strategy for alleviating wing rock. Simulation data have been collected that indicate not only the quasisteady and dynamical aspects of the model motion, but a wide range of data that are indicative of the fluid physics involved. Results indicate that quasisteady effects have a damping effect on the motion primarily because of the hysteresis behavior of vortex position normal to the wing. Additionally, spanwise camber when applied proportional to roll rate has been shown to be capable of alleviating the wing rock motion by mitigating the lag in normal vortex position.

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Definition of Primary Flight Reference

Richard L. Newman*
Crew Systems, San Marcos, Texas 78667-0963

Introduction

THE terms primary flight reference (PFR) and primary flight display (PFD) have been widely used but never clearly defined. Head-up displays (HUDs) were advertised as PFRs, but required the presence of other approved head-down PFDs in the cockpit. The terms PFR and PFD are controversial and raise red flags to many in the field. The civil cockpit design document[1] does not use the term (nor does it address see-through displays).

The definitions of PFR and related terms are seen as key to the development of flight display standards, designs, and evaluation techniques. Otherwise, approval of novel displays will continue to be subjective with vague and varying criteria.

Historically, HUDs were weapon-aiming sights. Beginning as simple reflecting gun sights, advances in technology allowed the inclusion of flight data in a virtual image that appears to float in front of the pilot's windscreen. In spite of the display of flight data, early HUDs were not developed as general flight instruments, but as weapon-aiming devices.[2]

At the same time civil applications of the head-up display concentrated on the landing approach, beginning with Klopf-

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*President. E-mail: rlnewman@rattlers.net. Associate Fellow AIAA.

stein.[3] The first civil HUDs were certified in 1974: the Sundstrand Visual Approach Monitor for the B-727 and the Thomson HUD for the Dassault Mercure. In the 1980s, HUDs were developed for use during category IIIa approaches. These initial civil HUD installations were developed solely for the approach and landing phases of flight.

As both military and civil pilots became accustomed to HUDs, they increasingly used their HUDs for general flight tasks. In other words, pilots found that HUDs worked well as flight displays and used them regardless of any formal approval.[4]

In 1993 the first HUD developed for general flight use was certified in the Beechcraft King Air.[5] Several other current and proposed HUDs are intended for use during all phases of flight (C-17, C-130J, Gulfstream).

The development and use of the HUD moved faster than the development of HUD criteria suitable for all flight phases. Beginning with Barnette's initial report,[2] the U.S. Air Force (USAF) began working to develop guidelines for HUD-based PFRs. Much work was spent detailing requirements, primarily in the area of symbology and human factors. The result is a symbol set that evolved from the Royal Aircraft Establishment's Harrier HUD.[6]

To a large extent, the USAF's hand was forced by the widespread population of HUDs in the fleet. Much of this work was spent in developing waivers for the existing fleet of F-16 aircraft. The benefit of this exercise has been the fairly rapid evolution of MIL-STD-1787[7] and the improvement in the cockpit design process for new aircraft (such as the F-22).

The recent application of HUDs to transport aircraft has led to the question: What should the requirements for PFDs [including HUDs and head- or helmet-mounted display (HMDs)] be? Unfortunately, there has not been agreement on what a PFR is, let alone what criteria apply.

Approach

We will develop the display definitions with similar concepts used in handling qualities' requirements: first, define the piloting task and then determining what aids are necessary to allow the pilot to accomplish this task. The use of nested control loops (as shown in Fig. 1) is an effective way to separate the piloting tasks of aircraft stabilization, navigation, mission tasks, and maintenance of situation awareness.

The task divisions are not always clear-cut. In particular, the awareness of threats and obstacles and the maneuvering required to avoid them implies an interaction between the inner stabilization loop and the outer situation awareness task. The same can be said for unusual attitude recognition and recovery.

Fig. 1 Pilot control tasks.

Aircraft Stabilization

This inner loop consists of controlling aircraft attitude and flight path in three dimensions. This loop is the domain of the PFR.

The general information required in PFRs has been based on the airspeed, attitude, altitude, and heading shown in the basic *T* (so called because of the physical arrangement of an attitude indicator with airspeed to the left, altitude to the right, and heading below). With the possible addition of rate-of-climb and sideslip, these data allow the pilot to control the aircraft during up-and-away flight.

It should be emphasized that the basic *T* was formalized during World War II when the attitude indicator was just becoming widespread. Using this data allowed the pilot to maintain an airspeed that (at a given weight and load factor) maintained an angle of attack α. Then if α is maintained (at constant thrust), a given pitch attitude will produce a specific flight-path angle γ.

The data to be shown in a PFD should not be stated in terms of matching the basic *T*, but rather in terms of what is needed for the task. The basic *T* is suitable for fixed-wing aircraft during up-and-away flight, but replacement of some data should be allowed, such as α replacing airspeed or flight-path angle replacing attitude.

Typical primary flight data requirements for fixed-wing aircraft are airspeed (or α), attitude (or γ), altitude, heading, and sideslip (for multiengine aircraft).

For rotary-wing aircraft, particularly during low-speed flight, the basic *T* may not be appropriate. Depending on the task, airspeed may or may not be appropriate. Aircraft attitude and altitude (particularly radar altitude) are important. Rotor torque is important. Perhaps the most important data are aircraft ground velocity, both longitudinal and lateral.

Typical primary flight data requirements for rotary-wing aircraft during hover/nap-of-the-Earth (NOE) tasks are attitude, ground speed (lateral and longitudinal), radar altitude, torque, and heading.

Navigation

Generally this middle loop concerns data relating to the present position and flight path relative to the desired flight plan. This loop is the domain of the navigation display.

During instrument approaches, time pressure may require incorporating some navigation information in the PFR.

Mission Requirements

Mission requirements include mission-related tasks, such as weapon aiming. From a pilotage point-of-view it also includes monitoring the flight plan and making changes to the flight plan.

Situation Awareness

Situation awareness (SA) includes overall awareness of obstructions and threats as well as aircraft status including unusual attitude prevention and recovery.

Some SA cues are necessary in a PFR. For example, the recognition of and recovery from an unusual attitude is an essential task for flight using a PFR in instrument meteorological conditions. As a result, any PFR should have at least gross aircraft attitude cues.

Definitions

Primary Flight Data

The information needed for the pilot to maneuver the aircraft about all three axes, control its flight path, and accomplish a mission segment, such as takeoff, instrument approach, or NOE flight. This information should be the minimum set sufficient to accomplish the task safety.

For most flight tasks this information does not include navigation, systems, or propulsion information. Traditionally, flight references have included the information shown in the basic *T*, i.e., airspeed, attitude, altitude, and heading. We have purposely not included a list of parameters as part of the definition to avoid restricting future systems to present capabilities.

PFD

PFD is the display or suite of displays on which primary flight-data information are made available to the pilot. By implication, the pilot is free to use the PFD as a source of data for flight-path control without referring to another display.

PFR

The source of primary flight data includes the various sensors, the transmission to the display, any computation required, and the display. Thus we can speak of a HUD, HMD, or another display as being suitable for use as part of an PFR, but they cannot, by themselves, serve as a PFR.

Supplemental Flight Reference

A supplemental flight reference provides information used by the pilot to control the aircraft, but does not qualify as a PFR. A supplemental flight reference cannot be used independently of the PFR for flight information. An example would be angle-of-attack displays that are used in conjunction with the airspeed information in the PFR.

Secondary Flight Data

Secondary flight data is the information required by the pilot for flight that is not needed for immediate control of the aircraft flight path, i.e., not required in the PFD. Secondary flight data can be shown on a navigation display, on a dedicated display or elsewhere. It need not be displayed on the PFD. Examples of secondary flight data include the altimeter setting, selected course, or time-of-day information.

Data-Integrity Requirements

What level of reliability must the data displayed on a PFR have? There are two issues: integrity and availability.

Data Integrity

Data integrity can be thought of as the likelihood of not displaying incorrect data without clear and effective annunciation of the fact.

In the civil electronic display's advisory circular,[1] the probability of displaying hazardously misleading critical data is addressed. All data required to be displayed in the PFR (the minimum data set) are, of course, critical data. The display of invalid data on a pilot's PFD should be improbable. More stringent requirements apply to a total loss of primary flight data.

Improbable is defined according the appropriate military or civil guidelines. In the civil transport airplane community it customarily means one failure per one-hundred-thousand hours.[8] It is not clear what the rates should be for other types of operation, such as military fighters or light airplanes.

Data Availability

Data availability can be thought of as the likelihood of displaying correct data.

In the civil electronic display's advisory circular[1] the probability of not displaying critical data is discussed. The loss of primary flight data should be improbable. The loss without a backup display (and a means to alert the pilot to switch to the backup display) should be extremely improbable.

Extremely improbable should be defined according to the appropriate military or civil guidelines. In the civil transport airplane community, it customarily means one failure per billion hours. It is not clear what the rates should be for other types of operation.

Requirements for Non-PFDs

Some HUDs have been certified without regard to data integrity on the belief that the pilot will act as the instrument comparator between the HUD and the head-down panel. In our opinion, this is a mistake. Any flight critical data shown to the pilot should meet the same integrity requirements. No relaxation of the integrity requirements should be allowed merely because the display is not a PFD.

On the other hand, a supplemental display need not have the same requirements for data availability. In other words, it is not necessary to display the data, but if you do, it must be correct.

Use of HUD/HMD as a PFD

The fundamental question is can a see-through display serve as the PFD? Concerns have been expressed about the suitability of HUDs as PFDs. This issue is equivalent to saying does there need to be a head-down PFD in addition to the HUD/HMD?

With few exceptions, HUD-equipped airplanes have also had a full-time head-down PFD always in view. Recently, aircraft have been proposed (C-130J, RAH-66) that do not provide a head-down flight reference during normal operations. Thus, a formerly theoretical issue has become timely.

Arguments in favor of HUD being used as a PFD have been proposed by Haworth and Newman.[9] These arguments, which also apply to HMDs, include the following:

1) Reduced pilot workload: Pilot workload is reduced when the overall piloting tasks require head-up, outside-the-cockpit flight references.

2) Increased flight precision: The expanded scale of the HUD data and their overlay on the external visual scene allows the pilot to fly more precisely.

3) Direct visualization of flight path: A conformal display allows the pilot to directly assess the aircraft performance relative to the ground or obstacles.

4) Increased flight safety: Essential flight information presented on the HUD reduces eyes-in-the-cockpit during critical flight maneuvers.

Arguments opposed to the use of HUDs as PFDs have included the following:

1) Decreased situation awareness: Geographic situation awareness may be less with head-up displays than with conventional head-down displays.

2) Difficult to cross check: It is difficult for a pilot to check the data displayed on other displays.

3) Unusual attitudes: It is more difficult to detect unusual attitudes while flying with reference to the HUD. Recoveries are more difficult using the HUD.

4) More difficult to use: The absence of color and often confusing background makes the use of see-through displays more difficult than with conventional panel-mounted displays.

5) Clutter: Because of the need to see through the displays, the amount of symbology that can be shown is limited. This makes the display of needed information more difficult.

6) Cognitive switching issues: Pilots have difficulty detecting outside cues when viewing through the HUD. Simulator results indicate they are less likely to detect runway incursions.

7) Increased training requirements: The HUD may add to pilot training requirements because the control techniques are different.

It is interesting to note that many of the arguments, for and against the use of HUDs as PFDs, arrive at opposite conclusions from the same premise.

There is no question that see-through displays can bring an increased sense of flight-path awareness to pilots, nor is there any argument that they allow much more precise control of an aircraft's flight path. The issue is can they serve as the only flight reference? These issues have been more fully discussed in other sources.[4,9–14]

Newman[10] recommended having a full-time head-down PFD always in view, unless mission requirements dictated otherwise. If it is not feasible to have a full-time head-down PFD, the head-down display should be recalled by a single button push (without the need for the pilot to remove his hands from the controls). This approach has also been adopted by the military fixed-wing community.[7]

A HUD may not be suitable as a PFD in all flight conditions because the background may be too bright or distracting. Therefore it is felt that there needs to be a PFD available to the pilot. The issue is does it need to be up full time? This issue remains to be resolved.

Most existing civil HUDs do not replace the head-down PFD. The exception is the C-130J that was designed to allow the HUD to serve as the only visible PFD. The C-130J uses a yoke-mounted button for head-down PFD recall. The head-down PFD is also recalled automatically under certain circumstances.[15]

Application to Low-Level Operations with an HMD

In the case of NOE flight or transition to visual flight, the pilot may not have the time available to look inside, particularly during night or adverse weather operations. Of particular importance in the low-level environment is the assessment of the aircraft trajectory relative to obstructions. In this instance the HMD would be the de facto PFD. Clearly, it would be the only flight display being used.

As stated earlier, HUD studies recommended full-time display of the head-down PFD at all times.[10] This is an excessive requirement for HMDs because the purpose of the HMD is too allow the pilot to look off-axis and, as a result, he would probably not be able to see the head-down PFD.

However, it is our opinion that similar arrangements should apply to the use of an HMD, i.e., there should always be a head-down PFD available that is not necessarily displayed at all times.

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Modeling Turbulence in the Presence of Adverse Pressure Gradients

M. S. Rao* and H. A. Hassan†
North Carolina State University,
Raleigh, North Carolina 27695-7910

Introduction

In an attempt to model a recent set of experiments by Skare and Krogstad,[1,2] dealing with equilibrium boundary layers near separation, it became clear that the traditional k-ω model was unable to reproduce the data. Careful investigation of the data suggested that the diffusion term in the k equation behaves differently in the presence and absence of unfavorable pressure gradients. This led to the conclusion that an important diffusion mechanism was missing from the k equation, and so a new diffusion model is proposed.

The only term that requires modeling in the k equation is the diffusion term.[3] Traditionally, it is modeled as

$$\frac{1}{2}\,\rho\overline{u_i' u_i' u_j'} + \overline{p' u_j'} = -\mu_t \sigma^* \frac{\partial k}{\partial x_j} \tag{1}$$

where ρ is the density, k is the turbulent kinetic energy, μ_t is the turbulent viscosity, u_i' is the velocity fluctuation, p' is the pressure fluctuation, and σ^* is a model constant.

The applicability of this model near separation is evaluated for an incompressible flow. In the near-wall region, the Wilcox k-ω model reduces to

$$0 = -\frac{\partial P}{\partial x} + \frac{\partial \tau}{\partial y} \tag{2}$$

$$0 = \frac{\partial}{\partial y}\left[\sigma^* \nu_t \frac{\partial k}{\partial y}\right] + \nu_t \left(\frac{\partial U}{\partial y}\right)^2 - \beta^* \omega k \tag{3}$$

$$0 = \frac{\partial}{\partial y}\left[\sigma_t \frac{\partial \omega}{\partial y}\right] + \alpha \left(\frac{\partial U}{\partial y}\right)^2 - \beta \omega^2 \tag{4}$$

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*Research Assistant, Mechanical and Aerospace Engineering. Student Member AIAA.

†Professor, Mechanical and Aerospace Engineering. Associate Fellow AIAA.