1. INTRODUCTION

Pilot in-the-loop oscillation (PIO) or aircraft-pilot coupling (APC) is an interaction between a pilot and aircraft that causes sustained aircraft oscillations to occur over a range of amplitudes and frequencies. These events occur through a variety of flight conditions and result from the efforts of the pilot to simply maintain control of the aircraft. Obviously, since these oscillations are unexpected by the pilot, this phenomenon can be very detrimental to the handling qualities of the aircraft. Unfortunately, it is not always obvious what will cause a PIO and what measures can be taken to prevent it from happening.

1.1 Objective

This report describes a method to analyze pilot-in-the-loop oscillation. The analysis is conducted through the use of limit cycle predictions in multiple order systems with multiple nonlinearities. In particular, the affect of asymmetric limiting on control stick and elevator deflection is studied as well as the affect of elevator rate limiting. These nonlinearities are analyzed for independent as well as simultaneous activity.

The pilot-aircraft system is arranged such that the linear and nonlinear portions are modeled separately. Nonlinearities are modeled through the use of multiple dual input describing functions (DIDF). The resulting model is represented in block diagram and state space form. The method presented reveals the tendency of a piloted aircraft to oscillate and examines the nature of any oscillation found. Included in the results are the predicted frequency, amplitude and mean point of oscillation. This method is meant to be employed in the design stage of aircraft development in order to prevent the production of an aircraft that is prone to PIO.

2. BACKGROUND

Recently, there has been an increase in research with regard to the causes and remedies for PIO. However, the PIO phenomenon is not a new event. The recent PIO incidents such as the USAF YF-22 and the Swedish Saab Gripen have been well publicized, but PIO events have occurred throughout the history of flight.[1] The Second World War was followed by a time of rapid advances in aviation, and it was at this time that the amount of PIO incidence increased dramatically. Subsequently, large amounts of research in this area began in an effort to overcome these difficulties. This research brought about the development of criteria and requirements to aid the designer in the development of an aircraft that would be free from PIO tendencies. [2]

2.1 Aircraft / Control System Design

Digital electronic flight control systems have allowed designers to implement sophisticated control systems not previously possible with other control system mechanizations[3]. A modern aircraft can have a number of digital flight control systems (modes) corresponding to different flight conditions. The complexity of these systems makes it difficult to predict possible aircraft flying quality problems.

Design of an aircraft's flying qualities is governed, nominally, by the standards of MIL-STD-1797A. The use of active control systems makes it possible for an otherwise poor handling aircraft to meet these regulations and be considered a "good" aircraft for operational use. Unfortunately, PIO's are essentially unforeseen events with regard to handling quality specifications. MIL-STD-1797A does recognize a PIO as "sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft" and states that aircraft will not have PIO tendencies.[4] Current military standards assume that PIO is a result of deficient handling qualities. Therefore an aircraft that meets level 1 requirements (Flying qualities clearly adequate for the mission Flight Phase) is assumed to have low PIO tendencies, whereas a level 3 aircraft (Flying qualities such that the airplane can be controlled safely, but pilot work load is excessive) may be highly susceptible to PIO.[1] It is important to recognize that no specific criteria in the military standard identifies the existence or non-existence of PIO susceptibility.

The problem of PIO persists, even with the current design guidelines of MIL-STD-1797A. The result of a PIO occurrence can vary tremendously. Pilots may be merely annoyed at this behavior or, in a severe case, the PIO can be catastrophic. A PIO known as nose bobble is a high-frequency (10 rad/s), small amplitude pitch oscillation that occurs during precision tracking tasks. Pilots usually indicate that an aircraft that demonstrates this characteristic has potential for PIO, but the phenomenon is little more than a nuisance. A more dangerous PIO has lower frequency and large oscillation amplitude. These oscillations can create large changes in flight path angle that may lead to an accident.[1]

2.2 Recent PIO Events

An instance of catastrophic PIO is the flight of a Navy pilot in a F-4H twin engine fighter aircraft on May 18, 1961. In this case, the pilot was attempting to break a speed record at low altitude near Albuquerque, New Mexico. The aircraft had reached a speed of approximately Mach 1.1 at a height of 200 ft above ground level. It was at this time that a severe PIO developed and within two seconds the aircraft reached -4 to +14 g in just three oscillations. This behavior resulted in a structural break up and the unfortunate death of the pilot. The accident was investigated thoroughly, however, no specific reason was ever found to explain the PIO. Possible reasons were thought to be a loss of pitch damper or a failure of the Mach trim system.[5]

The Space Shuttle Orbiter is a delta wing configuration that requires very high pilot attention during landing due to its low Lift/Drag ratio and lack of engine power. The use of elevons creates a relationship between pitching moment and lift that make it difficult for the pilot to control flight path angle directly. The center of rotation is ahead of the cockpit and therefore the pilot can not perceive any change in flight path angle for a full second after a control input. Furthermore, the pilot can not see the nose of the aircraft and therefore has no reliable reference point.

The first four orbiter landings were made without incident but during the fifth landing a PIO resulted. The landing was made on the Edwards Air Force Base 15,000 ft concrete runway, and the pilot's touchdown point was 5,000 ft beyond the threshold where most newspeople and spectators had gathered. The pilot realized that he would overshoot his touchdown point significantly, and was concerned about the opinions of the onlookers as well as being concerned that he would run out of runway. He decided to force the orbiter on, and a PIO ensued. This command sequence caused the orbiter to bounce up from the runway a number of times before finally touching down. Rate limiting of the elevon was present throughout the PIO that began seven seconds before first touchdown.[5]

The JAS 39 Gripen is a small, lightweight, tactical fighter with a canard and delta wing configuration. The aircraft has a fly-by-wire digital flight control system, and the small control stick used in the aircraft was a new design. The first flight of the test aircraft was in December 1988, and the aircraft had experienced four more successful flights throughout flight testing.

The sixth flight of the aircraft was performed in relatively heavy turbulence by a pilot who had no previous experience with the new aircraft. During final approach of this flight, the pilot was attempting to control flight path angle and met with insufficient control power. In response, he cycled the control stick very quickly which, subsequently, induced rate limiting on the hydraulic control surface actuators. A large amplitude PIO resulted as the aircraft was nearing the ground. The oscillation resulted in the crash and destruction of the test aircraft. The official cause of the accident was that the control system could be driven into nonlinear rate limiting modes at high command inputs.[5]

2.3 Possible Causes of PIO

The variations in modern configurations and control systems of aircraft seem to present an additional element of difficulty for the pilot. This difficulty appears to be, in part, pilot dependent. Each of the above aircraft had flown a number of times with a variety of different pilots before encountering a PIO. However, the pilots that encountered the PIO were no less capable than the pilots that did not encounter this event. This fact suggests that other conditions must be present for an aircraft to exhibit the PIO characteristic, although a PIO will not necessarily occur even in flight conditions in which a PIO has occurred previously. Hence, one might conclude that the occurrence of PIO appears to depend on a number of factors acting simultaneously.

The general cause of a PIO is commonly accepted to be a "trigger" event. This event causes the pilot to quickly alter his/her control strategy and can occur in a number of different situations. Causes can include changes in flight control gains with changing flight conditions, sudden gusts, wind shear, or the demands of precision tracking tasks in general.[1] Trigger events may lead to PIO, but not all trigger events necessarily will. The trigger event has its effect on the pilot, but the aircraft must respond to the pilots input in a manner that propagates a PIO. Aircraft characteristics that are known to facilitate this behavior include sluggish response modes, lightly damped modes, excessive phase lag or time delay, sensitive stick gradient, unusual coupling responses, and unstable modes.[6]

2.4 Combating PIO

Current specifications for the design of aircraft with regard to PIO susceptibility consider the above factors, but assume that each factor acts individually. This fact alone may explain the continued appearance of PIO events in recently developed aircraft. Unfortunately, the complexity of the pilot-aircraft system makes a PIO very difficult to predict. These nonlinear events depend largely on the reaction of the human pilot. This is not to say that PIO occurs through the fault of the pilot, but rather it is the interaction of the pilot-aircraft system that creates this phenomenon. Since the human pilot is trained to react in a particular way to the aircraft's behavior, methods of eliminating PIO lie within the design of the aircraft and flight control system. Therefore, methods of studying susceptibility to PIO are key to designing successful aircraft and flight control systems.

There have been a number of recent efforts to develop PIO specific criteria in the form of flying quality type specifications. These criteria use a variety of methods to predict aircraft susceptibility to PIO. The methods are based on pilot models and aircraft models. There are several of these techniques that have been developed and continue to be developed that show promise in the prediction of aircraft PIO tendencies.

Hoh's bandwidth criteria [7] attempts to predict longitudinal PIO through the use of frequency-domain information of the aircraft open-loop response. The underlying assumption with this technique is that the pilot may adapt to the response of the aircraft. Therefore, it is necessary for the closed-loop pilot-aircraft system to demonstrate responses that are adequately large in magnitude and occur at frequencies within the disturbance input range. The open-loop system must demonstrate frequency response behavior that allows the pilot to control the aircraft (close the loop) through a variety of pilot gains. The closed loop characteristics are defined by the Bandwidth Frequency, ω_{BW}, and the open loop characteristics are defined by the Phase Delay, τ_p. The Phase Delay is a measure of how rapidly the phase curve rolls off above the magnitude crossover frequency.[7]

Dropback is also used by Hoh as an auxiliary criterion within the bandwidth criteria. Dropback information is obtained through the use of a time history of aircraft pitch rate (q) and pitch attitude (θ) response to a boxcar stick input (step input of long enough duration to obtain q_{ss} followed by zero input). This information is used to ensure pitch rate overshoot and pitch attitude dropback are not excessive. It should be noted that dropback as defined by Hoh is not the same as that defined by Gibson [8]. In this case dropback refers to a criteria based on a boundary plot of q_{peak}/q_{ss} vs. $\Delta\theta_{peak}/q_{ss}$.[7]

The Smith-Geddes longitudinal PIO prediction technique [9] uses the frequency response of the aircraft to stick force input. This technique is a modification to the original Ralph Smith criteria in that the original required a simple pilot model.[10] The generation of such a pilot model is highly subjective since the individual designer must create a pilot model that is believed to be appropriate for the PIO examination. Therefore, this technique is not easily adaptable to military specifications.

The application of the Smith-Geddes criteria is broken into three separate types of PIO:

- Type I: Occurs when pilot switches from attitude control to acceleration control at resonant frequency
- Type II: Possible when any open-loop mode has a damping ratio less than 0.2
- Type III: Initiated by piloted control of attitude, regardless of acceleration dynamics

The criteria uses pitch attitude to stick force and normal acceleration to stick force frequency and time history information to predict susceptibility to PIO. Also, the criteria predicts an expected frequency of oscillation if a PIO is predicted.[7]

An evaluation of the techniques described above were made in 1986 by the USAF and are reported in [11]. The evaluation was performed by testing 18 different configurations of the USAF/Calspan variable stability NT-33A. PIO tendencies were predicted using both the Smith criteria [10], and Hoh technique [7]. The results of these predictions were compared to the pilot PIO ratings for each configuration flown.[11]

The study found that both methods were able to predict PIO susceptibility as well as predicting the probable severity of the PIO encountered. Smith's method was able to predict the frequency of oscillation as well, but this method required the development of an accurate pilot model which was felt to be a major drawback. Finally, the report recommended that more research was required and that the fundamental reason for PIO was still undetermined.[11]

2.5 PIO Research

An investigation into the causes of PIO is needed to determine a method of predicting PIO susceptibility of an aircraft. This investigation requires an accurate model of both the aircraft and pilot; however, it is unrealistic to model every facet of both pilot and aircraft. Therefore, it is necessary to assume that certain characteristics are large contributors to PIO and model these characteristics only. As mentioned previously, certain nonlinearities in the pilot-aircraft system are believed to facilitate the onset of PIO and it is logical to consider these chiefly in the examination of PIO. Ultimately, a straightforward method to determine aircraft PIO susceptibility is sought. This method should also give information as to the severity and nature of any expected PIO.

The recent work of Anderson and Page [12] considered closed-loop pilot-aircraft dynamics to examine PIO behavior. This work consists of an examination of complex pilot models as well as nonlinear aircraft dynamics. The following simultaneously acting nonlinearities have been considered:[12]

1. Aileron Rate Limit
2. Rudder Rate Limit
3. Roll Stability Augmentation System Gain
4. Yaw Stability Augmentation System Gain
5. Pilot Gain

Single input, symmetric describing functions were used to represent each nonlinearity in the system and a homotopy method was used to determine limit cycle existence in the closed-loop pilot-aircraft system. The existence of such a limit cycle indicates the tendency to PIO. Amplitude and frequency of the limit cycle correspond to the predicted amplitude and frequency of the PIO.[12]

Smith [13] has also implemented a closed loop method to examine PIO behavior. This closed loop system is quite simple and consists of only a nonlinear pilot model and linear aircraft dynamics. This method uses pitch rate feedback, but it is assumed that PIO could exist with pitch attitude or normal acceleration feedback as well. PIO characteristics are based on numerical simulation of the pilot-aircraft system. Once again, PIO tendency corresponds to limit cycle existence.[13]

The work documented in this paper is an extension of the analysis methods of [12]. PIO is analyzed through the use of limit cycle calculations. However, asymmetric saturation elements are incorporated into the longitudinal dynamics of the aircraft in an effort to examine the effects of asymmetric nonlinearities on longitudinal PIO. This analysis is motivated by the fact that aircraft typically contain longitudinally asymmetric nonlinearities. The introduction of these asymmetries leads to the use of dual input describing functions, and therefore, a method of solution that incorporates these dual input describing functions is presented. The nonlinearities considered in this paper include asymmetric stick limits, asymmetric elevator deflection limits, and elevator rate limits.