5. DISCUSSION OF RESULTS AND CONCLUSIONS

The DIDF prediction method uses limit cycle calculations to analyze PIO susceptibility in pilot-aircraft systems. This method shows promise in its ability to analyze limit cycle oscillations in an effort to gain insight into the causes and cures of PIO. Since limits are modeled individually with DIDF's, it is possible to predict the amount of individual saturation in each nonlinear element. This feature gives a good means in which to analyze simultaneously acting nonlinearities while still being able to identify their individual effect. Additionally, the use of DIDF's makes it possible to model asymmetric limits which allows the prediction of not only frequency and amplitude of oscillation but mean point of oscillation as well. Both the individual and the overall effect of asymmetric limiting can be identified through the use of the DIDF prediction method.

5.1 Conclusions about the PIO Analysis of the NT-33A Model

The NT-33A PIO analysis results showed that elevator rate limiting played a major role in defining the characteristics of limit cycle oscillations. In particular, the introduction of elevator rate limiting along with elevator deflection and stick position limiting created limit cycle behavior in an otherwise stable pilot-aircraft system. This limit cycle occurred at a pilot gain of about 7 lb/deg while limit cycles without the inclusion of rate limiting occurred at about 9 lb/deg. This result is very significant since low pilot gain limit cycle oscillations are the most dangerous oscillation tendencies since they appear in stable pilot-aircraft systems. Additionally, this behavior can not be identified by a simple linear analysis of the pilot-aircraft system. The identification of an unstable pilot-aircraft limit cycle oscillation could possibly be made through the use of a linear analysis, which would reveal that the pilot-aircraft system was unstable. The only way to predict the stable pilot-aircraft limit cycle oscillation would be to simulate or predict its occurrence with the DIDF prediction method. Fortunately, under these conditions, the DIDF prediction method retains the most accuracy with respect to simulated solutions, since the amount of saturation in the nonlinear elements is still rather small. During low saturation limit cycle oscillations, the behavior of the pilot-aircraft system is still fairly linear and the linear behavior can be predicted accurately with the DIDF method.

5.1 Recommendations for Continuing Work

There are a number of avenues that can be pursued in the investigation of PIO using DIDF's and limit cycle analyses. A piloted simulation could offer a means of validating the prediction method by creating an actual limit cycle that could be recorded and compared to predicted results. It is in this manner that PIO characteristics could be closely examined with the use of an actual pilot.

The end result of PIO investigation is the development of a method of elimination of this phenomenon. A set of PIO resistant design criteria could be established for use in the design stage of an aircraft and flight control system. Guidelines for modeling of the pilot should be established. These mathematical pilot models should include a specification on maximum reasonable pilot gain, which, from this preliminary study, suggests a pilot gain of about 7-9 lb/deg. Guidelines for the modeling of nonlinearities should also be established. This study shows that stick limiting, elevator limiting, and elevator rate limiting can all contribute to PIO behavior.

A longitudinal PIO limit cycle analysis could be defined as the representation of stick dynamics, actuator dynamics, short period aircraft dynamics, and a synchronous pilot model. Nonlinearities in this system could be defined as stick position, elevator deflection, and elevator rate limits. Accordingly, a design specification with regard to PIO might read as, "No limit cycle oscillations shall occur in the pilot-aircraft system for pilot gains of 7 lb/deg or less." An aircraft meeting this requirement would be considered "PIO resistant." In the event of limit cycle existence, the elements of N_A would give information as to the degree of aircraft PIO susceptibility. In other words, elements of $N_A > 0.7$ could show that the aircraft was "mildly susceptible to PIO", and elements of N_A in the range of $(0,0.7]$ might indicate that the aircraft was "highly susceptible to PIO."

A US Air Force PIO investigation performed with the NT-33A in 1997, [28], gives a good place to begin a more thorough investigation of the prediction method. These flight tests were performed with varied elevator rate limiting, and pilot PIO ratings were recorded. Therefore, a good database has been established with which to compare and validate PIO prediction techniques. By this comparison it should be possible to gain further insight into the characteristics and causes of PIO and establish some design specifications regarding PIO.

Refinements in the DIDF prediction method could be applied in an effort to increase accuracy and gain a further understanding of PIO. An extension of the describing function method could be made by use of multiple input describing functions to represent higher harmonics in limit cycle analyses. This technique should improve prediction accuracy and give insight into the accuracy of single harmonic solutions.