RECENT EXPERIENCE IN FLIGHT TESTING FOR PILOT INDUCED OSCILLATIONS (PIO) ON TRANSPORT AIRCRAFT

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Abstract

Though the subject of Pilot Induced Oscillations (PIO) is not new, it has garnered significant attention in the past several years. Since the mid 1990's, Boeing Commercial Airplanes has been conducting specific flight tests of its products in order to evaluate PIO tendencies. Beginning with the 777-200, a generic suite of test maneuvers has been used to evaluate PIO tendencies on each product. The testing has been conducted on a "window of opportunity" basis with the intent to gather data and evaluate each model. To date, specific evaluations have been carried out on six different airplane models spanning a wide range of airplane sizes, inertial characteristics, and control system implementations. Each maneuver in the generic suite is discussed in detail. In addition, along the way, a large number of other maneuvers have been used at various times to evaluate PIO tendencies. These are briefly described. No single test maneuver or technique has been identified which provides effective discrimination of PIO tendencies. Finally, the subject of the pilot in the loop is discussed with regard to achieving consistency in conducting PIO evaluations.

1 Introduction

Though certainly not new, the phenomenon of Pilot Induced Oscillations (PIO) has garnered vigorous attention since the publication of the U. S. National Research Council's report on the subject[1]. Research in government venues, academia, and rather more quietly within industry has produced a significant volume of literature ranging from required modeling to prediction and prevention methods to suppression techniques[2]. Moreover, the subject has gotten the attention of the world's regulatory authorities, and although it is currently the subject of international harmonization, specific testing to demonstrate freedom from PIO tendencies has been included in the Flight Test Guide for certification to Part 25 of the US Federal Aviation Regulations[3].

Boeing Commercial Airplanes has had ongoing for some time rather comprehensive evaluations of its products with regard to PIO. These evaluations, spanning hundreds of flight hours, have provided an understanding of the phenomenon, a detailed understanding of the characteristics of each product with regard to the phenomenon, and an in-depth understanding of the test techniques and subtle issues involved in conducting such investigations.

This paper will present a snapshot look at Boeing's flight test experience with investigating the PIO phenomenon. The information contained herein is presented in the hope that in sharing technical information, safety can be enhanced through cooperative focus of research, and reduced duplication of effort.

A large number of evaluation maneuvers have been examined in the course of flying a number of airplane models. This paper will detail the scope and depth of the flight test evaluations, including a review of the specific maneuvers flown and kinds of data collected.

2 Scope of Flight Test Evaluations

In order to examine the pilot-in-the-loop characteristics in detail, Boeing has chosen to conduct evaluations in flight. This has put the evaluation in context operationally and has eliminated questions about analytical assumptions, simulation fidelity and the like.

2.1 Breadth of Evaluations

Since 1995, specific, deliberate PIO evaluations have been carried out on 6 different models of Boeing transport airplanes:

777-200	777-300
737-700	737-800
757-200	757-300

In addition, each of these have been flown by several pilots to further increase the scope of the evaluation.

Fully instrumented test airplanes have not always been readily available, and for that reason, the evaluations have been conducted when a test article is at hand. This sample has so far provided a broad scope of airplane size and inertia characteristics, several body lengths, and several control system implementations. The database collected to date has provided significant insight into the phenomenon and the interactions of pilots with airplanes. Finally, there is a plan in place to include other airplane models as opportunities present themselves to provide an even broader base of data.

2.2 Depth of Evaluations

Actually trying to induce a PIO in flight has proven to be quite difficult. In general, those PIO's which have been encountered in development testing have tended to be "special case" events, each displaying different characteristics, and requiring application of unique analysis and flight testing techniques to understand. Even though they have not occurred in particularly obscure parts of the flight envelope or in extreme atmospheric conditions, each has been found to be related to details of the particular model and its control system implementation. A single maneuver or technique which will reliably expose PIO tendencies for PIO-prone configurations and at the same time identify PIO-free configurations has proven elusive.

For these reasons, and to satisfy internal requirements, a generic testing program has been conceived with the intent to conduct thorough and specific evaluations on each available model as opportunities presented themselves. The purpose of these evaluations has been to gather four types of data. These include

- end-to-end open loop dynamic response data
- control system response data
- qualitative evaluation during high gain piloting tasks
- quantitative evaluation during high gain piloting tasks

In addition to simply collecting data, the results have been both analyzed and digested with lessons learned documented in the form of design requirements for future products.

3 Evaluation Maneuvers

The four types of data referred to above have been grouped into open loop tasks and closed loop piloting tasks. Specific maneuvers in each group have been developed to insure consistent data collection as outlined below.

3.1 Open Loop Tasks

The open loop maneuvers, which provide analysis data for both airplane dynamic response characteristics and control system response include:

- log frequency sweeps
- control doublets
- control releases

These typically have been flown manually, and at flight conditions including high and low altitude cruise, approach, and landing flight conditions.

The results of these maneuvers have provided a broad database for analysis of both airplane and control system dynamics and the calibration of analytical methods. The value of this data cannot be understated. It represents the airplane's dynamic characteristics measured from the pilot's finger tips to airplane response. It characterizes what the airplane, including all of its systems, is and it accounts for all of its orders of complexity and relys on no assumptions of analysis. As noted in the discussion of the breadth of these evaluations, having data of this nature across a wide range of airplane sizes, weights, inertial characteristics, and flight conditions has produced a rich basis for future analytical work.

Of course, normal precautions regarding fidelity of the instrumentation and flight conditions need to be applied in order not to be misled by conclusions from these results. A general discussion of techniques for measuring airplane dynamic responses has been provided by Maine and Iliff[4].

3.2 Closed Loop Tasks

As important as it is to understand the details of the airplane's dynamic response characteristics, the pilot is also a critical element in PIO. In order to investigate an airplane's PIO tendencies, it is necessary to exercise the airplane+pilot combination. Popular guidance (e.g. [1]) suggested that any such evaluation should include tasks which

- Require high pilot gain
- Exhibit high urgency
- Require precise maneuvering

Preliminary discussions regarding tasks which produced these characteristics have identified close formation flying and precise ground reference maneuvering as candidates. Both have been used conduct PIO evaluations as discussed below.

3.2.1 Qualitative Pilot-in-the-Loop Tasks

Qualitative evaluations have been carried out during close formation tracking tasks. These represented the highest gain piloting tasks available.

Rather than instructing the pilot to simply fly in formation with a lead aircraft, however, specific maneuvers have been devised. These included aggressively acquiring new positions relative to the lead and holding in those positions before aggressively acquiring another position. Even when flown in relatively calm conditions, the non-linear flow field from the lead airplane generates enough airplane movement to make the maneuvering taxing for the pilot. For example, in order to fly in an in-trail position which is offset laterally typically requires cross-controlling the trail airplane.

An example of one of these maneuvers, the cross maneuver is shown in Figure 1. This maneuver is begun in a refueling position behind the lead aircraft. Each new position is acquired and held before moving to the next position. In the photo, a 777-200 is being flown against a 747-400 lead aircraft.

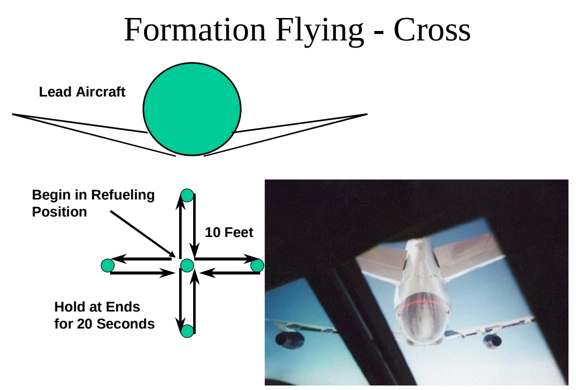

Figure 1

In the flaps-down conditions, the wake of the lead airplane becomes larger and the buffeting condition on the trail aircraft becomes more intense. With the lighter 737 aircraft, it was not possible to stay in a tight formation position in this condition. As a result, the maneuvers were moved to the wing tip. Instead of forming on the refueling position, the pilot was asked to use a position relative to the lead's wing tip as a reference for the maneuvers. Figure 2 depicts the wingtip maneuvers. In the photo, a 777-200 is forming on a 747-400. Figure 3 shows the very close formation position used by the pilot of the 737-700. This required very high pilot gains, particularly when the lead aircraft initiated even mild maneuvering.

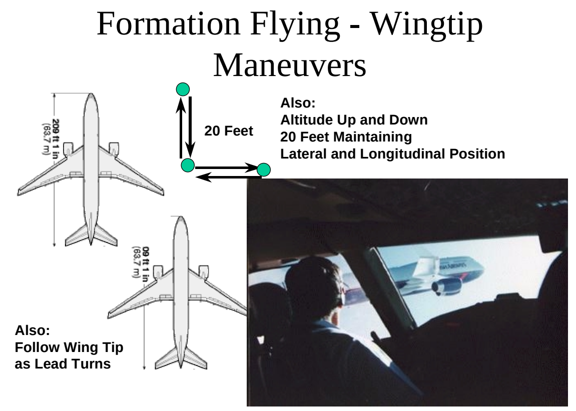

Figure 2

The close formation flying tasks have indeed provided a very high gain piloting task. In addition, maneuvers have been designed in which gross acquisition was combined with close tracking tasks. It has been found difficult, however, to conveniently measure pilot performance during the maneuver and provide feedback of performance. It has also proven difficult to enforce a consistent level of aggressiveness between pilots and across airplane models. For these reasons, the formation flying task evaluations have been limited to qualitative evaluations only. Nevertheless, the formation tasks have still been considered valuable in the context of the entire evaluation.

3.2.3 Quantitative Pilot-in-the-Loop Tasks

In order to achieve tight acquisition and tracking tasks in which the maneuver performance could be accurately measured (and thus consistently

Figure 3

enforced), additional tasks have been developed which involved flying close to a runway. These tasks were flown in the landing configuration only.

The first of these involved a constant-altitude fly-by. The pilot has been asked to fly the ILS to an altitude of 50 feet, then flare and maintain 50 feet ± 10 feet for the length of the runway, while maintaining the centerline and airspeed. Essentially closing a loop around radar altitude, the pilot flying has usually benefited from the pilot not flying continuously calling radar altitude values. This task is illustrated in Figure 4.

This maneuver was originally conceived as a way to evaluate characteristics in the landing

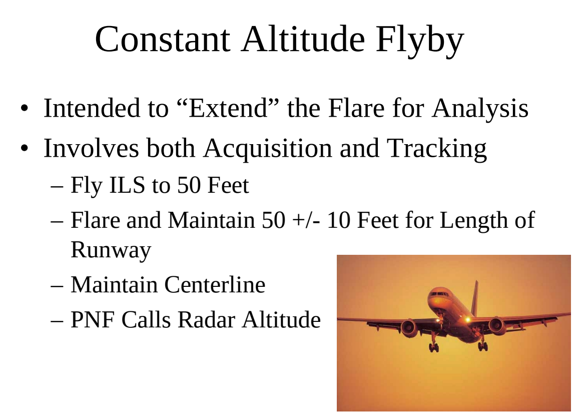

Figure 4

flare. Results have allowed the analysis of pilot-in-the-loop behavior as the pilot continuously attempted to achieve tight flight path control. Besides the PNF calling altitudes, the use of a portable differential global positioning system (DGPS) has allowed immediate feedback of the pilot's performance during a particular evaluation. Pilots have described the task as demanding but not particularly difficult to fly. This is a routine maneuver used for collecting simulation validation data in ground effect. The single most complicating factor has been reported to be the power change in the initial flare.

The fly-by task was then complicated further by the addition of a lateral axis task element. This is illustrated in Figure 5. In the Lateral S-turn, the pilot has again been asked to fly the ILS to 50 feet, flare, and maintain that height, but this time, instead of maintaining the runway centerline, the pilot has been asked to alternately acquire and track the runway edge lines for the length of the runway.

Lateral S-Turns

- Intended to Increase Workload by Adding Axis
  - Fly ILS to 50 Feet
  - Acquire as Rapidly as Possible one Runway Edge Line
  - Acquire as Rapidly as Possible the Opposite Edge Line
  - Repeat for Length of Runway
  - Maintain 50 +/- 10 Feet
  - PNF Calls Radar Altitude

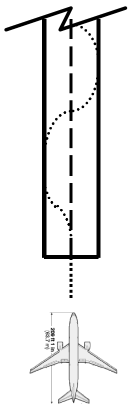

Figure 5

Vertical S-Maneuvers

- Further Increases Urgency
  - Fly ILS to 50 Feet and Capture 50 +/- 10 Feet
  - Acquire as Rapidly as Possible 30 +/- 10 Feet
  - Acquire as Rapidly as Possible 70 +/- 10 Feet
  - Repeat for Length of Runway
  - Maintain Centerline
  - PNF Calls Radar Altitude

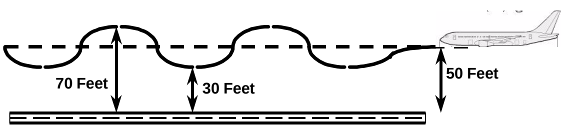

Figure 6

In an attempt to further increase the urgency, the pilot was then given the Vertical S-maneuver illustrated in Figure 6. Approaching as for the other runway tasks, after acquiring 50 feet, the pilot has been asked to aggressively acquire and track a radar altitude of 30 feet, followed by 70 feet, then back to 30 feet, and so on for the length of the runway. This has been done with fixed throttles once the initial power change at 50 feet has been made.

The last maneuver in the generic evaluation set has been the precision offset landing used by most organizations to investigate PIO tendencies. The maneuver used at Boeing has differed from that used by Calspan/Veridian. Whereas Calspan typically has asked the pilot to align initially with a drainage ditch conveniently offset from the runway centerline, the famous Niagra drainage ditch has been rarely available at airports in the US west. The solution has been to ask the pilot to fly the ILS intentionally two dots offset and two dots high, with the correction maneuver performed at 250 feet above ground level (AGL). The pilot has been asked to touch down in the specified touchdown box at the specified sink rate. The two dot – two dot specification results in a maneuver which is more aggressive than the Calspan maneuver as well. The maneuver is illustrated in Figure 7 This has proven to be very challenging for large transport aircraft.

In each of these quantitative tasks, gross acquisition of either pitch (flight path) or bank (lateral path) has been combined with tight tracking to produce a very demanding piloting task in a large airplane. This has been shown to produce very high urgency when performed close to the ground. In addition, with differential GPS available, the maneuver performance has been easily measurable and the pilots could be held to consistent performance levels. While these maneuvers conducted close

Offset Precision Landing

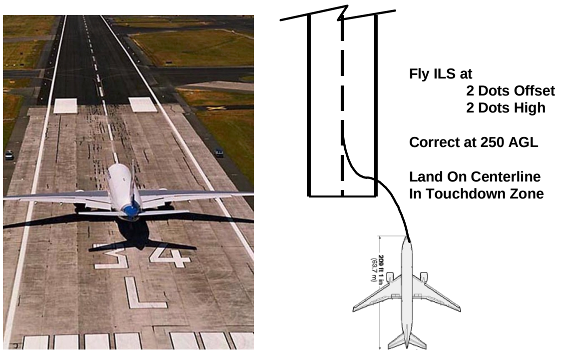

Figure 7

to the ground have represented significant risk, they have also provided deep insight into the pilot/vehicle interactions during high gain tasks.

3.2.3 Other Maneuvers

In addition to the generic task set used for broad investigations, a large number of special maneuvers have been developed and used in flight testing at Boeing. These include:

- Flight director tracking
  - Sum-of-sines
  - Steps and ramps
  - Log frequency sweeps
  - Added discrete disturbances
- Pitch attitude tracking
  - On ground
  - In flight
- Bank angle captures
- Heading Angle Captures
- Lateral Pilot Hand-off maneuvers
- Full rudder sideslips in ground effect
- Constant track rudder steps

In flight director tracking, whether the forcing function has been sum-of-sines, the Calspan steps-and-ramps, or log frequency sweeps, care has been taken to insure that the pilot remains in a compensatory mode. This has been done by subtracting the current airplane attitude from the target attitude in real time and displaying only the error on the Heads-Down-Display (usually the flight director on the Primary Flight Display (PFD)). The pilot has been asked to keep the error at zero.

In addition to the three programmed tracking tasks, the ability to insert a discrete (one cycle sine) disturbance into the target signal has been included. Insertion of the disturbance could be made at the discretion of the pilot not flying to insure that the pilot was not memorizing the task.

These tracking tasks when done at altitude have typically failed to produce adequate urgency. There was essentially no penalty for not meeting demanding performance standards, and some pilots approached the task more aggressively than others. In addition, post test analysis has proven less than conclusive. Measures such as time on target, number of overshoots, size of overshoots, etc. have failed to produce convincing correlations with regard to PIO tendencies.

Similarly, pitch attitude tracking, which has been implemented by having the pilot not flying call an attitude to track, suffered from lack of urgency in up-and-away flight. With the main gear on the ground, however, there was a much better correlation with PIO tendencies, as the risk of either a tailstrike or nosegear slap-down increased the pilot's gain. These results have been presented by Nelson and Landes[5].

Bank angle and heading angle captures have been conducted routinely, typically with capture angle precision, minimum time, and number of overshoots being parameters. At altitude these suffer from the same consistency in aggressiveness difficulties as the tracking tasks noted above for identifying PIO tendencies, although they have been used successfully to assess general handling in the presence of system changes.

Lateral Pilot Hand-off Maneuvers have been developed as a way to increase the urgency of the bank angle capture tasks. These maneuvers were bank angle captures from non-zero initial conditions. Typically, the non-evaluation pilot would begin a rolling maneuver (usually with full control), and relinquish control to the evaluating pilot while calling out the desired bank angle (usually just after passing it). This would cause the evaluating pilot to first have to check the roll rate, then capture the desired bank angle. Again, time and overshoots to capture were figures of merit. Like the bank angle captures, these data have been useful for general handling qualities, but have been inconclusive for identifying PIO tendencies.

Full rudder sideslips in ground effect were evaluated in one case. As pilots are comfortable with conducting de-crabbing maneuvers near the runway, these did not present any special difficulty to the pilots, nor did they produce significant correlations with respect to PIO tendencies.

The constant track rudder step maneuvers were intended to be essentially the sideslip-in-ground-effect maneuver, except done at altitude, using the nav track display to hold a course. These proved to be very difficult maneuvers for pilots to conduct, primarily because of unfamiliarity with doing sideslip maneuvers on instruments and did not produce good correlations with PIO tendencies.

Experience in conducting PIO evaluations has demonstrated that while there is merit in data collection, the nature of flight testing requires flexibility. Many investigations have required very specialized techniques and often specialized instrumentation. Boeing has acquired extensive experience in flight testing for Pilot Induced Oscillations involving hundreds hours of flying on six different models and using a very large number of techniques. The single most significant lesson from that experience is that no single maneuver or technique has been found which is effective in exposing PIO tendencies. The most effective strategy has been careful diligence during normal test flying, while prudent handling qualities design appears to be effective for prevention. Nevertheless, the evaluation process continues to evolve as new lessons are learned.

4 Additional Considerations for Flight Testing

In conducting specific, deliberate PIO evaluations, it is obvious that the pilot needs to be an important ingredient and an active player…in the planning, the evaluation, and the review of the data. When engineers ask the pilot to go looking for and attempt to induce a situation in which control might be lost, the pilot usually expresses an opinion. And management is usually not far behind. Flight test safety precautions are certainly necessary and prudent.

One way to minimize the risk of such endeavors has been to conduct the evaluations in a ground-based simulation environment. Experience has shown that while the engineering simulator has been quite useful as a tool to familiarize the pilot with the task at hand, the actual PIO results from the simulation have been largely inconclusive. This has perhaps been due to a lack of model fidelity, a lack of cue fidelity, a lack of real urgency or a combination of many factors. The simulation will continue to be a useful engineering tool for defining maneuvers, validating software, conducting engineering analysis, and for flight crew familiarization and training. PIO evaluations themselves, however, should be done in flight, preferably in the airplane in question.

In addressing the pilot's part of the PIO, it is important to realize that a critical element in the closed loop stability is the pilot gain. Unfortunately, most pilots cannot modulate their gain at will. While many can increase their gain when asked, it is rare that a pilot, once in a high gain situation, can consciously choose to reduce it. If standardized evaluations are to take place, there must be a way to normalize pilot gain both across pilots and across evaluations, or at least take account of it from different tests.

It should be noted that there are well known techniques for increasing a pilot's gain in a given situation. One is by demanding increasing maneuver performance. By reducing the allowed error tolerance or reducing the time allowed for the task, the pilot can be pushed to higher gain levels. Another is controlling the urgency of the flight situation. By making the consequences of maneuver performance errors higher and higher, the pilot's gain can similarly be increased. What remains uncertain, though, is finding a way to achieve consistency in the level of pilot aggressiveness or gain for the purposes of conducting an evaluation of PIO tendencies.

Having invested a great deal of energy in applying a large number of test procedures , an effective discriminator has yet to be found. What can be said about flight test techniques for evaluating PIO tendencies, though, is represented by a set of criteria for what an effective evaluation must do. Effective evaluations must:

- Identify PIO prone configurations
- Pass configurations which are not PIO prone
- Give consistent results across evaluation pilot populations
- Be available without undue cost or schedule impact.

High gain, high urgency tasks are relatively easy to find, but given the dependence on pilot gain levels, consistency remains a troublesome factor.

5 Summary

Boeing has accumulated significant experience in flight testing for Pilot Induced Oscillation tendencies on commercial transport aircraft. This experience encompasses significant size, weight, inertial characteristics, and control system implementations. The experience also includes investigation of a very large number of test maneuvers, and the set of maneuvers continues to grow with each new investigation. No single maneuver or technique for validation has yet been found, although the process of searching for one continues. At this time, the most prudent prevention strategy is prudent handling qualities design, while the most effective testing technique appears to be careful diligence in normal test flying.

6 References

[1] Anon. Aviation Safety and Flight Control: Understanding and Preventing Unfavorable Pilot-Vehicle Interactions, National Research Council, National Academy Press, Washington, 1997.

[2] Shafer, Mary, and P. Steinmetz. PIO Research: The Status at the End of the Century, Proceedings of a Workshop held at NASA Dryden Flight Research Center, April, 1999, In press.

[3] Anon. Flight Test Guide for Certification of Transport Category Airplanes, FAA Advisory Circular AC 25-7A, 31 March, 1998

[4] Maine, R., and K. Iliff. Application of Parameter Estimation to Aircraft Stability and Control, NASA RP-1169, 1986.

[5] Nelson, T., and R. Landes. Boeing 777 Development and APC Assessment, Presented at Society of Automotive Engineers (SAE) Control and Guidance Systems Conference, Salt Lake City, Utah, March, 1996.