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Identifying a Pilot-Induced Oscillation Signature: New Techniques Applied to Old Problems

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"Elimination of pilot-induced oscillations by design" remains an elusive goal. Throughout the history of powered flight, as manual flight control systems have morphed and evolved, so too have the pilot-induced oscillations that often plague them. In the mid-1990s, the United States Air Force declared as part of its Unified Pilot-Induced Oscillation Theory program that the cumulative reduction of pilot-induced oscillations shall be 80% via criteria, 99% via evaluation methods, and 99.95% via detection and compensation. This too remains an elusive goal. One reason lies in the lack of consensus regarding the definition of exactly what is a pilot-induced oscillation. The intent of this paper is to coalesce the many definitions of pilot-induced oscillation into a single entity. Then, newly developed analysis techniques are applied to a flight-test database to expose the unique characteristics or signature of pilot-induced oscillations, at least as they apply to a representative mission operation: the probe-and-drogue aerial refueling task.

I. Introduction

THE phenomenon of pilot-induced oscillations (PIOs) persists. Many have argued that the problems surrounding aircraft handling qualities have been solved, yet PIO, which may be considered a subset of the field of handling qualities, continues to occur. The design process of the airplane has matured, flight control systems have evolved, criteria and analysis techniques are available, yet PIO persists. It is hypothesized here that perhaps PIO persists because the signature of PIO is often unrecognized. Indicators of PIO may not be identified in the design process, because available measures are not used or used as intended. Indicators of PIO in fixed-base simulators may not be recognized because of the absence of needed cues such as the "seat of the pants" feel or anomalies are disregarded as a "feature" of the model. In-flight test programs, higher gain, or urgency maneuvers that can expose PIO indicators are often not performed, because they lack operational relevance, or so the argument goes. The end result is that PIO persists and the signature of PIO remains unrecognized.

A common misperception among those not familiar with the phenomenon is that there is one kind of PIO, and either you have one or you do not. The authors have participated in numerous meetings and conferences in which the single topic of debate has been whether or not a particular event was a PIO. Unfortunately, in most such cases, this debate has served only to obscure the obvious: that there is an undesirable response, no matter what we call it. The introduction of the term "aircraft–pilot coupling" (APC, or sometimes A-PC) in the mid-1990s contributed to the obscuration of the obvious: although the intent of this new term was to capture both oscillatory and nonoscillatory adverse behaviors of the aircraft–pilot system [1], it has further factionalized the debate, as there are now questions like, "Was this event a PIO or just APC?" and "What's the difference between PIO and APC?" to be addressed in the ongoing debates.

The truth, of course, is that there are in fact many different kinds of PIO, with many different causes and cures. There is a dire need to divide the phenomenon between dangerous (or potentially dangerous) PIO and minor but annoying PIO. To paint all PIOs with a single brush is to run the risk of panicking and rushing to judgment on the basis of a benign, common event, or doing the opposite: trying to whitewash a serious and potentially deadly design flaw. In this paper, the authors attempt to assemble knowledge on the phenomenon of PIO into a single publication.

To emphasize the ongoing impact of the phenomenon, a list of PIO events from the last 10 years was compiled in Table 1. This table serves to illustrate our key points: 1) that there are many different kinds of PIO, in many different kinds of aircraft; 2) that sometimes what we call PIO may not fit with commonly held definitions; and 3) that PIO continues to occur, causing disruptions of aircraft development programs, damage to aircraft, injuries, fatalities, and, on occasion, criminal convictions for the flight crew.

II. Defining Pilot-Induced Oscillations

A. What is a PIO?

The Department of Defense Interface Standard for Flying Qualities of Piloted Airplanes, MIL-STD-1797A [2], contains a concise definition of PIO: it consists of "sustained or uncontrollable oscillations resulting from efforts of the pilot to control the aircraft." It has been suggested that the word "unintentional" be added before "sustained," to distinguish from intentional oscillatory behavior.

Taken literally, the MIL-STD-1797A definition means that *any* oscillation that occurs during manual, piloted control may be classified as a PIO. Yet, many times this oscillation is nothing more than a result of pilot overcontrol in an otherwise normal circumstance. For example, to the outsider, the typical ballooning in-flight path angle that any student pilot encounters during landing training may appear to be a PIO. This ballooning is simply part of standard pilot compensation and is usually no more than one or two cycles, with no threat of developing into a life-threatening PIO. Indeed, visual inspection of the time history records from even the experienced pilot in the landing flare with a known good airplane will reveal small corrections that might appear to be signs of a PIO. These

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Table 1 PIO events from the past 10 years

Aircraft	Event date	Location	Fatalities	Injuries	Comments
Beech Baron	2/1/96	landing, Morganton, NC	2	1 serious, 3 minor	jury awarded victim $3.95 million for "negligence and pilot-induced oscillation in the landing phase"
F-16 DBTC	6/26/96	terrain following, Edwards AFB, CA	0	0	display-induced PIO
MD-11 (JAL 706)	6/8/97	descent, Japan	1	3 serious, 9 minor	Captain indicted
757 (unknown)	multiple	approach and landing, various airports	0	0	11 reported incidents of roll oscillation; Boeing Service Bulletin for fixes issued as FAA Airworthiness Directorate
767 (American Airlines)	1/15/99	landing, Heathrow, London	0	0	buckled fuselage
V-22	2/1/99	hover over ship	0	0	suspended sea trials
F-18F	3/8/99	landing on carrier	0	0	FCS modifications made
Falcon-900 (Olympic Airways)	9/14/99	descent, Romania	7	2 serious	pilot convicted of manslaughter
Falcon-900	10/9/99	descent, Grand Rapids, MI	0	1 serious	lawsuit settled out of court
A321 (Air France)	2/8/01	landing, Heathrow, London	0	0	damaged wing tip, fence, aileron
A320 (Northwest 985)	3/17/01	takeoff, Detroit, MI	0	3 minor	injuries could have been during emergency evacuation
X-35B JSF	6/1/01	hover, Palmdale, CA	0	0	very minor; FCS modifications
C-17A	2001–?	approach and landing, war zone	0	0	numerous events, some with damage to wings, flaps, engine nacelles, landing gear
A321 (Air France 457)	12/7/02	landing, Toronto	0	0	hard landing
A321 (Air France 1130)	12/7/02	landing, Toronto	0	0	go-around (landing uneventful)
F/A-22	9/28/04	air-to-air tracking, Edwards AFB, CA	0	0	damaged aircraft (landed safely)

are *not* what MIL-STD-1797A is referring to, nor are they to be feared.[†]

There is a certain appeal to declaring every unintentional oscillation a PIO: we can attempt to remove the stigma attached to the phenomenon. A sure way to raise eyebrows in a full-scale development flight program is to have a pilot in a postflight debrief hint that the aircraft in question exhibits PIO. The usual result from such an event is an immediate investigation as to why and what should be done, even if the pilot clearly states that the oscillations were extremely minor, resulted from very high-bandwidth manual control, and could easily be stopped. If we could destigmatize PIO, logic would prevail instead of emotion, and the pilot would be asked about the frequency, amplitude, tendency to diverge, etc., for the event in question, and experts could then determine if there is real cause for concern. Of course, what is really needed in this instance is a systematic method for quantitative analysis of the event and an investigation of its causes. Quantitative analysis of PIO is a major theme of this paper.

Residual oscillations that continue, even if the pilot is no longer making an effort to control the aircraft, are not PIO. This distinction can become fuzzy if the cause of the residual oscillations can lead to a PIO. For example, failure of a pitch damper could result in an effective short period mode with zero damping; this will most definitely be difficult to control and will lead to PIOs, and the airplane will continue to oscillate after the pilot has released the stick. Technically, the airplane experiences PIO when the pilot is flying and undamped motions when the pilot is not flying.

Many of the PIOs recorded in older (1950s and earlier vintage) aircraft are traceable directly to low inherent damping of the short period or Dutch roll. We therefore need to exercise the definition of the military standard and emphasize that we are *only* interested in such PIOs when there is clear evidence that they result from "efforts of the pilot to control the aircraft." In the search for PIO time histories, numerous references to PIO were found in which the time traces themselves showed residual oscillations (hands off controls) and not true PIOs.[‡] Because the PIO is evidence of an undamped closed-loop, pilot-vehicle oscillation, then there must exist during the PIO at least one measurable aircraft state that is 180 deg out of phase with at least one pilot control. This leads to the following proposed definition: A PIO exists when the airplane attitude, angular rate, normal acceleration, or other quantity derived from these states, is approximately 180 deg out of phase with the pilot's control inputs.

There are many, perhaps hundreds, of time traces in the open literature that illustrate the two precepts for PIO introduced so far: 1) oscillatory characteristics, and 2) out-of-phase behavior. As an illustration, consider the three rather well-known sets of traces in Fig. 1. They are the stick inputs (force or position) and angular attitude outputs for the YF-22 low-altitude pitch PIO [3] at Edwards Air Force Base in 1992; the roll PIO of an MV-22 near a ship [4] in 1999; and a pitch PIO [5] of an F-14A, operating on its backup flight control module, while attempting an in-flight refueling in 1990. The F-14A example is described in greater detail later in this paper.

Whereas there is evidence of high-frequency control activity on all of the stick traces in Fig. 1, a lower-frequency, sinusoidal oscillation is evident as well. Angular attitude is approximately 180 deg out of phase with stick at the start of the oscillations, and in all cases is more than 180 deg out of phase by the end of the traces.

Because of the critical importance of distinguishing between a potentially catastrophic PIO and nuisance oscillations, one solution is to change the definition of PIO. The primary emphasis is to make a distinction between closed-loop pilot/aircraft oscillations that are a side effect of the pilot's tracking effort and those that have a potential

[†]The reader may note that the very first entry in Table 1 refers to a crash during a landing attempt in a Beech Baron. There were no aircraft data records to prove that this unfortunate event was actually a PIO; it must have been one, however, because it was stated as such by a jury in a trial. This event might appear to be contradictory with the authors' conjecture about pilot activity in normal landings, but the facts in the case suggest that this was far from a normal landing, whether or not there was a PIO as we define it in this paper.

[‡]In most instances, these oscillations were the result of low modal damping (short period or Dutch roll), and, although explicit evidence of PIO could not always be located, it is recognized that low damping of these modes may lead to PIO in closed-loop piloted control.

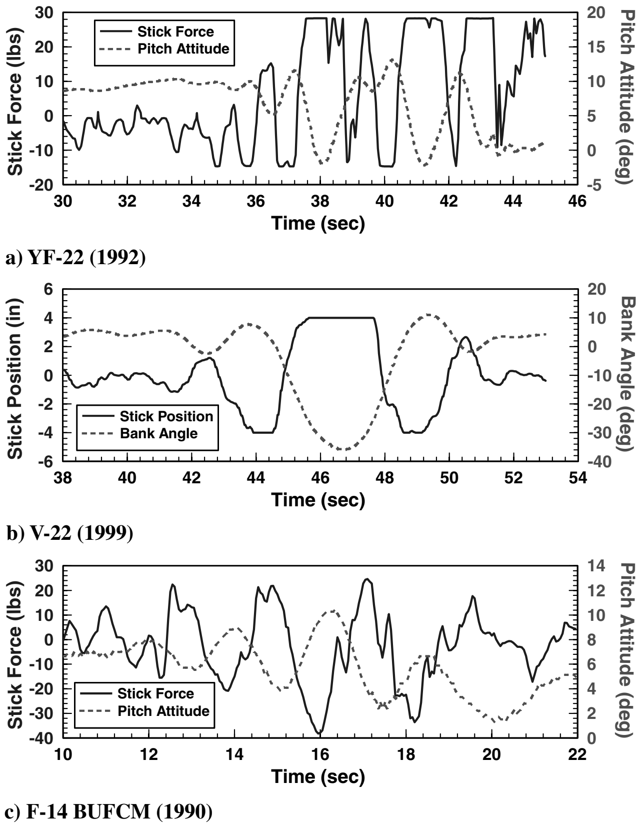


Fig. 1 Input–output pairs for three well-known PIO events show out-of-phase oscillatory characteristics.

for loss of control. These oscillations may look identical on recorded data, and only the pilot can properly make this crucial distinction.

One way of viewing the crucial distinction between oscillations resulting from degraded handling and those that can result in a divergent PIO is to note that in the former case the pilot *drives* the oscillation, whereas in a "real" PIO (as defined here) the pilot is *driven* by the oscillation. If the oscillation requires that the pilot redirect efforts away from the primary task by a noticeable amount, we say that a new task has been created (stop the oscillation). In such cases, the pilot is being driven by the oscillation (forced to do a new task). In extreme cases (e.g., YF-22 and JAS 39 [1]), the pilots thought that they had experienced a flight control system failure, and that the new task was to cope with that failure. This is the phenomenon that we must quantify if we are to achieve clarity on the difference between degraded handling qualities and PIO.

One important way to characterize PIO is by the amplitude of the pilot's input and the aircraft's response. If both input and output are below a certain threshold, we should not care if the first two definitions (oscillations and out-of-phase) are met, because the pilot will not even see it, or it will appear to be nothing more than a minor nuisance. We are left with the observation that, to be called a real PIO, the input, or output, or both, must be large enough to be noticed.

B. Eight Definitions

To establish what we mean by PIO, we will call upon definitions that have been submitted by the authors and others in the industry. This section summarizes the most salient of these definitions based on the illustrations in Fig. 1 in a list that is adopted from those first published in a report [6] written for the U.S. Air Force in December 2000. (The original list of 10 definitions has been reduced here to eight.)

1) PIO is a sustained or uncontrollable "unintentional" oscillation resulting from the efforts of the pilot to control the aircraft. This is the MIL-STD-1797A definition, with the word unintentional added.

2) PIO occurs when a response state of the airplane is approximately 180 deg out of phase with the pilot. This is exemplified by the three examples in Fig. 1. It could be any response state of the airplane, though the most common are pitch attitude, roll attitude, and load factor.

3) PIO may be either constant-amplitude, convergent, or divergent with time.

4) PIO may be any number of cycles of oscillation; there is no minimum number to declare it a PIO.

5) PIO may occur at very low frequencies (near the phugoid mode in pitch) up to frequencies of around 3 Hz ("roll ratchet"). The most common frequency is in the range for pilot closed-loop control, typically $1/6$ Hz to slightly above 1 Hz (1–8 rad$/$s), but frequency alone does not determine whether an oscillation is a PIO.

6) High-frequency, small-amplitude oscillations in pitch (sometimes referred to as "pitch bobble"), and in roll (roll ratchet), may be considered a "mild" form of PIO, and may not even be judged as PIO in all cases. If the amplitudes of the oscillations become intrusive on the piloting task, they are PIOs.

7) PIO that interferes with, but does not prevent, performance of a primary mission task is a "moderate" PIO; if a Cooper–Harper Handling Qualities Rating (HQR) [7] is obtained, it is usually in the range of 4–6 (level 2 by handling qualities specifications). In general, moderate PIO is associated with peak-to-peak angular rates of less than ± 10 deg$/$s and control forces less than ± 5 lb [8]. Moderate PIO requires corrective action for normal operation of the airplane, but if it occurs in developmental testing, the flight test program can continue.

8) PIO that prevents performance of the task, or that requires the pilot to abandon the task in an attempt to stop the oscillation, is a severe PIO; if a Cooper–Harper Handling Qualities Rating is obtained, it is usually 7 or worse (level 3 or unflyable by handling qualities specifications). Peak-to-peak angular rates are usually greater than ± 10 deg$/$s, and control forces greater than ± 10 lb, though rate limiting can attenuate the former and result in large increases in the latter [8]. Severe PIO requires immediate changes to the airplane, and if it occurs in developmental testing, the flight test program should be postponed or redirected until the corrections are made.

Based upon the authors' experience with the phenomenon, PIO is an event that results from faulty aircraft design, extension of the airplane's operational usage into an area for which it was not intended, or following a failure, and is not the fault of the pilot. PIO is commonly found to be related to deficiencies in basic flying qualities characteristics, though it should be treated independently from flying qualities. Most PIOs outside of the research world are related to rate limiting of a control effector or software element upstream of a control effector, but rate limiting can be both the cause of PIO and the result of it [9].

In the authors' experience with the analysis of PIO, it is possible to characterize virtually every PIO documented in the open literature (and, for that matter, virtually all with which we are familiar that are *not* published in the open literature), with the following statement: PIO is a sustained or uncontrollable unintentional oscillation in which the airplane attitude, angular rate, normal acceleration, or other quantity derived from these states, is approximately 180 deg out of phase with the pilot's control inputs, and in which the amplitude of pilot control inputs, aircraft response, or both, is large enough to be intrusive on normal flying.

C. Methods for Verifying PIO

It is paramount that we reach a consensus on the definition of PIO. This is the best way to be sure that we are all talking about the same phenomenon, even if there is wide variation in the details of its causes and characteristics. To this end, the authors have been actively engaged in the development of methods for verifying the existence (or lack of existence) of PIO in real time. There have been numerous other attempts to develop such methods, some documented for public viewing, some not. The two methods developed by the authors' respective companies have shown considerable promise when applied to postflight time histories and to real-time, ground-based simulation applications; neither has yet made it to a real-time, in-flight application. Both of the methods call upon the definitions of PIO outlined in Sec. II.B and are the subject of the remainder of this paper.

III. F-14 Flight Test Database

A. Background

The following two sections of this paper describe real-time PIO detection methods. They provide ways to quantify what we mean by PIO, using the definitions of the previous section. The methods are best described by showing their application to a specific data set. For this purpose, we will use a PIO database generated during a flight program with an F-14A airplane. This section describes that flight program and the subset of the database used in the next two sections.

B. F-14 Dual Hydraulic Systems Failure Flight Test Program

Problems with the F-14 hydraulic system began with the second flight of aircraft 1 in December 1970, during full-scale development testing [5]. On this flight, both primary hydraulic systems failed, as did a valve in the backup hydraulic system. The aircraft was lost just before touchdown. Hydraulic failures of this type have been an issue for the F-14 for most of its operational life. From October 1990 to March 1991, the U.S. Navy conducted a flying qualities evaluation of the F-14 with simulated dual hydraulic failure. In this study, the backup flight control module (BUFCM) was evaluated to define areas of operation for in-flight refueling and landing. The BUFCM has two modes that are available to the pilot. The BUFCM-high mode features a maximum stabilator rate of 10 deg/s, whereas BUFCM-low has a 5 deg/s maximum rate. Although the aircraft demonstrated good handling qualities using the BUFCM in formation flight with a tanker, a number of PIOs were encountered during in-flight refueling (see Fig. 2), drogue tracking, and offset field landings. Because the F-14 was fully instrumented, a valuable PIO database was inadvertently created. The Naval Air Warfare Center, Aircraft Division (NAWCAD), in Patuxent River, Maryland provided selected flight test data from the F-14 dual hydraulic failure flight test program in digital ASCII and Matlab file formats with corresponding documentation. These high-quality data included a subset of the flight test runs and a number of frequency sweep runs that were generated as part of the flight test program in [5]. An analysis of this database was reported in [10,11].

C. Description of the Data

The run numbers and configurations identified in this paper correspond to those identified in the documentation provided by the U.S. Navy. The altitudes, airspeeds, and Mach numbers provided here were taken directly from the data files. In Table 2, the aerial refueling cruise (CR) configuration runs used herein are identified by wing sweep and flap positions, flight condition [i.e., altitude, speed in knots indicated airspeed (KIAS), and Mach number as recorded at the start of a run], and flight control system mode (i.e., SAS-on, SAS-off, or BUFCM-high).

Example time histories for a no-PIO and a severe-PIO run are shown in Fig. 3. For each example run there is a longitudinal stick force and average stabilizer position and a pitch rate and pitch attitude time response plot. For the no-PIO run, increasing stick

Fig. 2 Pilot gain increases as the aircraft approaches the refueling drogue.

forces are observed as the aircraft approaches the drogue. Once a successful hookup is made, the stick force inputs decrease in amplitude. The control surface responses to these inputs are essentially in phase throughout the maneuver with no evidence of nonlinear behavior. The maximum pitch rate corresponding to the hookup is just over 5 deg/s. There are no peak-to-peak pitch rate amplitudes that would indicate stability issues associated with PIO. The same cannot be said for the severe-PIO example. First, the stick force amplitude has increased significantly when compared with the no-PIO case. Also, the higher frequency content of the pilot input is absent. Furthermore, the average stabilizer position is more than twice the amplitude of the no-PIO run, and the trianglelike characteristic of rate limiting, an important part of the PIO signature, is clearly seen. Another important part of the PIO signature, the peak-to-peak rate, now falls within the range common to PIO. Finally, and most importantly, the pitch attitude is approximately 180 deg out of phase with the stick force input. Thus, the signature of this severe PIO includes large-amplitude pilot inputs, control surface rate limiting, relatively high peak-to-peak body axis rate, and an aircraft attitude that is 180 deg out of phase with the pilot input. These are all important parts of the definition of PIO introduced earlier in this paper.

IV. Real-Time Oscillation Verifier

A. Description

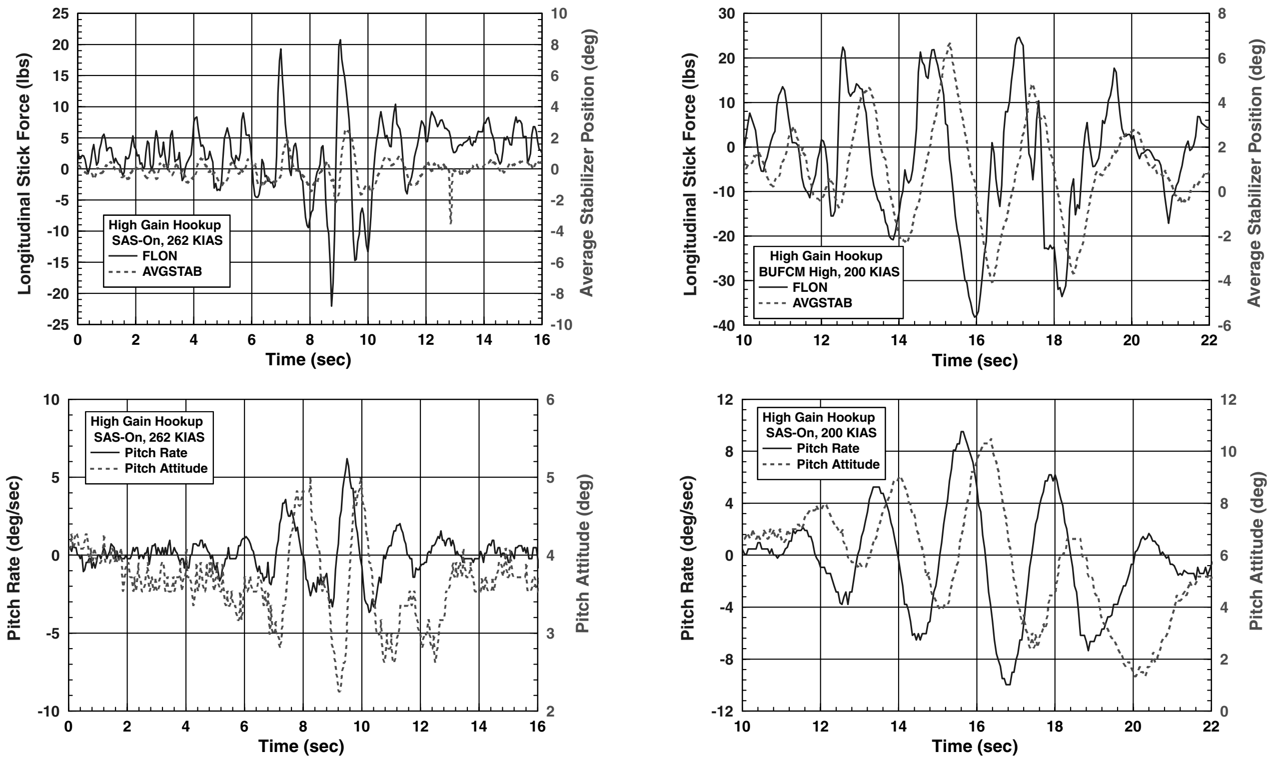
The real-time oscillation verifier (ROVER) concept was first developed for the U.S. Air Force [6]. It has since been refined and evaluated in ground-based simulations under sponsorship from NASA Dryden Flight Research Center [12]. A fundamental assumption for ROVER is that there is no such thing as a "pre-PIO condition": PIO will never be prevented in real time, and so the best we can hope to do is detect it early and minimize the effect on the aircraft.

Given the four conditions for PIO given earlier in this paper, ground rules can be established to determine if an oscillation is a PIO. In research performed for the U.S. Air Force to develop methods to predict PIO [6], the following general ground rules were established.

Table 2 Run log of probe-and-drogue aerial refueling hookup cases

Run no.	Configuration[a]	Flight control system ID[b]	Altitude, ft	Airspeed, KIAS	Mach no.	HQR
J_01	CR-20-0	SAS-on	14,000	262	0.51	4
J_03	CR-20-0	SAS-off	20,000	307	0.67	8
J_04	CR-20-0	SAS-off	20,000	200	0.44	5
J_05	CR-20-0	BUFCM-high	19,000	200	0.42	10
J_06	CR-20-0	BUFCM-high	19,000	200	0.42	10
J_07	CR-35-0	SAS-on	17,000	256	0.53	3
J_08	CR-35-0	SAS-off	17,000	252	0.52	4

[a]Configuration CR-XX-YY denotes landing gear retracted, wing sweep at XX deg, and flaps at YY deg.
[b]SAS-on: hydraulic system and stability augmentation system (SAS) active; SAS-off: hydraulic system active, SAS switched off; BUFCM-high: hydraulic system and SAS switched off, backup module (stabilators in 10 deg/s mode).



a) Run J_01, SAS-On, No PIO

b) Run J_05, BUFCM-High, Severe PIO

Fig. 3 Example time histories for two F-14 probe-and-drogue in-flight refueling cases.

1) Assume every aircraft response is an oscillation. Although the classical definition of a PIO is a sinusoidal input/output relationship, the real event seldom resembles a true sinusoid. Attempts at establishing criteria for detecting PIO based on the nature of the oscillation have been only partially successful. A more straightforward, if overly simplistic, approach is simply to interpret every detectable aircraft motion to be an oscillation, and then to perform further tests to determine if the oscillation is a PIO.

2) Limit the search to a reasonable frequency range. Given the wide range of possible oscillations, from divergent motions at the phugoid frequency to high-frequency roll ratchet, it is not practical to worry about all possible frequencies of oscillation. The narrower the frequency range of interest, the more specific the search criteria.

3) Focus on aircraft response, then look for a corresponding control input. Rather than closely monitor both control inputs and aircraft responses, it is far less complicated to monitor only the aircraft motions for oscillations in the frequency range of interest. If such motions are detected, then a backward search can be performed to determine if the response was the direct consequence of the pilot's actions.

4) Check for phase differences between aircraft response and pilot input. Using assumption 1, that every detectable motion is an oscillation, it is possible to make an estimate of the effective frequencies of the output and input, and compute the phase angle between them. If the phase difference is large enough, the motion may be a PIO.

5) Use an easily monitored aircraft state. Though PIO is classically defined as an out-of-phase oscillation between aircraft attitude and pilot inputs, angular attitude is a challenging state to monitor because it has nonzero mean and can have relatively small magnitudes at the start of a PIO. It is much easier to monitor angular rate instead, remembering that PIO will now be characterized by a phase difference of 90 deg, not 180 deg.

6) Check the amplitudes of peak angular rate and cockpit control inputs. Based on the data in [6], thresholds can be set to declare an oscillation a true PIO and not a minor bobble.

These ground rules were used to develop ROVER. The methods used in ROVER to search for PIO are outlined in the flowchart shown in Fig. 4. ROVER operates on smoothed signals of angular rate and pilot control input; smoothing is performed using low-pass filters that remove high-frequency noise and data spikes. Every time a peak in angular rate is detected, the time between the current and previous peaks is used to compute oscillation frequency (the assumption is that the peak-to-peak response is a half-cycle of a sinewave). If this frequency is in the range associated with PIO, a flag is set. A magnitude flag is set if the peak-to-peak amplitude is above the threshold for PIO. The time between peaks in angular rate is compared with the time between peaks of the most recent past stick oscillation, the time difference is converted to phase angle using the frequency determined from the rate response, and if this phase angle is in the range for PIO, a third flag is set. The fourth and final flag is set if the peak-to-peak control input amplitude is above a predefined threshold value.

Severe PIO requires that all four flags are set for a single half-cycle of oscillation. ROVER is therefore capable of detecting severe PIO in the first half-cycle. It is also possible to have severe PIO with only three of the flags set; for example, if rate limiting is present, there can still be out-of-phase oscillatory response, but angular rate will be suppressed by the rate limiting. The two prerequisites for PIO, in any case, are frequency of oscillation in the range for PIO and aircraft out of phase with the pilot.

The critical output from ROVER is the algebraic sum of the four flags. It is common, even for aircraft with no hint of PIO, to have ROVER output values of two and three: the frequency range for PIO is essentially identical to that for piloted manual closed-loop control [13,14], and large control inputs or aircraft responses will trip the magnitude flags, but as long as the input and output are in phase, no PIO is detected. Similarly, it is surprisingly common to find that the pilot's inputs produce out-of-phase responses, usually at quite high frequencies and very low amplitudes, and so trips of the phase-angle flag are not unexpected. Activation of all four flags, however, indicates presence of PIO.

ROVER has proven valuable as a tool for analyzing historical flight research and ground simulation data. Time history data can be postprocessed to determine if PIO (or the conditions normally associated with PIO) occurred.

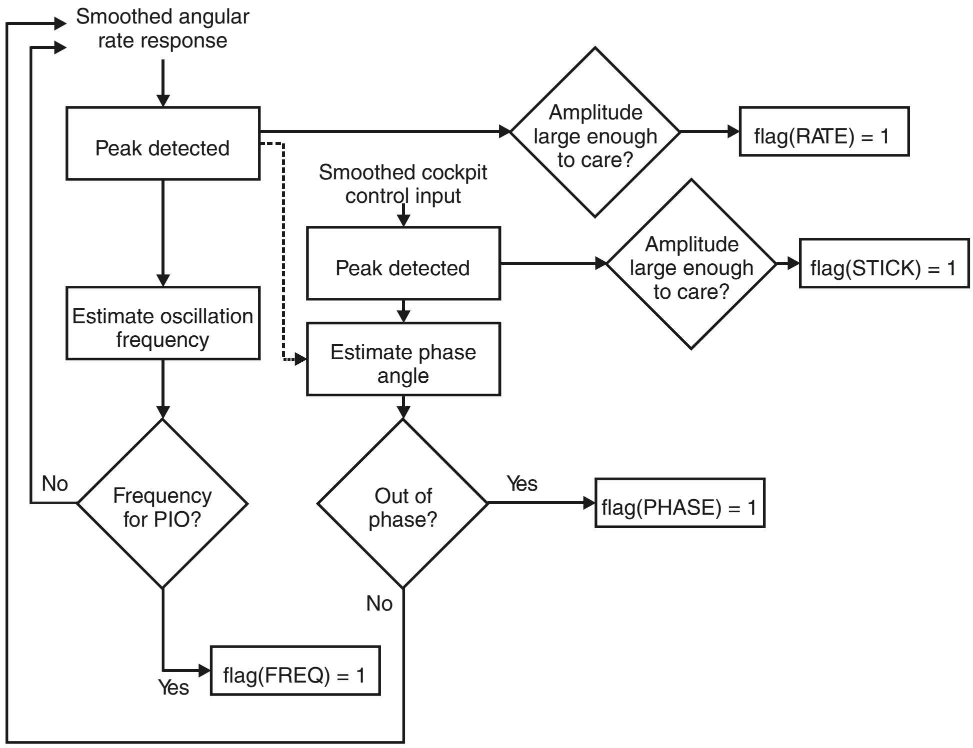


Fig. 4 Flowchart for ROVER PIO detection method.

It is very common for oscillatory behavior to appear in time responses, especially during periods of high-gain, closed-loop pilot activity. It would be a serious mistake to declare all such oscillations PIO, especially if the airplane is responding perfectly to the pilot's commands. ROVER uses the established ground rules as listed earlier in this section to determine if the oscillations meet the definitions of PIO.

B. Analysis of F-14 Aerial Refueling Cases

As evidence of the application of ROVER, data from the two F-14 in-flight refueling runs illustrated in Fig. 3 were analyzed with a non-real-time version of ROVER. Results are shown in Fig. 5 for the SAS-on run J_01 (no PIO reported in-flight) and Fig. 6 for the BUFCM-high run J_05 (severe PIO reported in-flight). Data for the full runs were applied to ROVER; the segments in Fig. 3 are portions

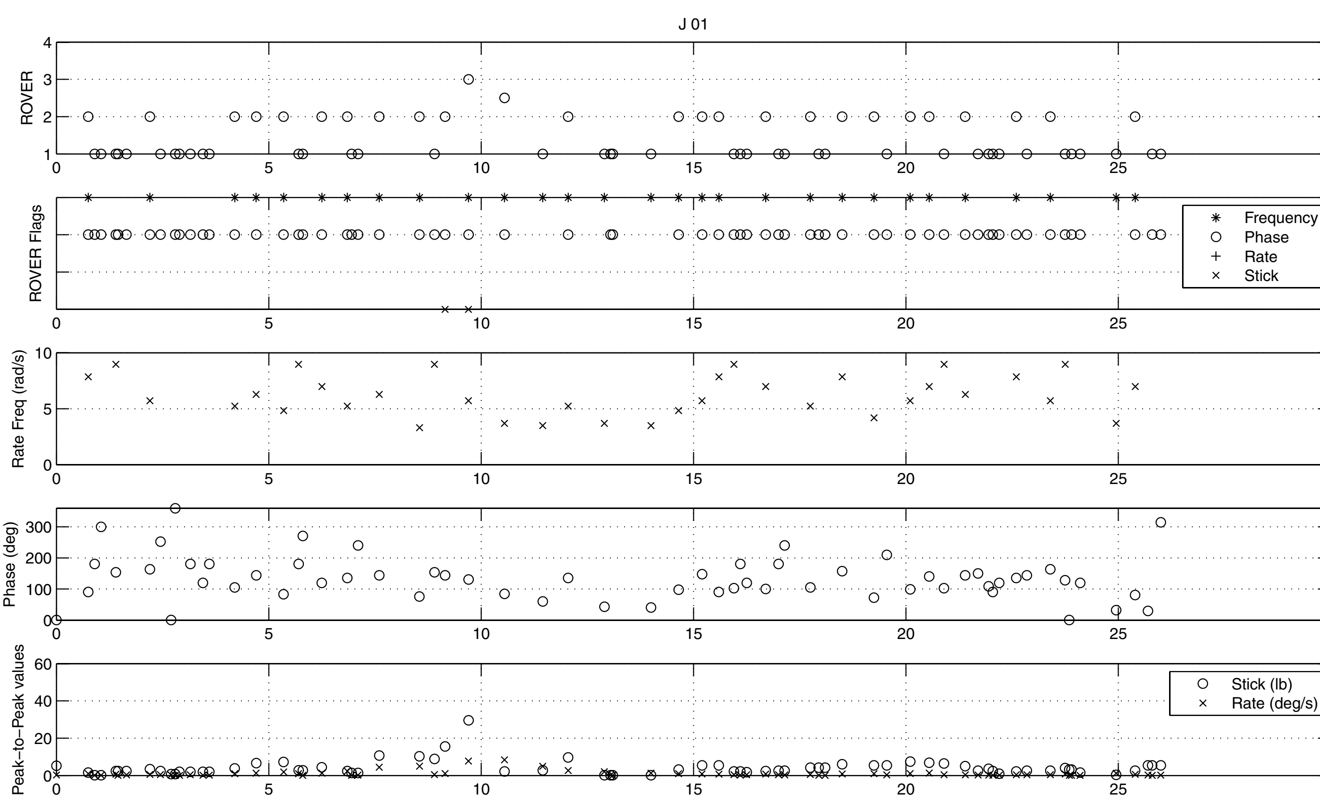


Fig. 5 ROVER detects no PIO for F-14 refueling run J_01 (SAS-on, no PIO reported).

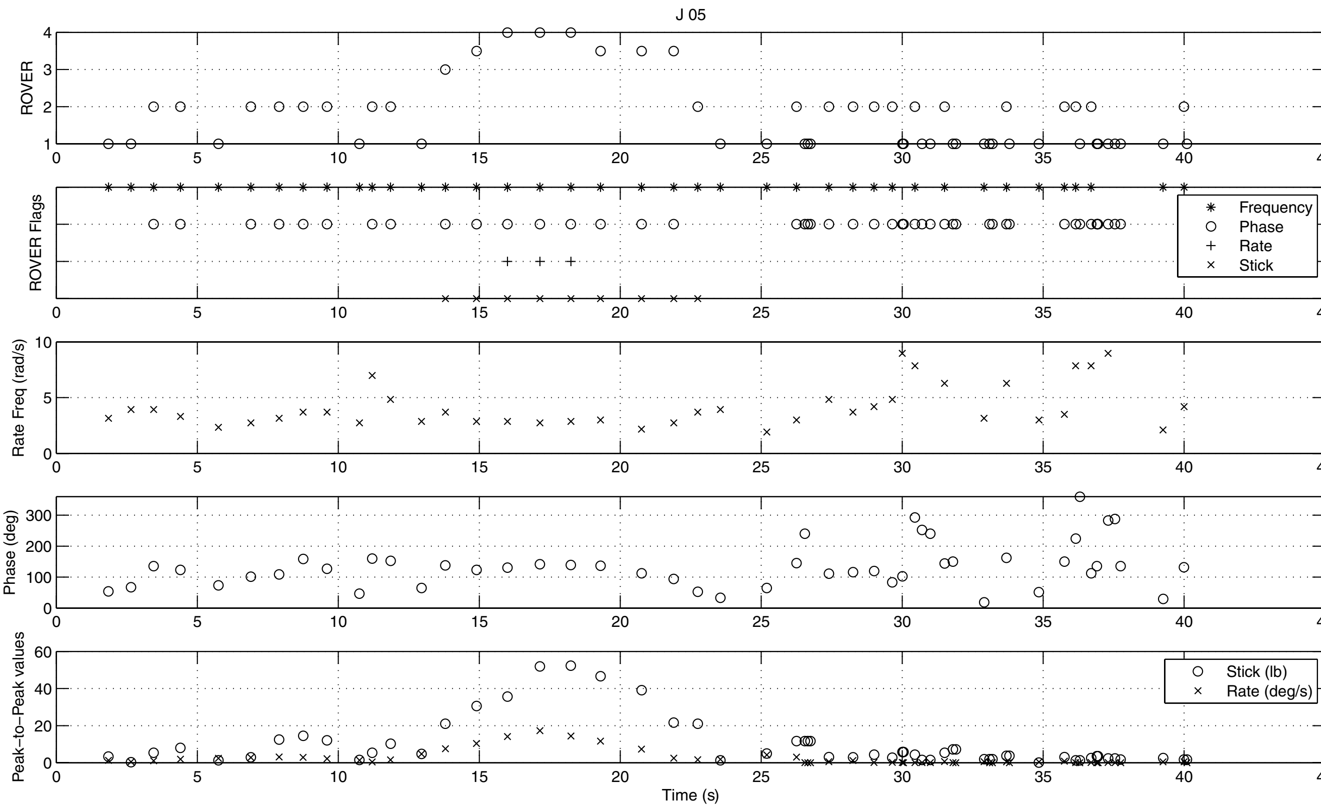


Fig. 6 ROVER detects severe PIO for F-14 refueling run J_05 (BUFCM-high, PIO reported).

of the complete runs. In each figure, the bottom three graphs show the data used to determine flags and thresholds for ROVER, whereas the top two graphs are the actual flags. A data point is plotted each time a peak in pitch rate is detected. The five graphs in each figure show the following, from top to bottom:

1) ROVER: the algebraic sum of the four flags from Fig. 4. A reading of four is PIO.

2) ROVER flags: indicators for each of the four flags. A data symbol is plotted if a flag is set. The flags are frequency of pitch rate (Frequency), phase angle (Phase), peak-to-peak pitch rate (Rate), and peak-to-peak stick force (Stick). This graph can be used to determine which flags have tripped for each ROVER output flag.

3) ROVER rate frequency: identified frequency (in radians per second) of the oscillation based on pitch rate.

4) ROVER phase: identified phase angle between stick and pitch rate (in degrees).

5) Peak-to-peak values: the magnitudes of peak-to-peak pitch rate (degrees per second) and stick force (pounds) each time a peak in pitch rate is detected.

For the non-PIO run J_01 (Fig. 5), ROVER flags are two or less (output values of zero are not plotted because they are uninteresting to us) for the entire run, with the single exception of a lone value of three just before 10 s. Comparison with the time histories in Fig. 3 suggests that this is the point of hookup with the drogue, and the large amplitudes for one-half cycle caused three of the flags to trip. There is no indication of PIO for this entire run.

For the PIO run J_05 (Fig. 6), ROVER detected PIO at the 16 s point, corresponding to the time when large oscillations can be observed in Fig. 3. There is no hint of PIO before or after this time sequence.

V. Wavelets and Scalograms

A. Description

Fourier transform methods have been used to estimate the frequency response of a system for many years [15]. Recently, the use of wavelet transforms for this same application has been investigated with a particular emphasis toward time-varying systems. When using a continuous wavelet transform, the time function is decomposed into basis functions that translate in time and whose length and magnitude scale with frequency as defined in the following equation:

$$W_\phi(\omega, u) = \int_{-\infty}^{\infty} f(t)\omega^{1/2}\phi^*[\omega(t-u)]\,\mathrm{d}t$$

The transform $W_\phi(\omega, u)$ is interpreted as the frequency content of the input $f(t)$ in the neighborhood of the point ω, u in the frequency-time plane. The subscript ϕ indicates that the transform is defined for the wavelet function $\phi(t)$, the so-called mother wavelet. All of the basis functions $\omega^{1/2}\phi^*[\omega(t-u)]$ are derived from $\phi(t)$. The multiplication by $\omega^{1/2}$ is included so that all of the basis functions have the same norm. The mother wavelet can be real or complex, and in many wavelet applications it is defined as a real function, but for system identification where phase information is important, the complex exponentials are a natural choice, and therefore wavelets of the following form are used:

$$\phi(t) = g(t)e^{jt}$$

Details of the development of wavelet techniques for system identification and detection of impending loss of control can be found in [16].

As a simple example, start with the system $g(s)$ shown in Fig. 7 and compute wavelet transforms of the input and output, in which u and y are the input and output time series, respectively, and W_u and W_y are the corresponding input and output wavelet scalograms.

Under ideal conditions, the frequency response estimate is the ratio of the wavelet transforms

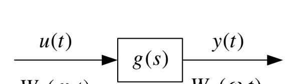


Fig. 7 Transfer function estimation using wavelet transforms.

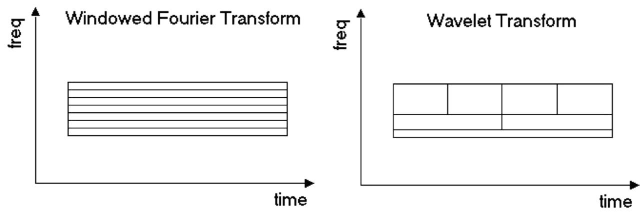


Fig. 8 Comparison of frame sizes for windowed Fourier transform and wavelet transform.

$$g_{\text{est}}(\omega, t) = \frac{W_y(\omega, t)}{W_u(\omega, t)}$$

Essentially ideal conditions can be achieved in practice using sum-of-sine inputs, where all of the input power is centered at distinct frequencies. Results using this technique were reported in [17].

Changes in the system, particularly changes that affect stability, can be estimated and used for safety and health monitoring. With windowed Fourier transform methods, the time window depends on the lowest frequency $T = 1/f_{\min}$, whereas for wavelet transform methods, the time window varies with frequency, being equal to $T = 1/f$ for each of the frequencies at which the transform is estimated. As illustrated in Fig. 8, the time window is smaller at higher frequencies, hence the ability to respond more rapidly to changes at high frequencies. A good way to measure the window length is in cycles. The window length is a constant number of cycles.

The different frame sizes for the wavelet transform allow for transient analysis, whereas the windowed Fourier transform is an average response for that frame. To further illustrate these differences, the windowed Fourier transform and wavelet transform of a simple time series input consisting of two sinusoids is shown in Fig. 9. Note that the power spectra of the windowed Fourier transform shows the two distinct peaks associated with the input sinusoids shown in Fig. 9a. In the top left of Fig. 9b, the mother wavelet is the shifted Morlet [16]. The Morlet is probably the most popular of the continuous wavelet transforms and is defined by setting the window function $g(t)$ to a Gaussian envelope. To make this wavelet causal, the wavelet function is shifted to the right and the tails of the distribution are truncated. A Fourier transform of the shifted Morlet with a center frequency of 1 rad/s is shown in the top right of Fig. 9b. When compared with the windowed Fourier transform, the wavelet scalogram of the same example time series not only shows the peaks in power, but also shows when in time the sinusoids occurred. It is this characteristic that makes wavelets a powerful tool for detecting changes in time-varying systems. It is this capability that will be exploited for identifying key components of the PIO signature from the example flight test data set.

If the conditions used for estimation are not ideal, and outside of an experimental setup this will almost certainly be the case, then some sort of smoothing technique must be used. The proper way to pose the estimation problem is to determine the variance of the estimate. An estimate with a lower variance uses a smoothed estimate of the cross-spectral density divided by a smoothed estimate of the input power spectra density. In the following equations, the tildes indicate smoothing, shown as an average over a frequency range, where $\tilde{S}_{yu}$ is the smoothed cross scalogram between u, y and frequency ω, and $\tilde{S}_{uu}$ is the smoothed scalogram of the input u and frequency ω:

$$\hat{g}(\omega, t) = \frac{\tilde{S}_{yu}(\omega, t)}{\tilde{S}_{uu}(\omega, t)}$$

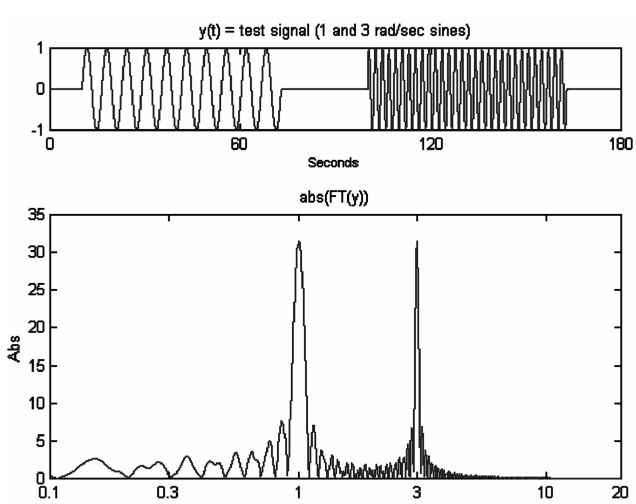
In the next equation, $\tilde{S}_{\alpha\beta}$ is the smoothed cross scalogram that is used to define the smoothing method, whereas F_α is the unsmoothed scalogram and F^*_β is the conjugate of the unsmoothed scalogram.

$$\tilde{S}_{\alpha\beta}(\omega_{\text{avg}}, t) = \frac{1}{\omega_1 - \omega_0} \int_{\omega_0}^{\omega_1} F_\alpha(\omega, t) F^*_\beta(\omega, t)\, \mathrm{d}\omega$$

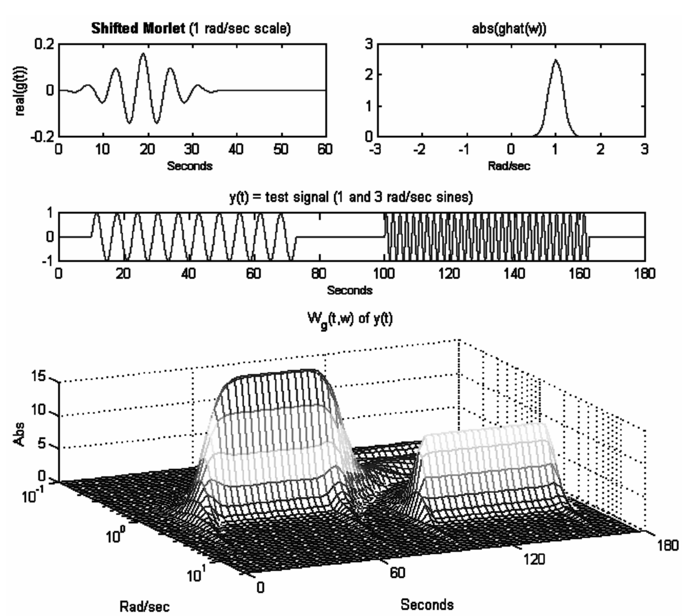
This is the wavelet-based estimation technique that was used to assess the F-14 probe-and-drogue refueling data set as described next. Of course, there is always a tradeoff between smoothing and detection of changes. That is, the more the signal is smoothed, the longer it will take to identify a change in the system. With wavelets, the estimated system responses can be smoothed in the time domain, the frequency domain, or both. The reader is referred to [16] for further details on the use of wavelets for time-varying system identification.

B. Analysis of F-14 Aerial Refueling Cases

Wavelet scalograms of stick force and pitch rate are shown in Fig. 10a and 10b for the SAS-on, no-PIO case and the BUFCM-high, severe-PIO case, respectively. Scalograms, as described before, are essentially time-varying power spectra density plots that not only show at what frequencies the peak power is occurring, but also at what point in time [16]. Ten seconds of data are included in the plots

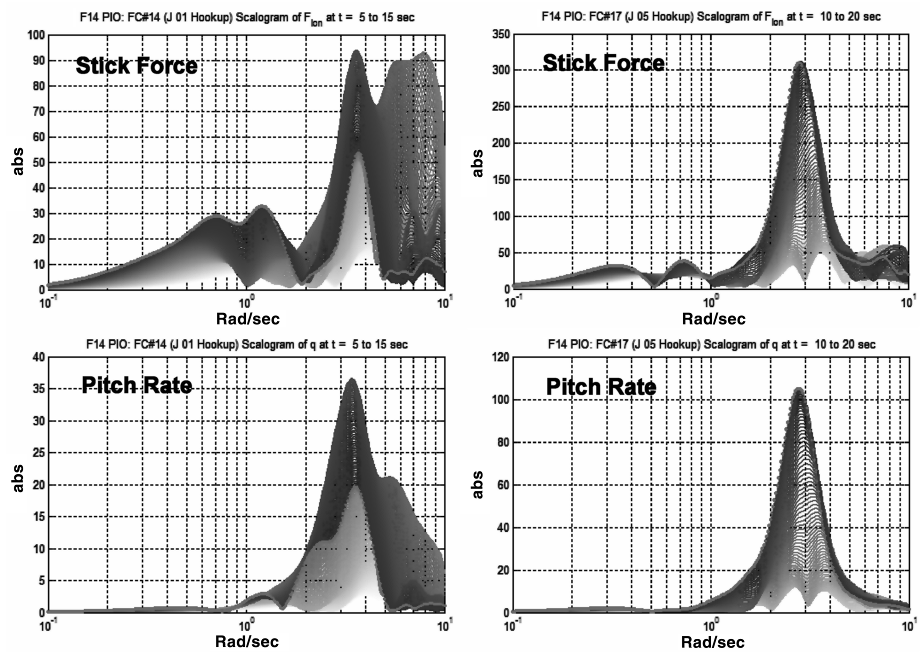


a) Windowed fourier transform



b) Wavelet transform

Fig. 9 Transforms of an example time series.



a) Run J_01, SAS-On, No PIO **b) J_05, BUFCM-High, Severe PIO**

Fig. 10 Stick force and pitch rate scalograms for two probe-and-drogue in-flight refueling cases.

shown here with the current time slice (i.e., the 15 s point in Fig. 10a and the 20 s point of Fig. 10b) displayed as a series of dots. As time moves back to the earliest interval displayed on the plot, the "lines of persistence" change from dark to light.

It has been shown previously [10] that during a PIO event, input and output power coalesce in the neighborhood of the PIO frequency. This is certainly the case here as the very distinct peaks in both stick force and pitch rate power occur at approximately 2.8 rad/s. Looking at the faintest lines of persistence that correspond to the earliest time slice of 10 s (just before the onset of PIO), the input and output power are significantly lower, an order of magnitude lower, than that observed for the last time slice of 20 s (within the PIO). From the onset of the PIO around 12 s, the input and output power increase rapidly to the peak values and remain there throughout the PIO event.

The SAS-on case, on the other hand, displays a different character. The final time slice (15 s) displayed in Fig. 10a occurs post-probe-and-drogue hookup. The actual hookup occurs several seconds earlier, where dark persistence lines attain their peak values. Unlike the severe-PIO case, there is no single dominant frequency seen in the pilot's stick force input. There is a dominant pitch rate frequency around 3.3 rad/s, but there is significant power in a band of higher frequencies as well.

A most important observation from the preceding comparison is that the resulting peak input and output power are approximately three times smaller than that seen for the severe-PIO case. Further exploring this result, the peak input and output power was computed for all of the runs identified in Table 2. The results are shown in Fig. 11. The trend observed for the Fig. 10 examples is repeated here for the remaining five cases. That is, the three severe-PIO cases all have peak input and output power values that are three times higher than those observed for the no-PIO cases.

This result reflects a key element of the PIO signature that can be exploited in a flight test control room environment. Using scalograms that are computed in real time, the signals identified in this paper that provide clear indicators of PIO can be monitored throughout the flight. These signals include pilot command inputs and associated aircraft accelerations, rates, and attitudes. Given baseline power levels expected for a given task, large deviations from these expected values can be flagged and a "knock-it-off" call can be given. Some work will be required to establish the baselines. Experience and identified values from previous flight tests can be used initially. Such measures can be strengthened when used in

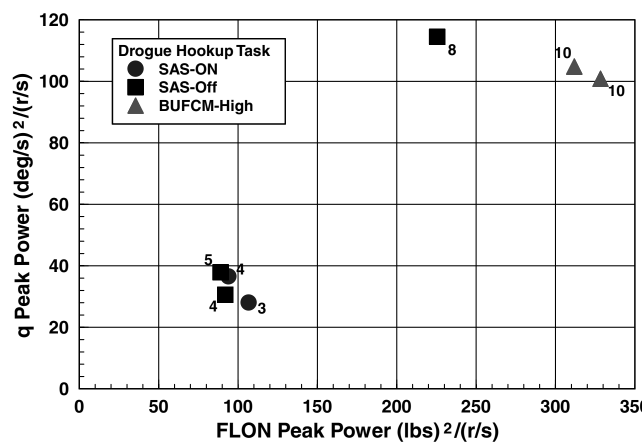


Fig. 11 Peak output power (pitch rate *q*) vs peak input power (longitudinal stick force, FLON) for F-14 probe-and-drogue in-flight refueling cases (numbers next to symbols are Cooper–Harper Handling Qualities Ratings for the configurations).

conjunction with other tools such as ROVER that are looking for complimentary measures of the PIO signature.

VI. Conclusions

The argument has been made in this paper that PIOs continue to persist at least partly because the signature or nature of PIO often goes unrecognized, whether in the design process, flight test, or normal operations. That is, it goes unrecognized until a catastrophic or near catastrophic event occurs. To lay the groundwork for a road forward, a definition of PIO has been introduced herein: PIO is a sustained or uncontrollable unintentional oscillation in which the airplane attitude, angular rate, normal acceleration, or other quantity derived from these states, is approximately 180 deg out of phase with the pilot's control inputs, and in which the amplitude of pilot control inputs, aircraft response, or both, is large enough to be intrusive on normal flying. There must also be recognition that there are different types of PIO of varying intensity. Not all PIOs are severe enough to ground an airplane, however, all PIOs do require comprehension, so that the likelihood of a catastrophic event is diminished. To this end, the following elements that encompass the PIO signature should be considered throughout the life of the airplane, even late in its operational life, as missions are expanded and new loading configurations are added:

1) Closed-loop pilot-vehicle system: Comprehension of the interacting elements of PIO is paramount to recognizing the PIO signature. PIO shows itself in those closed-loop scenarios that can result in reduced pilot–vehicle system stability margins, such as the probe-and-drogue aerial refueling task explored in this paper. The pilot typically responds with higher gain inputs in such scenarios due to the nature of the task, environmental conditions, or an unpredictable aircraft response, such as that associated with actuator rate limiting.

2) Oscillations: PIO is by definition an oscillatory response; however, the presence of oscillations alone does not indicate PIO. It is important that oscillatory behavior in which the airplane is responding as intended to pilot inputs not be identified as a PIO. Look for the complete PIO signature before making such judgments.

3) Control inputs: For a given task, control inputs are generally significantly higher in amplitude in a PIO when compared with a non-PIO case.

4) Body axis rates: For a given task, body axis rates are generally significantly higher in amplitude in a PIO when compared with a non-PIO case.

5) Input/output phase: In a PIO, a key aircraft response will be at least 180 deg out of phase with the pilot, typically attitude or acceleration. If this out-of-phase character is not present, then it is not a PIO, even if other elements of the PIO signature are present.

6) Large increase in input/output power: As shown in this paper, there is a dramatic increase in input and output power when a PIO is encountered. For the probe-and-drogue refueling task, this increase was a factor of three times higher when compared with non-PIO hookups. Peaks in input/output power are centered at PIO frequency.

Be prepared for PIO, look for its signature using onboard detection schemes or real-time control room tools, comprehend the nature of the event, and make necessary improvements to the vehicle if PIO occurs. Use the PIO signature and validated criteria to identify increased susceptibility to PIO. Make configuration changes when required. With better recognition and comprehension of PIO, the future may become more PIO free.

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