AIAA-2000-4316

VISUAL, CRUISE FORMATION FLYING DYNAMCS

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ABSTRACT

In order to develop a performance baseline for future cooperative, dual aircraft operations, an experimental evaluation of pilot-in-the-loop, dual aircraft system dynamics in visual meteorological conditions (VMC) was undertaken to examine pilot response time and system frequency response characteristics. Stanford University flew a Beechcraft Queen Air and a Cessna Caravan in cruise formation flights to gather system data. Using this data along with system identification tools, models have been created to quantify the human-in-the-loop performance of cooperative dual aircraft flight as a function of lead aircraft attitude and initial separation.

INTRODUCTION

With precise positioning in the form of differential GPS and commercial air-to-air data links becoming widely available for aircraft in the next five to ten years, it will be possible to precisely position and control multiple aircraft flying in close proximity to each other. Currently, all proximate flying, designated here as "cruise" formation flying (greater than 100 ft separation), is performed with a pilot controlling the aircraft, although in the future, multi aircraft concepts such as the military's Uninhabited Combat Air Vehicle[1] and micro Uninhabited Air Vehicle[2], as well as the Federal Aviation Administration's closely spaced parallel approach procedures[3] may rely exclusively on autonomous, distributed control systems. Other researchers have investigated optimal performance of close formation flying[4,5]; however, there has been little experimental research on the characteristics of VMC, piloted, cruise formation flying.

In order to develop a performance baseline for cruise formation flight operations, an experimental evaluation of pilot-in-the-loop, dual aircraft cruise formation flying system dynamics in visual meteorological conditions (VMC) was undertaken to examine pilot response time and system frequency response characteristics.

In order to determine the trail pilot's reaction time as a function of lead aircraft maneuver and initial separation, various maneuvers such as roll inputs, pitch changes, and wings-level yaw were performed by the lead aircraft. The trail pilot's task was to attempt to maintain the current separation distance by following the lead's maneuver. These maneuvers were then repeated at closer range in order to model the pilot's response also as a function of initial separation distance.

To quantify the pilot-in-the-loop cruise formation flying system dynamics, the lead airplane acts as the input to the system, while the trail aircraft response is the output. Parameter identification techniques may then be used to model the overall dual aircraft system dynamics. Both single input/single output and multiple input/single output models were developed.

FLIGHT TEST SETUP

Three formation flights were performed using a Beechcraft Queen Air as the maneuvering, lead airplane and a Cessna Caravan as the responding trail aircraft. The same pilots flew each airplane for all flights. In addition to the three formation flights, a solo parameter identification flight with the Caravan was performed to gather dynamic response data.

INSTRUMENTATION

The Queen Air and Caravan both had a prototype Wide Area Augmentation System (WAAS) installed to produce differentially corrected GPS position and velocity. The WAAS system broadcasts corrections from a geosynchronous satellite at the rate of 1 Hz on the L1 frequency (1575 MHz). A Novatel Millenium receiver passed GPS and WAAS correction messages to a Stanford University algorithm which then calculated corrected aircraft position and velocity at a rate of 4 Hz. All of these flights were performed prior to the removal of selective availability from the GPS signal. During the formation flights, the Queen Air also had a Honeywell HG1150 Inertial Navigation System (INS) installed which recorded roll, pitch, and heading angles at up to 50 Hz. For the parameter identification flight, the INS was installed on the Caravan. Control surfaces were not instrumented nor were the yoke or rudder pedals. Video footage was acquired during the second formation flight.

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FORMATION FLIGHT PROCEDURE

The nominal Caravan test conditions were 4000 ft MSL and 130 kts. The Queen Air flew at 3900 ft at the Caravan's 9 to 11 o'clock position. A block of up to seven test points were given to both pilots and the Queen Air pilot randomly chose the order. Each test point was performed twice (not consecutively) at each separation distance. Nominal initial lateral separation distances tested were 2500, 2000, 1700, and 500 ft. In order to ensure safety, but avoid predictable maneuver times, "ready for maneuver" calls would be confirmed by both pilots and at some time subsequent to those calls, typically five to twenty seconds later, the lead pilot would maneuver the Queen Air. Roll and yaw maneuvers discussed in the following sections are for maneuvers only toward the trail aircraft.

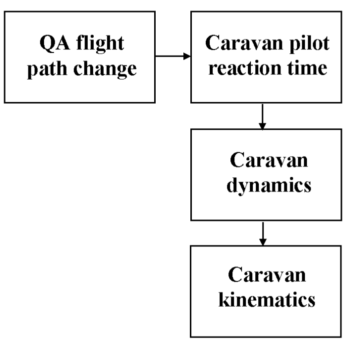
PARAMETER IDENTIFICATION FLIGHT

Data on the Caravan's dynamic response were gathered in order to identify appropriate time constants and frequencies. Step and hold inputs as well as doublets were performed to gather data on roll mode time constant, steady state roll rate, dutch roll characteristics, and pitch dynamics. Data on long period phenomena such as phugoid and spiral divergence were not obtained.

PILOT RESPONSE TIME

A block diagram of the dual airplane formation flying system is presented in Figure 1. With instrumented yokes, the pilot response time would simply be the time difference between the pilot yoke inputs. The aircraft used in this experiment did not have instrumented yokes, and thus, the aircraft response must be separated from the pilot response analytically.

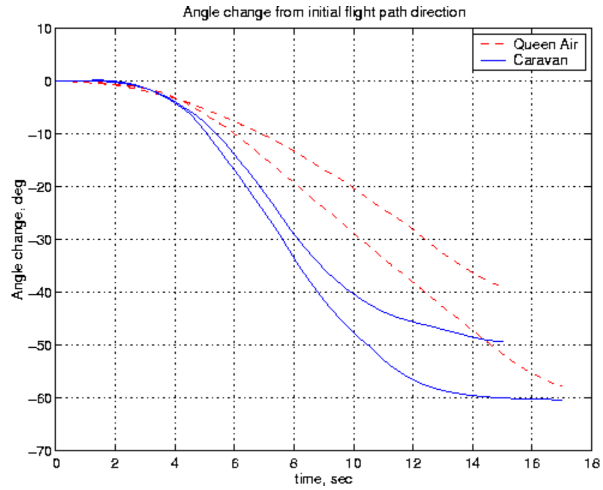
Figure 1. Block diagram of formation flying dynamics



ROLL ANGLE CHANGE MANEUVERS

As an example of removing aircraft dynamics from the total system response, let us examine flight test maneuvers that had a significant roll angle change component: rolls (15 and 30 deg) and climbing turns. Only turns *toward* the flight path of the trail aircraft were analyzed. A representative ground track is presented in Figure 2, where the x-axis is time and the y-axis is change in ground track angle, which was derived from WAAS-based instantaneous velocity measurements. In order to back out the pilot's response, the roll dynamics of the Caravan must be accurately modeled and the various errors sources determined and quantified.

Figure 2. Ground tracks during two roll maneuvers



Caravan Roll Dynamics

One flight was performed in order to estimate the dynamic response of the Caravan at the test conditions of the formation flight: 130 knots and 4000 ft. Step inputs and doublets were used to excite the various modes, with time history data being recorded at approximately 50 Hz by the Honeywell HG1150 INS. Based on the data obtained, the roll mode time constant and steady state roll rate were determined, which in turn were used to generate predicted flight path trajectories.

Beginning with the linearized, small perturbation aircraft dynamic equations of motion[6], assuming x-z plane symmetry and simple roll without perturbation in the other axes:

$$\frac{\partial L}{\partial \delta_a}\Delta\delta_a + \frac{\partial L}{\partial p}\Delta p = I_x \Delta\ddot{\phi} \quad (1)$$

where L is lift force, δ_a is aileron deflection, p is roll rate, I_x is moment of inertia in the x-plane, and ϕ is bank angle. $(\partial L / \partial \delta_a)\Delta\delta_a$ is the roll moment due to the deflection of the ailerons and $(\partial L / \partial p)\Delta p$ is the roll-damping moment. Eqn 1) may be rewritten as

$$\tau\Delta\dot{p} + \Delta p = -\frac{L_{\delta a}\Delta\delta_a}{L_p} \quad (2)$$

where

$$\tau = -\frac{1}{L_p} \qquad L_p = \frac{\partial L/\partial p}{I_x} \qquad L_{\delta a} = \frac{\partial L/\partial \delta_a}{I_x}$$

and τ is defined as the roll mode time constant. For a step change in aileron deflection, Eqn 2) may be analytically solved to produce

$$\Delta p(t) = -\frac{L_{\delta a}}{L_p}(1 - e^{-t/\tau})\Delta\delta_a \qquad (3)$$

As $t \to \infty$, the steady state roll rate, p_{ss}, becomes

$$p_{ss} = \frac{-L_{\delta a}}{L_p}\Delta\delta_a \qquad (4)$$

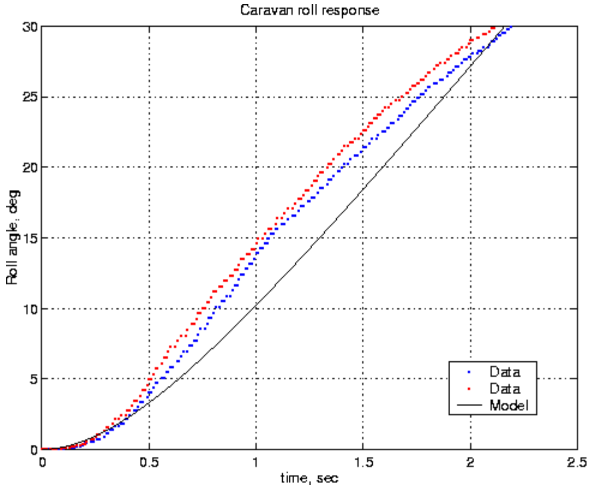
Substituting this expression into Eqn 3) results in an expression for roll rate as a function of time with only two unknowns: the roll mode time constant and the steady state roll rate:

$$\Delta p(t) = p_{ss}(1 - e^{t/\tau}) \qquad (5)$$

From flight test data, using an approximate step input in aileron deflection, a time history of roll rate may be generated from which p_{ss} and τ may be determined.

For the flight test, an approximately constant amplitude step input in aileron was performed[7] by marking the desired yoke input on the yoke housing. Time histories of two roll events are shown by the dotted lines in Figure 3. From this time history, a steady state roll rate of 18 deg/s and a time constant of 0.5 sec were calculated, which produced the modeled roll response (the solid line).

Figure 3. Caravan roll response



Modeled Roll Dynamics

The modeled roll mode time constant and various steady state roll rates were then combined with the kinematic equations presented below to create a ground track of the Caravan without pilot delay.

$$\phi(t) = \int p_{ss}\left(1 - e^{\frac{t}{\tau}}\right)dt$$

$$\psi(t) = \int \frac{g}{V}\tan\phi(t)dt$$

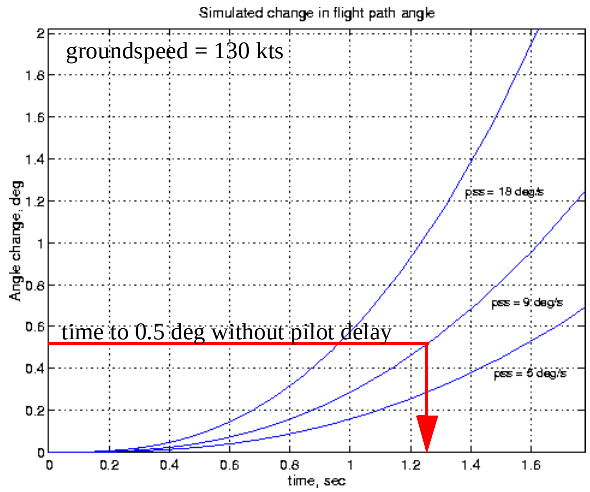
$$V_y(t) = \int V\sin\psi(t)dt \qquad (6)$$

$$Vx(t) = \int V\cos\psi(t)dt$$

$$\text{ground track angle} = \operatorname{atan}\frac{V_y}{V_x}$$

Using this modeled ground track for a Caravan at 4000 ft and 130 kts, one can determine the time to a flight path angle change of 0.5 deg as shown in Figure 4.

Figure 4. Modeled Caravan ground tracks



As an example, without pilot delay and a steady state roll rate of 9 deg/sec, the modeled Caravan time to a flight path angle change of 0.5 deg is 1.25 sec, as shown in Figure 4. The total time to 0.5 deg during the formation maneuver presented in Figure 2 is approximately 3 sec. Using the simple formula in Eqn 7),

$$\text{pilot delay time} = \text{total time to 0.5 deg} \\ -\text{modeled Caravan time to 0.5 deg} \qquad (7)$$

the calculated pilot delay time would be 3 sec - 1.25 sec = 1.75 sec.

The 0.5 deg flight path angle change was chosen as the critical point for two reasons: 1) the signal to noise ratio of WAAS velocity could clearly capture this change in angle and 2) it is more accurate to estimate pilot response time early in the maneuver before other factors such as wind, unmodeled aircraft dynamics and station-keeping factors all become significant.

Since roll rate was not available on the trail airplane during the formation flights, an estimate of 9 deg/s was used for modeling purposes. This is based primarily on the average lead aircraft roll rate of 8 to 9 deg/s. Due to the assumption of a steady state roll rate of 9 deg/s, errors of +0.3 sec and -0.1 sec are possible which allow for the range of actual roll rates to be as low as 6 deg/s and as high as 12 deg/s. This effectively translates to a pilot delay time error of +0.1/-0.3 sec.

WAAS Velocity Accuracy

The following table presents WAAS velocity errors over 15 hours of data taken from a static antenna located at Stanford University. Relative to the ground speed of about 67 m/s, the error in ground track caused by the inaccuracy of WAAS velocity is negligible.

Table 1. WAAS velocity errors

	68th percentile (m/s)	95th percentile (m/s)
East	0.042	0.142
North	0.037	0.137
Up	0.098	0.278

Determining the Start of the Lead Maneuver

The start of the lead aircraft's maneuver was defined to be the point at which bank angle begins to change from its steady state value just prior to the maneuver. The determination of the time of roll angle change was performed manually and is estimated to be accurate to within +/- 0.1 sec.

Summary of Roll Response Errors

Not discussed, but error estimates that must also be included in the final synopsis are errors due to wind speed versus ground speed (+/- 0.05 s) and those due to differing time tags on the various sensors (+/- 0.05 s). Summing the components, the maximum error bound on pilot response to roll maneuvers is then +0.3/-0.5 sec.

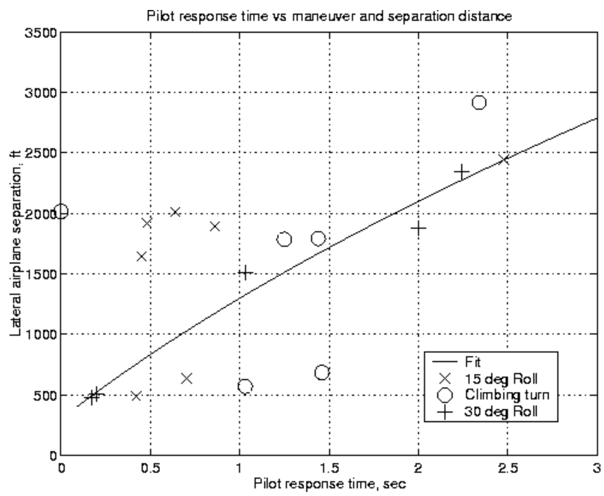
Summary of pilot response to roll maneuvers

Figure 5 presents pilot response time as a function of separation distance and type of roll maneuver: roll to 15 or 30 deg and climbing turns. Below 2000 ft separation, the roll into trail maneuver generally shows no particular trend; the pilot usually responds in less than 2 sec, with an average time of about one second. For the case of the roll to 30 deg bank angle, there is a trend with distance and the solid line shows the best fit for the data. The polynomial equation for the curve fit is expressed as

$$t = 1.37024e^{-7}d^2 + 7.81378e^{-4}d - 0.24615 \qquad (8)$$

where d is separation distance in feet and t is predicted pilot delay time in seconds.

Figure 5. Pilot response times versus rolling maneuver and separation distance



CLIMB AND DESCENT MANEUVERS

Climb dynamics are a function of not only pitch and pitch rate, but static stability and angle of attack, neither of which could be measured. An approach using the conservation of energy was employed.

Determining Aircraft Pitch Response

For a given initial specific energy, the time to reach some predefined change in height may be measured by performing step inputs in elevator. This time would then be subtracted from the combined pilot/aircraft response to isolate the pilot response when responding to a climb or descent maneuver during formation flying. This method is reasonable for up to three seconds after the climb or descent is initiated. After that, induced drag becomes significant and conservation of energy is no longer valid. Specific energy, or energy per unit mass, is defined by

$$\frac{E}{m} = \frac{1}{2}V(t)^2 + g\Delta h(t) \qquad (9)$$

where V is the airspeed. The initial airspeed was known and from this, one may calculate the initial specific energy just prior to the maneuver:

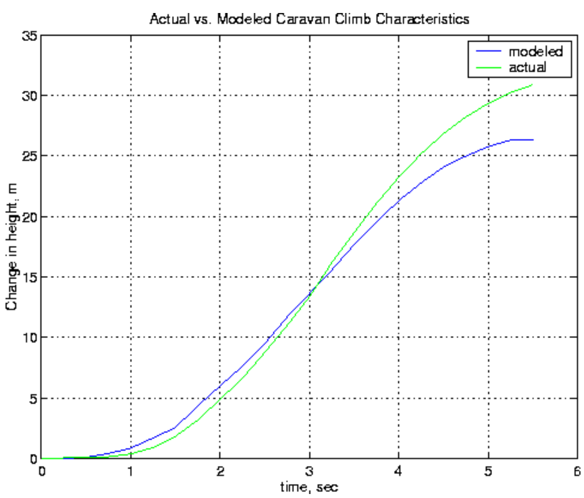
$$\frac{E}{m} = \frac{1}{2}V_i^{\ 2} = \text{constant} \qquad (10)$$

Since the initial airspeed was the same for each maneuver, this expression will be the same regardless of change in aircraft weight, since energy required to reach the initial airspeed will increase proportionally. In order to calculate V(t), the wind speed is determined by subtracting the known initial airspeed from the calculated three dimensional WAAS groundspeed. At each time step then, the wind speed is removed from the calculated groundspeed before determining change in altitude, resulting in

$$\Delta h(t) = \frac{1}{g}\left(\frac{1}{2}V^2{}_i - \frac{1}{2}(V_g(t) - V_{wind})^2\right) \qquad (11)$$

This calculated change in altitude may be compared with actual change in altitude measured by WAAS during step inputs in elevator. Figure 6 shows a comparison of actual versus calculated altitude change.

Figure 6. Modeled versus actual change in height during step elevator input



For the first three seconds of the maneuver, the model matches the data within 0.2 sec at the 2 m mark, giving a confidence check on the WAAS vertical position measurement. Using the data, the time to a height change of 2 meters exclusive of pilot delay is 1.53 seconds. This time will then be subtracted from the time to 2 meters during the formation flying maneuver.

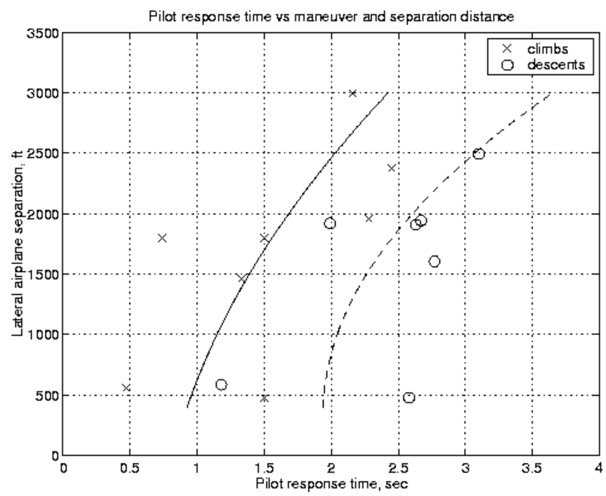
The additional parameter which will affect the delay time is the static margin, which is a function of aircraft center of gravity. A weight and balance was performed for each flight configuration. The change in center of gravity location was so small that this effect will be neglected for the pilot response studies.

A similar method was employed for the pushover maneuver. The time to a change in height of 2 meters was determined to be 1.15 seconds. Two meters was chosen as the critical height change to minimize the increased induced (or reduced) drag effect.

Pilot Response to Climb and Descent Maneuvers

Pilot response time as a function of separation distance and pitch maneuver is shown in Figure 7. Approximate error is +0.10/-0.25 sec. A second order polynomial curve fit is also presented for climbing and descending maneuvers. One can see that the response to a climb is quicker than to a descent, but that responses to both do slightly increase with increasing separation distance.

Figure 7. Pilot response to pitch-type maneuvers



Climb response may be represented by the second order polynomial shown in Figure 7 and written as

$$t = 1.03042e^{-7}d^2 + 2.25537e^{-4}d + 0.81896 \quad (12)$$

where 't' is pilot response time in seconds and 'd' is separation distance in feet. Pilot response to pushovers may be expressed as

$$t = 2.4289e^{-7}d^2 - 1.6838e^{-4}d + 1.96913 \qquad (13)$$

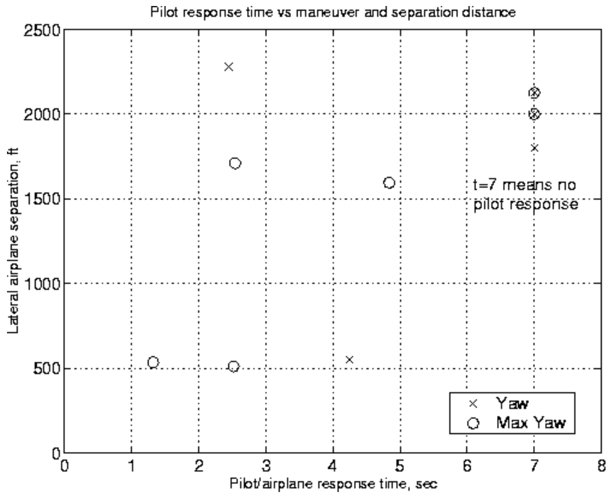
WINGS-LEVEL YAW MANEUVERS

The final class of maneuver performed in formation flying was a wings level yaw, with varying maximum yaw angle. Although such maneuvers are rarely performed during normal flight operations, they may represent the effect of an aircraft drifting or a sideslip maneuver during a glideslope recapture.

Aircraft/Pilot Response to Yaw

In the case of yaw, the pilot was not accustomed to making a pure rudder input as a response and would typically respond with a combination of roll and yaw. Since the response was variable, it is very challenging to accurately remove the airplane response without an INS on the Caravan to record aircraft attitude. For this analysis then, it is presumed that the pilot made a roll-only input, thus enabling us to use the procedure outlined for the roll only maneuvers. Using these results, Figure 8 presents the pilot response characteristics to a 1/4 or 1/2 (max) rudder pedal yaw input by the lead aircraft. Error bars around the data points are approximately -0.4/+0.4 sec due to the presumption of a roll-only response.

Figure 8. Pilot response to wings level yaw maneuvers



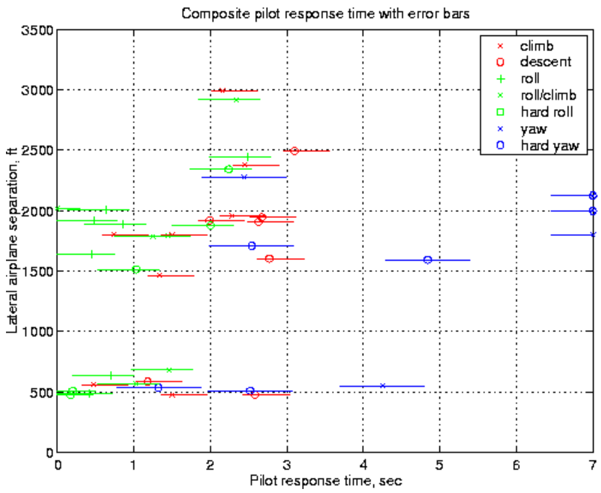
The feature unique to this series of maneuvers is that the trail pilot did not respond to five out of the eleven maneuvers. Although the pilot responded to all of the maneuvers occurring around 500 ft separation, at distances greater than 1500 ft, he could only perceive changes in either attitude or spacing 37.5% of the time. In this case, it appears that maneuver maximum amplitude is critical to successful yaw identification, a phenomenon that was not exhibited by the roll or climb/descent maneuvers.

SUMMARY OF PILOT RESPONSE TIMES

A composite graph of the data from the previous three sections is presented in Figure 9. Error bars around each test point delineate the possible range of pilot response.

One can see that the pilot generally responds the fastest to bank angle changes, followed by pitch changes, and is the least responsive to heading angle changes. Both pitch and heading angle changes exhibit some sensitivity to separation distance; however, pilot response to bank angle change at separation distances less than 2000 ft is consistently less than 2 seconds. Above 2000 ft, pilot response is slower by half a second, but the quantity of data above 2000 ft is significantly lower than that below 2000 ft and additional data should be obtained before direct comparison made.

Figure 9. Composite of pilot response times with error estimations



CONCLUSIONS FOR PILOT RESPONSE

The preceding analysis suggests that a pilot discerns bank angle change more quickly than either pitch or yaw angle changes. This response time averages about one second for separations less than 2000 ft. Response to a climb maneuver is faster than that to a descent and is probably because pitching the nose up to climb is a more natural response than pushing over in order to descend. Pilot response to a wings-level yaw maneuver is between one and five seconds, but frequently there is no response at all.

This series of flights forms a basis for analyzing pilot response; however, additional issues such as individual differences in pilot response, differences in lead aircraft maneuver entry characteristics, and atmospheric factors such as sun angle, background terrain, and cloud coverage have not been addressed.

CRUISE FORMATION FLYING SYSTEM DYNAMICS

In addition to basic pilot response time, the dynamics of a multiple aircraft, pilot-in-the-loop cruise formation flying system were analyzed. These models may then be used as a basis for specifying the performance of future, unpiloted, multiple aircraft cruise formation flying systems. The system model will also indicate the pilot's ability to accurately track and respond to the maneuver of an adjacent aircraft, thus creating an analytical model of the human collision detection and resolution algorithm. A complete description of the parameter identification methods follow using example data gathered from a lead aircraft roll towards the trail at various separation distances.

THE PARAMETER IDENTIFICATION MODEL

The example data sets chosen for this case were the 15 deg roll into the trail airplane from an initial separation distance of 1700 ft. Two data sets were taken at a 4 Hz update rate, one with which to estimate the parameters and the second for model validation. Because of the excellent signal to noise ratio of the system (approximately 100:1), the error is virtually zero and a second order Auto-Regression with eXtra inputs (ARX) model[6] with a two-step time delay exhibited the best fit for the physical system. The ARX model form may be described by[8]

$$Ay = Bu + e \tag{14}$$

which results in a discrete transfer function of the form

$$G(z) = \frac{b_0 z + b_1}{z\left(z^2 + a_1 z + a_2\right)} \tag{15}$$

for a second order model with a two-step time delay. Using a Tustin approximation, the model was then converted to the continuous time domain.

SINGLE INPUT VS. MULTI-INPUT MODELS

Given the importance of controlling the spacing between two aircraft, the first parameter identification was performed using the flight path angle change of each aircraft in a single input/single output (SISO) model. This model is simple and the data readily available to any aircraft equipped with WAAS or other precise positioning system. With selective availability now turned off, even stand-alone GPS may be sufficient for this analysis. However, given the assumption that the pilot senses bank angle change as the first indication of a roll maneuver, formation flying may be better modeled by using multiple inputs, i.e., position and bank angle. This situation creates a multi input/single output (MISO) system where the lead aircraft's flight path angle change and bank angle are the inputs and the trail aircraft's flight path angle change is the output. The MISO system was also modeled using a second order ARX model.

Residual Error Analysis

The residual error is defined as the difference between the actual and modeled system output. In order to determine the "goodness" of the model, the residuals should be a normally distributed, white noise process with zero mean that is uncorrelated with past inputs.

To determine if the residuals are a white noise process and uncorrelated with past inputs, an output auto-correlation of the residuals and a cross-correlation of the residuals with the inputs, respectively, may be performed. The auto-correlation is defined as

$$\hat{R}_{\varepsilon} = \frac{1}{N}\sum_{t=\tau}^{N} \varepsilon(t)\varepsilon(t-\tau) \tag{16}$$

and the cross-correlation is

$$\hat{R}_{\varepsilon u} = \frac{1}{N}\sum_{t=\tau}^{N} \varepsilon(t)u(t-\tau) \tag{17}$$

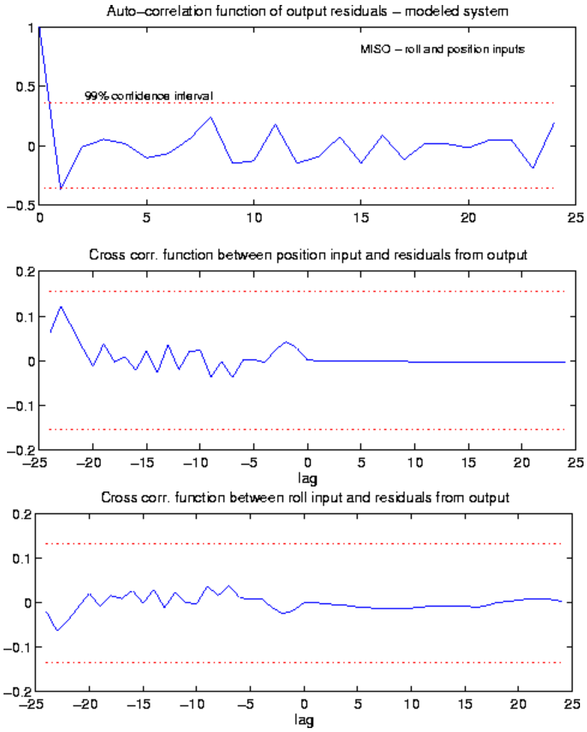
To determine if the residuals are "small enough", one may define a confidence interval for a normal distribution whereby if all of the residuals fall within the 99% confidence interval, one may say that the residuals are gaussian and all fall within 3 sigma of the mean.

Two SISO cases were modeled: 1) lead aircraft flight path angle change input with trail aircraft flight path angle change output and 2) lead roll angle input and trail flight path angle change output. One MISO case was analyzed: lead flight path angle change/roll angle inputs and trail flight path angle change output. Not only does a model have to exhibit acceptable residual behavior for the data subsuming the model, but the residuals on the validation data set must also be acceptable. The auto- and cross-correlations for the MISO case using the data set used to create the model are presented in Figure 10. There are two cross-correlation figures, one for the flight path angle input and the second for the roll input. All of the data lies within the 99% confidence interval, from which we may conclude that the model adequately captures the highest order dynamics and accurately models the system delays.

The residual analysis of the validation data set showed that this model also adequately captured the dynamics of another roll maneuver at the same separation distance. From this we may conclude that the ARX MISO model adequately captures the formation flight dynamics of a general right roll maneuver at 1700 ft.

The residual analysis for the two SISO cases showed slightly degraded modeling performance from the MISO case.

Figure 10. Auto- and cross-correlation functions for MISO case, modeled data set



Model Output Performance

Another means to assess the goodness of the ARX model is to compare the predicted system output with actual system output and examine the average error. Figures 11, 12 and 13 present modeled and actual output data for the two SISO and one MISO case. In each plot, there are two data sets: the data used for creating the model and the data used for validation. The same ARX model is used to create both predicted system outputs.

The “goodness of fit” number presented in each graph is the mean square fit, calculated by

$$\text{fit} = \text{norm}(\hat{y} - y)/(\sqrt{N}) \qquad (18)$$

where $\hat{y}$ is the modeled output value, y is the actual output value, and N is the number of output elements. The SISO models were better at predicting the behavior of the data set used for modeling (‘model’ in the plot); however, the MISO model performed better on the validation data (‘validated’).

Figure 11. SISO model: lead flight path angle change.

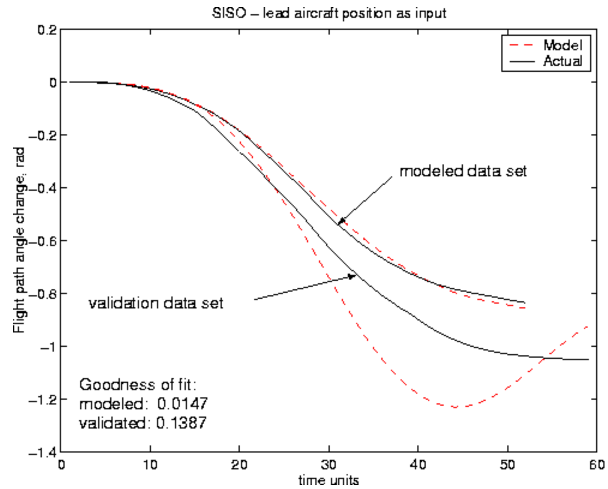


Figure 12. SISO model: lead aircraft roll angle change.

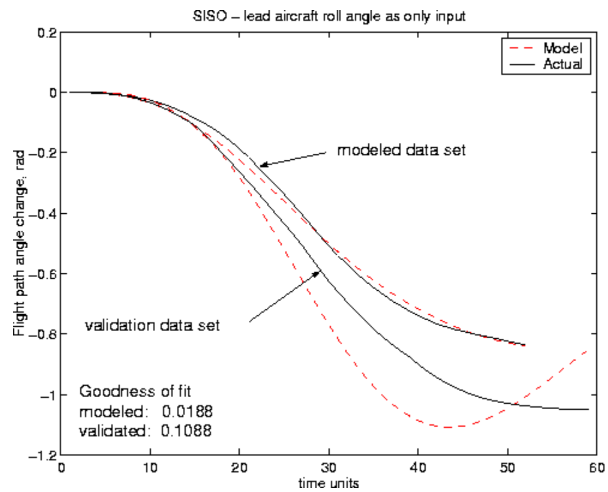
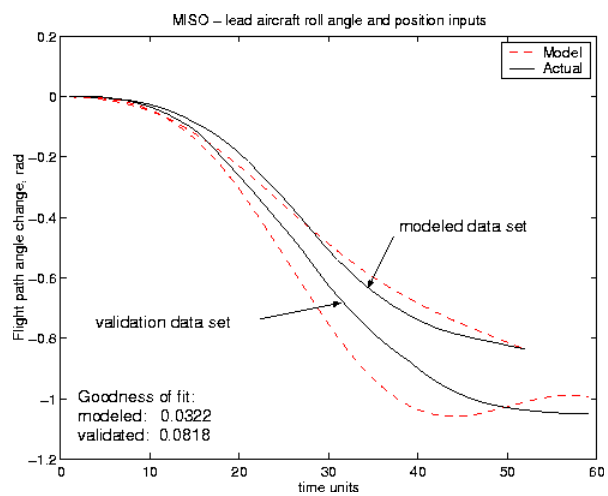


Figure 13. MISO model: lead aircraft flight path angle change and roll angle change



CONCLUSIONS OF SYSTEM MODELING

Overall, the reaction of a pilot and aircraft to another aircraft performing a roll into the trail airplane may be modeled as a second order system with pilot time delay. The signal to noise ratio for the system is on the order of 100:1 and permits use of the relatively simple ARX parameter identification model assuming gaussian noise properties.

MISO and SISO models were also applied to the other roll separation distances, the climb response, and the yaw response. In the case of roll and yaw, the MISO model was superior; however, the SISO model using flight path angle change as the input may be adequate for predicting system behavior and requires less information. In the case of climb, the SISO case using pitch angle as the input exhibited the best behavior. This is likely due to the less accurate WAAS altitude measurement used in the other models.

FORMATION-KEEPING CHARACTERISTICS

Once a pilot has determined the intent of the lead aircraft, how well can he or she follow the lead's maneuver? Obviously, for formation flight at distances closer than 50 feet or so, the trail pilot must follow the lead exactly or risk collision. For distances larger than that, there is more uncertainty in diagnosing the intentions of the lead as well as more airspace in which to maneuver.

Formation keeping characteristics will be quantified in terms of the damping ratio and natural frequency of the trail aircraft's response to roll, pitch, and yaw maneuvers. These numbers were generated from the parameter identification method outlined in the previous section for the SISO case with lead aircraft flight path angle change being the sole input. From the damping ratio, one may infer how well the pilot/aircraft combination can track the maneuver of the lead aircraft. The natural frequency of the system is indicative of the pilot input frequency as well as the aircraft dynamics.

For this test, the pilot was instructed to "attempt to maintain initial separation distance" and to do so, as much as possible, by matching inputs. For instance, if the lead aircraft is executing a yaw maneuver, the trail airplane should also execute a yaw maneuver.

PILOT TRACKING CHARACTERISTICS

At each of the test points, the lead pilot provided a step input maneuver for approximately ten to twenty seconds in one of the different axes: roll, pitch or yaw. The task of the trail pilot was to follow the maneuver and maintain the initial separation distance. As one may see from the following plots, the trail pilot responds quite differently to the different axes. For instance, Figure 14 presents a time history of a roll maneuver. The response of the Caravan (the trail aircraft, solid lines) is well damped and the pilot is able to formation-keep on the Queen Air (dashed lines) well. However, when the lead input is a wing's level yaw maneuver, the trail aircraft ground track is much more oscillatory, as shown in Figure 15. The implication is that either the pilot or the pilot/aircraft dynamics combination prevent a well damped response to the yaw maneuver. These characteristics may be further quantified in the frequency domain.

Figure 14. Time history of two roll maneuvers at 500 ft

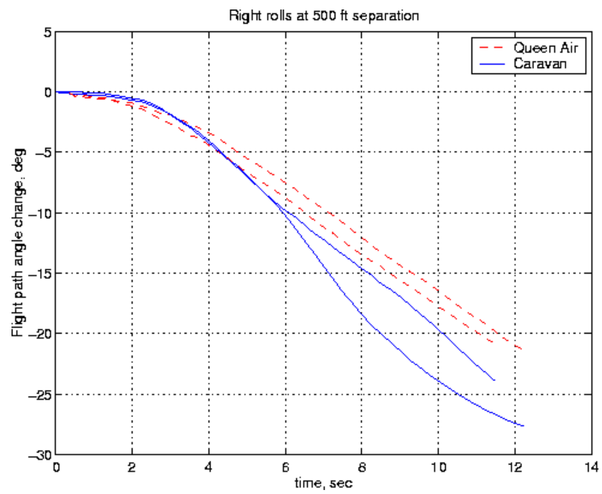
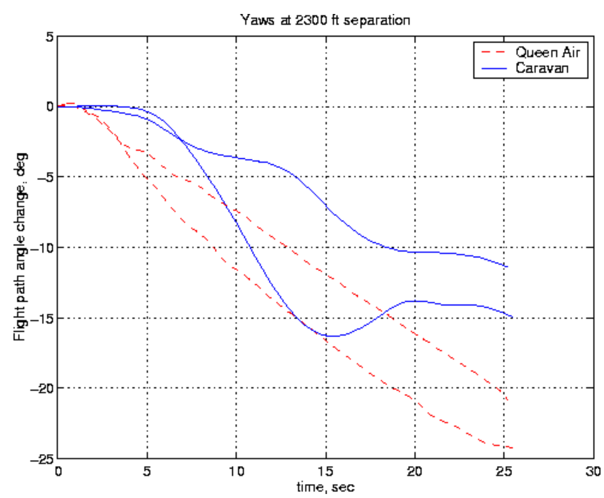


Figure 15. Time history of two yaw maneuvers, 2300 ft

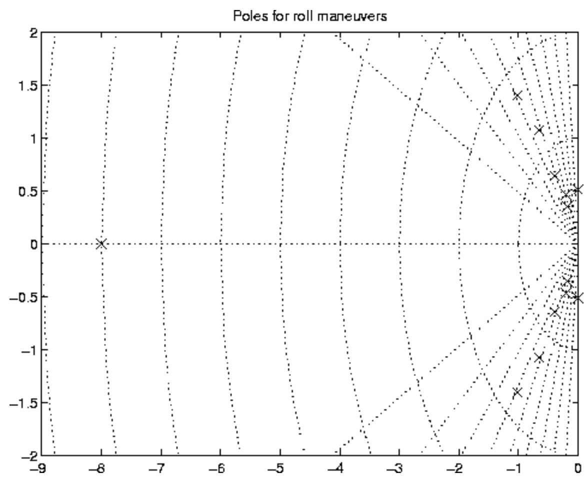


ROLL TRACKING CHARACTERISTICS

The poles of the open loop formation flying system for roll maneuvers at various separation distances are presented in Figure 16. Roll response is a third order system consisting of a pilot delay time and an oscillatory characteristic. Note that there are overlapping poles at s = -8. Except for the hard right roll at 480 ft, all of the poles have damping ratios between 0.5 and 0.6. The natural frequencies are between 0.3 and 1.1 rad/s, translating to a period of 20.9 sec and 5.7 sec, respectively. In general, the pilot must adjust his formation-keeping position more frequently at further separation distances. Intuitively, this may be due to the need to re-estimate closure rates more frequently and adjust accordingly.

The fast pole at s = -8 rad/sec is attributable to the pilot response time, corresponding to a delay of 0.25 sec, which is very close to the calculated delay time of 0.3 sec at 1700 ft. It is not identical due to the fact that pilot delay is also embedded in the second order response.

Figure 16. Pole locations for roll maneuvers at various separation distances



YAW TRACKING CHARACTERISTICS

Since the pilot neglected to respond to roughly half of the yaw test points, there are two possible valid models then for yaw tracking: one that has zero response and one that is third order with undamped oscillations, as shown in Figure 17. The period of the oscillatory response is approximately 18 sec. Undoubtedly, the dutch roll mode is excited, but the primary factor influencing the light damping ratio of the formation-keeping response is the strong directional stability of the Caravan[9]. The large vertical tail exerts a restoring moment whenever the pilot reduces pressure on a rudder pedal. This does not account completely for the oscillations, but does exacerbate any change in pilot input.

CLIMB TRACKING CHARACTERISTICS

The formation-keeping characteristics of a climb are presented in Figure 18 and demonstrate that the system is primarily composed of pilot delay and a translation mode. If modeled as a second order system, the damping ratio and period is approximately 0.62 and 14 sec, respectively. The short period dynamics, with a time constant of 3 sec and very small amplitude, are not a factor.

Figure 17. Frequency response to a wing's level yaw

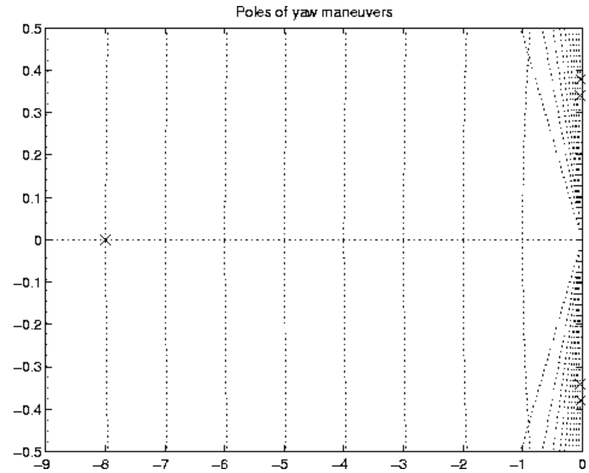
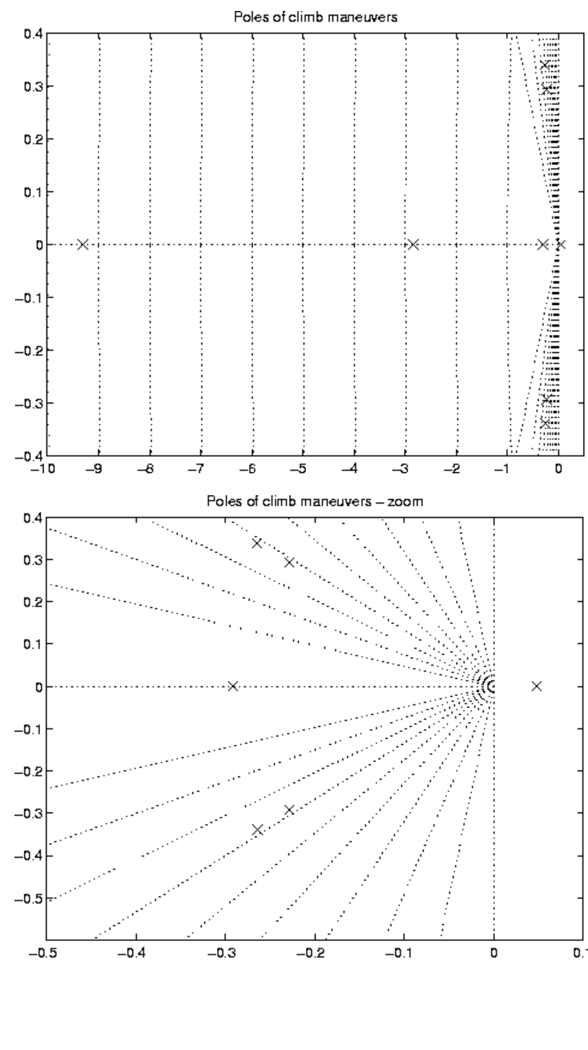


Figure 18. Frequency response to a climb, normal and zoom view



FREQUENCY RESPONSE - CONCLUSIONS

Although the specific system response characteristics are unique to this aircraft/pilot combination, a few observations may be made. In general, the open loop, formation-keeping characteristic of a climb maneuver is virtually deadbeat, while the response to a roll maneuver is moderately damped. The response to a yaw maneuver is either non-existent or exhibits virtually undamped oscillations, in part due to the strong directional stability of the Caravan. The short period and dutch roll dynamics do not factor significantly into the formation-keeping response due to their higher frequency and smaller amplitude.

The roll maneuver is the only system with sufficient data to remark upon the effect of separation distance on the natural frequency of the system. Excluding the test point at 2445 ft, the pilot makes more inputs as the separation distance increases, possibly due to the additional uncertainty induced by the reduced resolution in observing the maneuver.

OVERALL CONCLUSIONS

The preceding analysis suggests that a pilot discerns bank angle change more quickly than either pitch or yaw angle changes. This response time averages one second for separations less than 2000 ft. Response to a climb maneuver is faster than that to a descent and this is probably because pulling the nose up to climb is a more natural response than pushing over in order to descend. Pilot response to a wings-level yaw maneuver is one to five seconds and frequently there is no response at all. The superior trail aircraft response to lead aircraft roll maneuvers compared to yaw maneuvers strongly suggests that roll information is valuable to the pilots for collision avoidance in situations such as closely spaced parallel approaches.

Overall, the reaction of a pilot and aircraft to another aircraft performing a roll into the trail airplane may be modeled as a second order system with pilot time delay. The signal to noise ratio for the system is on the order of 100:1 and permits use of the relatively simple ARX parameter identification model assuming gaussian noise properties. In the case of roll and yaw, the MISO model was superior; however, the SISO model using flight path angle change as the input may be adequate for predicting system behavior and requires less information. In the case of climb, the SISO case using pitch angle as the input exhibited the best behavior.

In general, the open loop, formation-keeping characteristic of a climb maneuver is virtually deadbeat, while the response to a roll maneuver is moderately damped. The response to a yaw maneuver is either non-existent or exhibits undamped oscillations, in part due to the strong directional stability of the Caravan.

ACKNOWLEDGMENTS

The authors would like to thank the FAA Satellite Navigation Office for sponsoring these tests. Thanks also go to the two pilots, Ben Hovelman and Sky, and to Doug Archdeacon, Andy Barrows, Frank Bauregger, Demoz Gebre-Egziabher, Roger Hayward, Wendy Holforty, and Chad Jennings for their outstanding flight support.

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