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Pilot-in-the-Loop Evaluation of a Yaw Rate to Throttle Feedback Control with Enhanced Engine Response

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This paper describes the implementation and evaluation of a yaw rate to throttle feedback system designed to replace a damaged rudder. It can act as a Dutch roll damper and as a means to facilitate pilot input for crosswind landings. Enhanced propulsion control modes were implemented to increase responsiveness and thrust level of the engine, which impact flight dynamics and performance. Piloted evaluations were performed to determine the capability of the engines to substitute for the rudder function under emergency conditions. The results showed that this type of implementation is beneficial, but the engines' capability to replace the rudder is limited.

I. Introduction

In traditional aircraft, the flight and propulsion control systems are independent and coordinated by the pilot. There are advantages to having an integrated flight and propulsion control, as the propulsion system has great potential to enhance performance when used as an additional flight control effector. This is especially important when the aircraft has been impaired or the flight control surfaces are not fully functional. This integration has not yet occurred, although it has been a topic of research, including flight experiments using the propulsion system to control the aircraft.[1] Although the highly nonlinear nature of the propulsion system may limit the practicality of a complex integration scheme currently, simple integration schemes are feasible to realize, utilizing the existing flight and propulsion control systems. This paper describes a preliminary approach to the implementation of yaw rate feedback to the engines, which provides differential thrust to aid the pilot in maneuvering an aircraft with a damaged rudder. This scheme is then evaluated in a fixed base piloted flight simulator.

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Previous flight testing and flight simulator research with throttles-only control was conducted in the aftermath of the 1989 Sioux City accident (when all flight control was lost after an uncontained rotor failure). As a result of this work, it was concluded that throttles alone are often not capable of providing safe landings due to weak control moments, difficulty in damping phugoid and Dutch roll oscillations, coupling between pitch and roll, and sluggish engine response.[1] More recent work evaluating just the effect of rudder failure with possible vertical stabilizer damage has focused on the use of the engines to automatically compensate for the loss of the rudder for aircraft stabilization, Dutch roll damping, and performance of turns.[2-5] This more recent work took the additional step of evaluating the impact of enhanced engine response, meaning faster than normal acceleration (Fast Response) and higher than normal maximum thrust (Overthrust). This enhanced engine operation was achieved through controller modification to increase engine responsiveness and thrust range while still maintaining safe engine operation.[6]

In a multi-engine aircraft, use of the propulsion system to compensate for the lost rudder can be achieved through yaw rate feedback to the throttles, which provides differential thrust to create a yawing moment. The concern with using differential thrust to dampen yaw oscillations due to Dutch roll, particularly when initiated by a pilot, is that the engine response is too sluggish and may actually aggravate the problem.[1] Faster engine response, achieved through modification of the propulsion control, is designed to improve handling qualities, and has the potential to improve the probability of safe landing.

Analysis to determine engine response requirements for aircraft lateral-direction stability has been carried out through the linear analysis of the closed loop aircraft dynamics using yaw rate to throttle feedback.[3] This enabled the exploration of varying engine response on the closed loop aircraft dynamics. The analysis showed that the results are highly dependent upon the flight condition (altitude, speed, etc.) which is consistent with the results from Ref. 1. The ability to improve engine responsiveness safely also depends upon flight condition, as well as other factors such as engine deterioration. Situations may exist in which differential thrust cannot stabilize an aircraft with a missing rudder and damaged tail, independent of engine response.[2,3] However, it was shown in Ref. 3 that yaw rate feedback and fast response will often be able to provide some benefit for stability and control.

The paper focuses on the implementation of a yaw rate to throttle feedback control. It discusses flight simulator evaluation of the system on an aircraft with an impaired rudder using nominal and enhanced engine response. Conclusions are drawn based on pilot observations.

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II. Test Bed Description

The piloted evaluations were performed using a nonlinear, full envelope airframe simulation with four realistic, nonlinear, wing-mounted engines in the 40,000 lb thrust class. The airframe has its own flight control system, and the enhanced propulsion control modes (Fast Response and Overthrust) were incorporated into the control system of each engine. The flight simulator, the enhanced propulsion control modes, and the other information pertinent for the testing performed here are described below.

A. Flight Simulator

The enhanced propulsion control modes were implemented for the engines[7] of a nonlinear simulation of a four-engine transport aircraft. The nominal engine performance is representative of actual engines in their thrust class,[8] and the enhanced control modes are realistically achievable. This simulation was incorporated into a fixed-base flight simulator that was developed to evaluate the impact of propulsion control innovations on flight operation. The cockpit has two throttles that are used for the left and right side engines, meaning that the inboard and outboard engines on each side are always at the same power setting. The pilot has switches in the cockpit to turn the Overthrust and Fast Response modes on and off individually. The pilot can set the flaps and landing gear. The cockpit also has rudder pedals and a stick. There are no other controls.

B. Overthrust

The impact of the Overthrust control mode is shown in Figure 1. The throttle position, which corresponds to the thrust setpoint, is moved higher than the normal 100%, and control limits that might otherwise be hit are relaxed to enable the engine to produce thrust beyond its normal maximum. In the figure, the black curve corresponds to the normal 100% power level. The blue curve, which extends beyond

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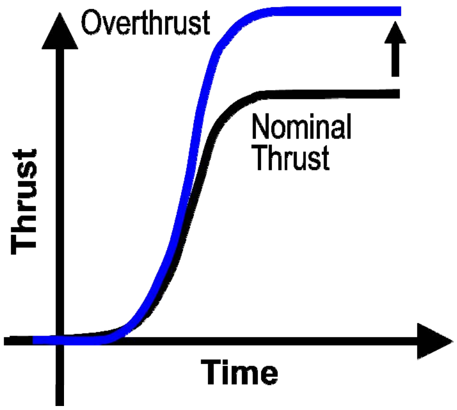

Figure 1. Example of Overthrust operation. The thrust level reaches above the normal maximum level as the setpoint is raised above 100%.

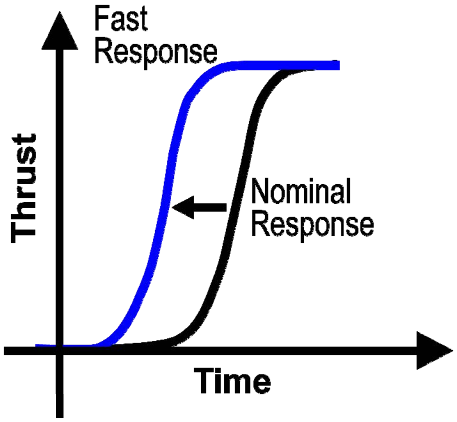

Figure 2. Fast Response transient showing the ability of the engine to accelerate more rapidly than normal when controller limits are relaxed.

the 100% power level, represents Overthrust. For the engine models used in this work, the normal throttle range is from 40 to 80 degrees, and Overthrust mode extends the range up to 90 degrees. This mode was originally designed to enable takeoffs in a shortened distance.[5]

C. Fast Response

The impact of the Fast Response control mode is shown in Figure 2. In this case, the engine is more responsive to large throttle changes because the limits that restrict acceleration have been adjusted to allow faster command following. The thrust response of an engine is typically restricted to accommodate the worst case stack-up of detrimental effects (inlet distortion, engine deterioration, engine-to-engine variation, Reynolds number effects, etc.) to avoid stall and surge.[9] If one is willing to accept higher risk of surge, or knows with certainty that there is still margin available, the engine can be allowed to accelerate more rapidly. Fast Response to small throttle changes may be accomplished by increasing the controller bandwidth. This type of modification reduces gain and phase margins, but the impact on surge margin will be minimal.[6]

D. Yaw Damper

The rudder plays a critical role in the flight control system. It enables coordinated turns, performs yaw damping, and provides sideslip necessary for crosswind landings. The yaw damper provides stability augmentation for improvement of handling qualities.[10] In an aircraft with a functional flight control system, it works by creating a rudder deflection proportional to the aircraft yaw rate that will act to damp out unwanted oscillations in the lateral-directional dynamics. However, to avoid countering a turning command initiated by the pilot, some additional logic must be added to the design. Generally the Dutch roll oscillations are at a significantly higher frequency than the pilot inputs, which tend to be constant or slow, such as those required for a holding pattern or crosswind landing. This frequency separation can be exploited when designing the yaw damper. Thus the simple proportional control implementation described above is modified to include a washout filter in the yaw rate feedback path. The washout filter is simply a high-pass filter whose effect is to hide the response to pilot inputs from the yaw damper, while allowing the Dutch roll oscillations to be observed and eliminated.

E. Yaw Rate Feedback to Engines

If the rudder fails in flight, lateral-directional control could be severely compromised. Manual manipulation of the throttles by the pilot could be used to provide differential thrust as a way to effect sideslip, but the other rudder functions are not feasible for the pilot to perform. Thus it is necessary to implement a yaw rate control of the type previously described, but with the commands diverted to the throttles. An implementation similar to that used in Ref. 11 is shown in Figure 3, and was used for this research. Here the rudder command, which is the sum of the inputs from the yaw damper and the pilot, is split between the two sides of the aircraft: thrust on one side is increased while it is decreased on the other to create a yawing moment while approximately maintaining total thrust. Such a system can be tuned to improve the dynamics of the impaired aircraft, although handling qualities generally cannot match those of the unimpaired aircraft. This is due to the relatively slow response of the engines compared to the rudder and the weak control moment they provide (a function of number of engines and their placement).[1] In the setup shown in Figure 3, the command to the engines consists of three components: Pilot PLA input (Power Lever Angle or throttle command), rudder pedal input ($r_{command}$), and a signal proportion to the yaw rate (r) of the airframe. Note that in this implementation the rudder pedal input to the throttles and yaw rate feedback to the throttles are always active together.

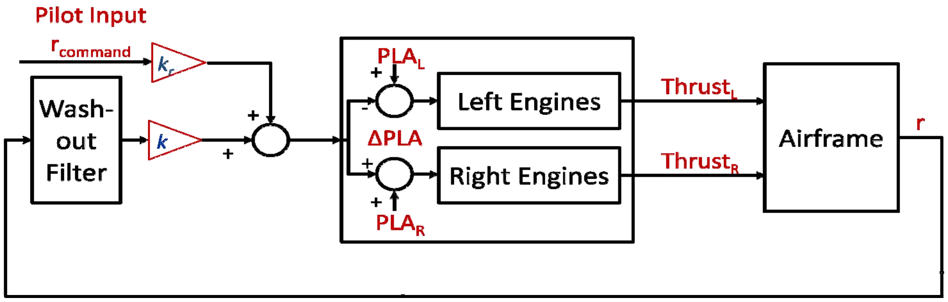

Figure 3. Yaw rate to throttle feedback including pilot input. The gain k_r determines the amount of differential throttle the rudder pedals can produce. Ideally the effect of depressing the pedal should be similar for both rudder and differential thrust, but this is a function of engine placement and thrust range, which create a moment arm, so it may not be possible to match the rudder's power. Note that PLA and throttle are used synonymously.

When using the propulsion system to perform rudder functions, it is critically important to maintain performance as much as possible, for both stability and control. If the engines are operating near a limit (full power or flight idle) the addition of differential throttle might cause the thrust produced by the engines on one side to saturate. Thus a scheme to maintain thrust differential at the expense of total thrust has been implemented. Here the unachievable throttle movement from one side of the aircraft is reversed and added to the other side, as shown in Figure 4. Here, if the differential throttle command would cause the throttle to move above its maximum position, it stops at the top of its range, and the throttles on the other side are reduced by the unachievable amount in addition to the commanded reduction. Likewise, saturation at low power would cause the throttle on the opposite side to be increased by a commensurate amount. Thus, differential thrust is favored over total thrust during maneuvers or for yaw damping.

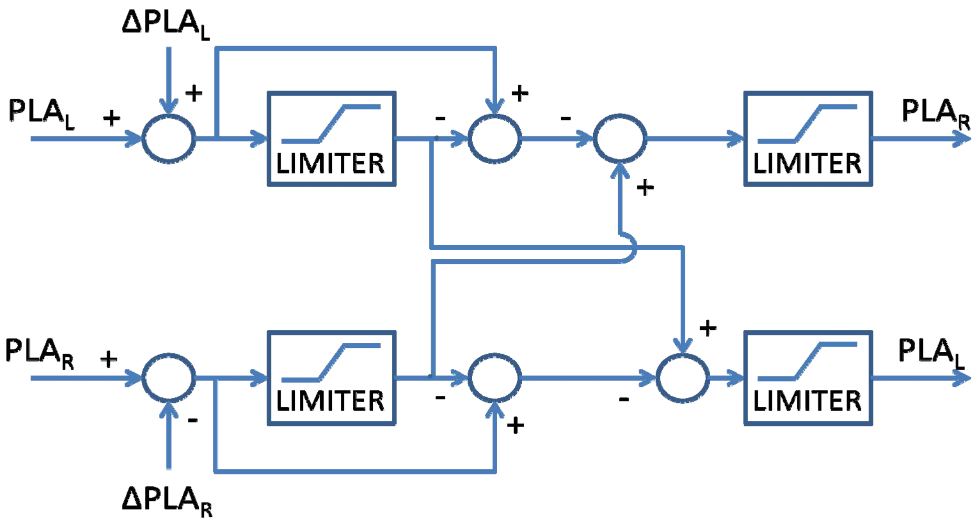

Figure 4. Diagram of method to maintain thrust differential when a throttle is at its upper or lower limit. The demand in excess of the ability of the engine to provide it is transferred to the other throttle in order to maintain differential thrust at the expense of total thrust.

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III. Evaluation Results

Various tests were performed in a flight simulator to evaluate the ability of the propulsion system to fulfill the rudder function when the rudder becomes inoperable. The tests were selected to cover a variety of tasks the rudder performs. These include yaw damping and providing sideslip for crosswind landings. The simulated test vehicle was a large, four-engine transport aircraft.

A. Yaw Damping

Dutch roll is a combined roll and yaw oscillation that is normally very lightly damped in swept-wing aircraft such as modern airliners. To increase the damping of the Dutch roll oscillations, a yaw damper is installed that measures the yaw rate of the aircraft and makes necessary commands to the rudder to compensate. With no rudder, the yaw damper will become ineffective.

Results from Ref. 5 demonstrated the effectiveness of the yaw rate to throttle feedback for Dutch roll damping. The pilot initiated the Dutch roll by banking and turning, then rolling out suddenly and releasing the stick, making only minor adjustments to maintain a relatively wings-level attitude. The use of yaw rate to throttle feedback dampened the oscillations significantly faster than in the case with a stuck rudder and no yaw rate feedback, although not as quickly as for the baseline aircraft. Additionally, Fast Response showed vastly improved yaw damping over nominal engines when evaluated at certain flight conditions.

To demonstrate what is happening inside the yaw damper, a detail of a trial is shown in Figure 5. This focuses on the end of the run from the point at which the Dutch roll is initiated. From the left side of Figure 5 it is clear that in the case using yaw rate feedback to the throttles, the oscillations are damped out faster than in the case with no yaw rate feedback. The right side of Figure 5 shows the throttle command to the engine. It consists of the sum of the pilot input, which at this point in the run is a constant input equal to each throttle's value at 75 s, and the dynamic, oscillatory deviation, which is proportional to the yaw rate.

The pilot said he felt that the fast responding engine helped achieve a wings level attitude and provided consistency from turn to turn.

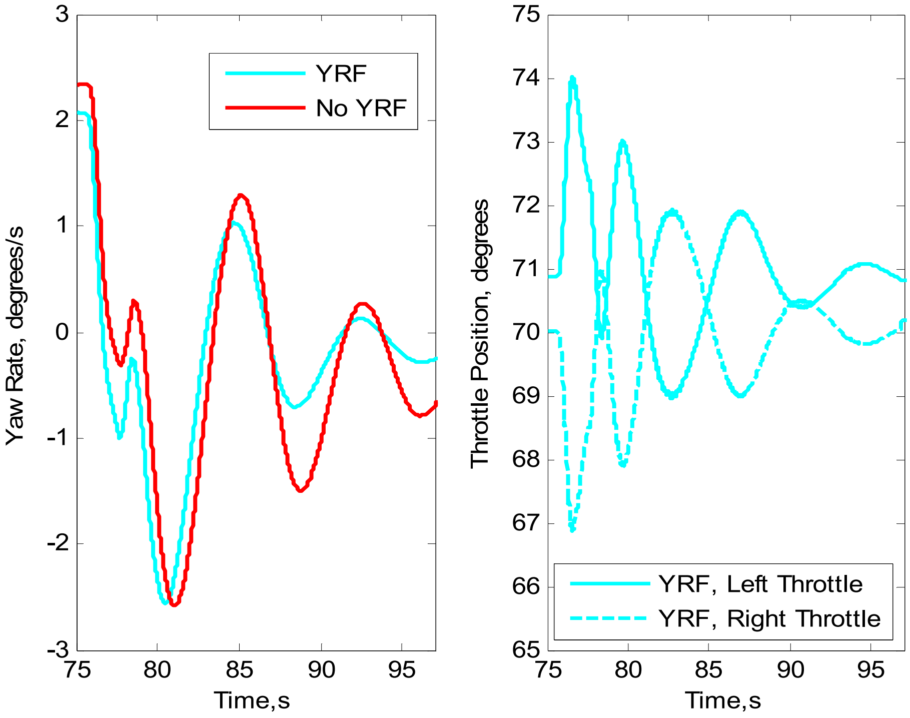

Figure 5. Yaw rate of an aircraft with an impaired rudder after a maneuver to induce Dutch roll. The left plot compares a case with yaw rate feedback (YRF) to a case without, demonstrating improved damping with YRF. The right plot shows the differential throttle movements used to produce the thrust that dampens the oscillations.

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B. Crosswind Landing

Figure 6. Approach to CLE. Testing performed with a crosswind from the left.

For this scenario, shown in Figure 6, the pilot attempted two sets of approaches to Cleveland Hopkins Airport (CLE) with a wind coming from about 45° to the left of the runway. In the first set, a 15 kt wind resulted in an approximately 10 kt crosswind and headwind, in the other, a 25 kt wind resulted in a 17 kt crosswind and headwind. Neither of these crosswinds is high for this aircraft under normal conditions, but here, in addition to flying the baseline aircraft, the tests included approaches with a disabled rudder. The pilot's tactic was to "cross control" the aircraft using, in this case, right rudder and left bank. This type of control input results in the aircraft heading deviating to the right from the flight path. The final ground track, which is the vector sum of the wind and flight path, is along the runway centerline and the "cross control" aligns the aircraft heading with the runway heading. As Figure 6 shows, these approaches were nearly straight on, meaning that the pilot did not have to maneuver to align with the runway except to overcome the crosswind. Previous testing without crosswind that required an S-curve approach[5] demonstrated that yaw rate feedback with Fast Response reduced oscillation resulting from turns, but provided no noticeable benefit for minor corrections.

In a baseline aircraft, the use of differential thrust is generally redundant because of the availability of the rudder. If use of the rudder is lost as in these examples, the engines can take on multiple roles—they can provide not only thrust, but yaw damping and sideslip. In the implementation used here (shown in Figure 3), the rudder pedals provide the equivalent of split throttles sufficient to counteract a moderate crosswind, but not enough to saturate the throttles differentially. It is necessary for the pilot to maintain control authority so that he can change total thrust while still maintaining the thrust differential using the rudder pedal, and that the engines can provide automatic yaw damping. Therefore, the rudder pedals enable a maximum amount of differential throttle, while the pilot can further adjust thrust by manipulation of the throttles. When Overthrust mode is initiated, the pilot's control authority is increased as is the total available thrust, but the rudder pedal's authority on the throttle remains the same.

1. 10 kt Crosswind

In the baseline aircraft, the pilot had little problem performing the approach with the crosswind. The rudder was able to accommodate the crosswind easily. In fact, when the rudder was disabled and the pedals were redirected to differential throttle, in all cases the pilot was able to line up with the runway and land without much trouble. With the disabled rudder, he did encounter small Dutch roll oscillations resulting from constant minor corrections, and Fast Response did not improve the situation over the case with nominal engines, which is consistent with the results of Ref. 5. With Overthrust mode active, the pilot appreciated having the additional power available, although it was not necessary to land with this wind. Without Overthrust, he had commented that he needed to keep high enough altitude to avoid requiring high power. The pilot noted that the use of Overthrust provides control sensitivity over a wider range.

Without yaw rate feedback, the results were mixed. Because the crosswind is a steady disturbance, it is possible by manually splitting the throttles to achieve the thrust differential required for a straight on approach to the runway. In one of the runs without yaw rate feedback, the pilot was able to set the throttles just right to allow for a very smooth approach, but he considered this result to be unusual, because even minor corrections can set off oscillations. He stated that he would not have been able to achieve such a result had there been wind gusts. In another split throttles test, he encountered large oscillations and "ballooned" the landing.[1]

Figure 7 shows some representative examples of throttle commands to the engines for the various cases evaluated. The plots show the total throttle command (top plot), the rudder input (either to the rudder, or to the throttles for cases with yaw rate feedback; note that the rudder pedal saturates just below 4 volts)

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[1] Ballooning is climbing unexpectedly while transitioning from glide, usually caused by flaring at too high a speed, resulting in raising the nose too high and creating excess lift.

(middle plot), and the pilot's PLA input (bottom plot). Note that in these runs, the throttle is almost never saturated at either the high or low end. In the manual approach (no rudder pedal to differential throttle), there is room to adjust power by moving the throttles together while maintaining the split. When not using a manual approach, any throttle split (bottom plot) is inadvertent and due to minor misalignment of the throttles, which are consistently moved together.

The red trace in the top plot of Figure 7 shows a case with Fast Response and Overthrust modes active. In this case, at about 135 s one throttle command goes above 80 degrees while the other saturates at 40 degrees, providing a larger split than would be possible without Overthrust. The large rudder input at this point in time (middle plot) appears to be an attempt to make a late correction, resulting in a large oscillation, but in both cases utilizing yaw rate feedback, the Dutch roll damping mechanism is evident (top plot).

2. *17 kt Crosswind*

Again in this case the baseline aircraft could accommodate the crosswind and land without difficulty. The approaches with the disabled rudder, however, were much more challenging than those with the lower crosswind. The pilot had difficulty staying lined up with the runway, although he landed successfully in almost all cases. He had the most trouble with the split throttle approach due to oscillations, while the approaches using yaw rate feedback, both with and without Fast Response, tended to be more satisfactory in his opinion. Again, Fast Response did not seem to provide a benefit for damping. On several runs without Overthrust he complained about not having enough power to line up, and even on one attempt using Overthrust he landed on the center runway rather than the target leftmost runway. However, the available differential thrust was shown to be sufficient for approach and landing when utilized properly, and the alignment problems in the early runs appeared to be a combination of the pilot's unfamiliarity with the situation and unwillingness to be aggressive enough at the beginning of the approach, requiring extra thrust to compensate later.

Figure 8 illustrates some representative cases with the 25 kt wind resulting in about a 17 kt crosswind. Here the pilot's rudder input for the baseline case is nowhere near its limit, indicating that the rudder still has plenty of authority. However, when he tried to do the same approach with the rudder stuck in the neutral position, the throttles were almost fully split, indicating that this is close to the maximum crosswind that the engines can accommodate (Figure 8, top plot). In the manual approach (no rudder pedal to differential throttle), the throttles are fully split, there is no ability to adjust power while maintaining the split. In general for the tests using this level of wind, aligning with the runway seemed to be much more of a concern to the pilot than oscillation, although Dutch roll damping is clearly evident in the cases with yaw rate feedback. When the pilot tried the approach with Overthrust mode active, he felt he had more control margin to maintain the necessary ground track for a successful approach. The top plot of Figure 8 shows the throttles saturating low at 40° and high at 80° for the cases without Overthrust, and saturating at 40° and 90° (although not simultaneously) with Overthrust enabled.

These tests demonstrate the full functionality of the implementation: the enhanced control modes, the yaw rate feedback system, and the saturation compensation system. It also points out the limitations of using the engines to replace the rudder function. In this case, even with wing-mounted engines that produce a relatively large moment arm, there is barely enough thrust differential available to overcome a moderate crosswind.

With the higher crosswind, the headwind was also higher and the pilot had trouble getting down to the runway because he kept the power up and tended to come in high. Still the differential had the throttles split close to the full range due to the crosswind. Comparing this to the case with the lower crosswind (Figure 7), the throttle split and average throttle position is higher with the higher wind. Higher crosswind and headwind require higher thrust, which is achieved with the higher average throttle position. What is interesting about the Overthrust case shown in Figure 8 is that the actual throttle split never exceeds 40°, although the additional available thrust is utilized considerably toward the end of the run.

One particularly interesting result of this testing is that the pilot seemed to like flying with the yaw rate control and the fast-responding engines more than without them. This is in opposition to the results of previous testing in which the pilot preferred no yaw rate feedback.[5] This turnaround can be attributed to two factors: he had more familiarity and therefore more comfort with the system, and the crosswind provided an additional load that made him more focused on the task and less aware of the control. He felt that yaw rate feedback made necessary corrections smoother and smaller.

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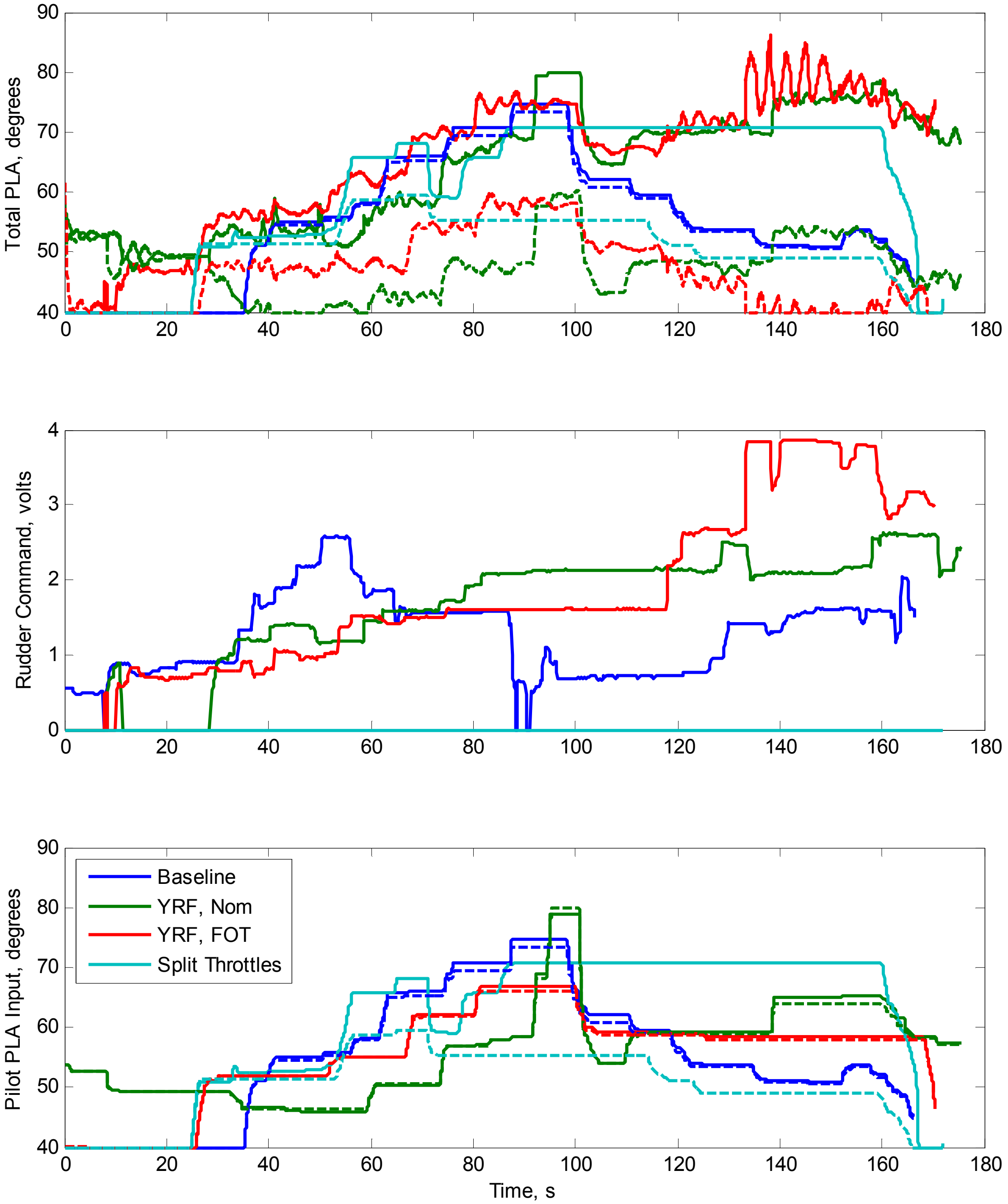

Figure 7. Left (solid lines) and right (dashed lines) throttle on approach in 10 kt crosswind for several representative runs. The top plot shows the total command to the engines. It consists of the rudder pedal input (second plot), the pilot's PLA input (third plot), and the proportional yaw rate feedback from the airframe. After about 135 s, the case with Fast Response and Overthrust (red) has an input to the engines of above 80 degrees, and the saturation compensation is apparent as the right throttle hits the lower limit (top plot). (Note: YRF=yaw rate feedback, Nom=nominal engine, FOT=Fast Response and Overthrust)

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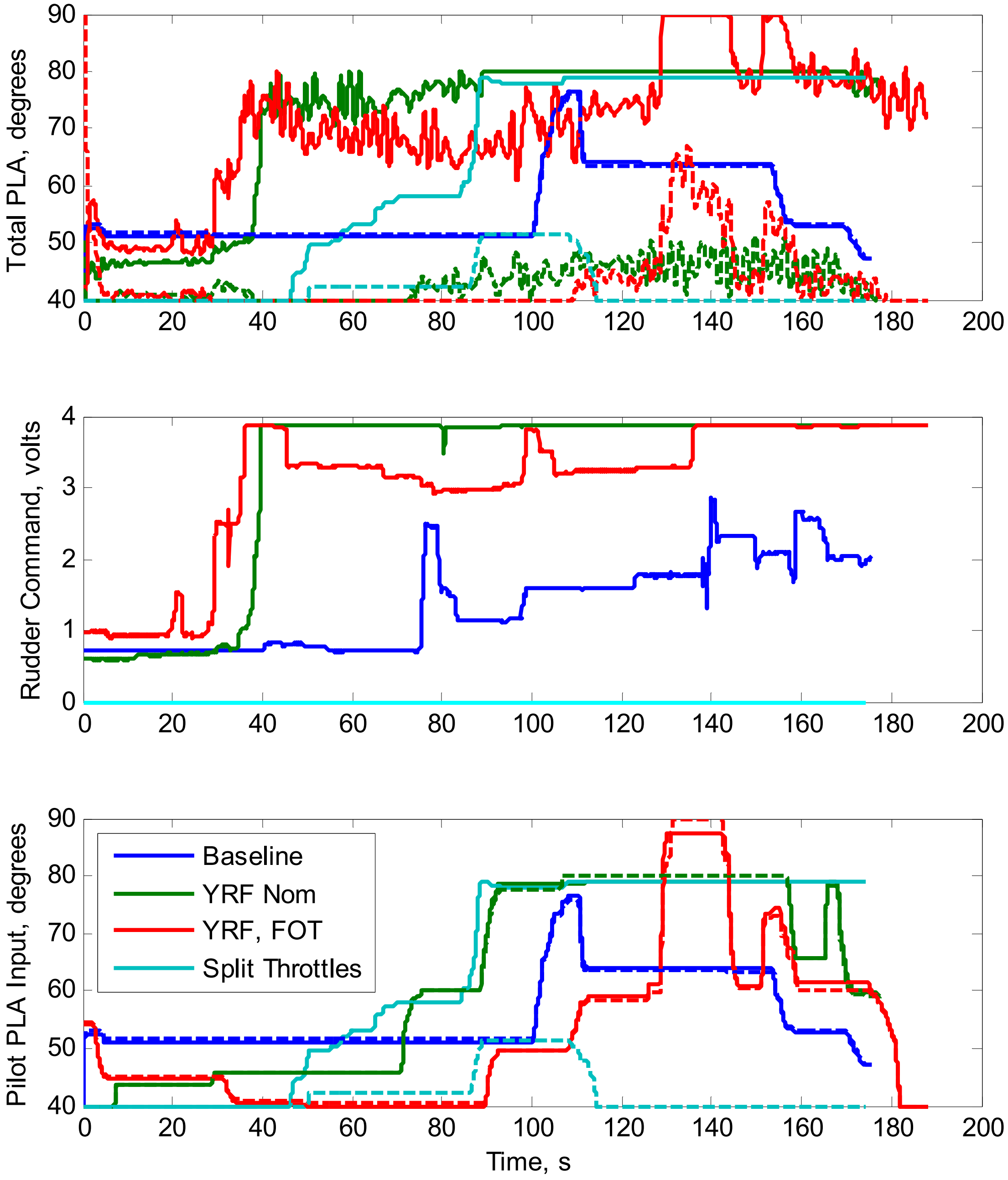

Figure 8. Left (solid lines) and right (dashed lines) throttle on approach in 17 kt crosswind for several representative runs. The top plot shows the total command to the engines. It consists of the rudder pedal input (second plot), the pilot's PLA input (bottom plot), and the proportional yaw rate feedback from the airframe. Here the throttles are close to being fully split throughout the run, except in the case with Overthrust where there is more throttle authority remaining. (Note: YRF=yaw rate feedback, Nom=nominal engine, FOT= Fast Response and Overthrust)

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IV. Conclusions

A yaw rate to throttle feedback system that enables pilot rudder input to be redirected to the throttles was implemented and evaluated in a flight simulator. A control logic innovation that redirects a saturated throttle command to the opposite throttle was included. Potential aircraft stability and control improvements achievable using enhanced propulsion control modes were assessed. Two types of tests were performed: Dutch roll damping and crosswind landing. The yaw rate feedback system provided improvement over the stuck rudder case for Dutch roll damping, which confirmed previous results. Ease of crosswind landings was improved through the pilot's use of rudder command to throttle input, especially when compared to manual manipulation of the throttles because of the yaw damping capability, although it was much more limiting than what the actual rudder can provide. The rudder pedal to differential throttle input also eliminated the need to manually adjust the throttle split. Compensating for a higher crosswind required the pilot to fully depress the rudder pedal, which contributed to saturation of the throttle. The yaw rate feedback system was still able to perform Dutch roll damping, even while counteracting the crosswind, because of the throttle saturation compensation scheme that enables full throttle differential to the extent possible. The use of Overthrust during the crosswind landing to increase the available throttle range provided additional improvement and pilot satisfaction. The yaw rate to throttle feedback with saturation compensation and pilot rudder commands redirected to differential throttle generally provided improvement over manual manipulation of the throttles in the stuck rudder scenario, both in Dutch roll damping and in directional control. It is anticipated that the inclusion of wind gusts would show even greater benefit.

Acknowledgments

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