SECTION IV

SPECIAL PROBLEMS 1

TASK-ORIENTED FLYING QUALITIES FOR AIR-TO-GROUND GUN ATTACK

June 1978

By

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Prepared for

Air Force Flight Dynamics Laboratory
Symposium and Workshop on Flying
Qualities and MIL-F-8785B
September 12-15, 1978

TASK - ORIENTED FLYING QUALITIES FOR AIR-TO-GROUND GUN ATTACK

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Abstract

The A-10 Stability Augmentation System (SAS), designed to provide good overall flying qualities based on the standard MIL-F-8785B criteria, performed very well during prototype testing and early operational deployment. As user experience was gained, progressively more aggressive close air support tactics were developed. It was recognized that the SAS could benefit from reevaluation, with a view toward determining potential low cost improvements in performance. The starting point of the evolution of the task-oriented SAS was a study of current close air support weapon delivery maneuvers, which established two typical evaluation maneuver scenarios, namely: curvilinear strafe and abrupt heading change maneuvers. These maneuvers, in turn, motivated the definition of the task-oriented control variable, the cross-track component of the perceived hit point. The ability to rapidly and predictably produce changes in this quantity with 1-second aileron doublet inputs was chosen as the evaluation criterion. Examination of the contribution of lateral stick motions to cross-track hit point led to the definition of five candidate beta-dot ($\dot{\beta}$) systems for the SAS. The most cost-effective form of the SAS was evaluated via manned simulation and motivated a flight test program. Flight test results, showing tracking time reductions of more than 100 percent were in excellent agreement with the previous work. The A-10 aircraft will be equipped with this task-oriented SAS in the near future.

1. Introduction

In the close air support (CAS) role, a wide variety of attack maneuvers may be characterized by three general phases. The first phase, initiated by the pilot perceiving the target, consists of a target acquisition maneuver. This maneuver consists of a rapid rollin toward the target while a normal load factor of 4-5g is developed. The roll angle and load factor are maintained until the gun cross or pipper line of sight is near the target. At this point a rollout to wings level, together with a load factor reduction to 1g, occurs. The second phase of the attack maneuver is the weapon delivery or tracking/firing phase. In this phase, the errors present at the conclusion of the target acquisition phase must be eliminated, and the pipper should be maintained on the target while the gun is fired. The final portion of the attack is characterized by a break phase, which consists of a gross maneuver generally intended to place the aircraft in position for another attack while maximizing aircraft survival. Figure 1 presents a specific example of this ground attack maneuver scenario. Each of these attack phases will now be examined to obtain the functional requirements.

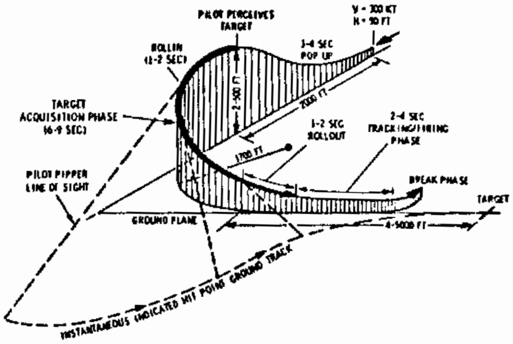

Figure 1. Ground Attack Maneuver Scenario

The target acquisition and break phases are considered first. Both of these phases involve gross maneuvers. A gross maneuver is defined as one utilized to produce a large change in the aircraft velocity vector. The target acquisition gross maneuver has an additional essential requirement, namely, that the terminal direction of the velocity vector must be highly predictable. The realization of the proper terminal orientation of the velocity vector is vital to minimizing the duration of the relatively vulnerable weapon delivery phase. The target acquisition and break maneuvers are achieved (as is any gross maneuver) by developing a large, unbalanced, aerodynamic force vector (lift) and orienting it with roll angle control so that the resultant, with the gravitational force vector, is oriented in the direction of the desired velocity increment. This type of maneuver requires that large amounts of lift be obtained at optimum low altitude attack speeds (275-350 knots) and that the aircraft show excellent roll control characteristics in terms of speed of response, while maintaining adequate turn coordination when necessary.

The weapon delivery phase is typified by relatively straight, roughly 1g flight. There are, however, two distinct types of functional requirements. These requirements are motivated by unguided bombs as one weapon type and the GAU-8 gun as the other. Other weapons will have requirements encompassed by the requirements of these two weapons. The impact point of an unguided bomb is determined essentially by the aircraft velocity and position vectors at the time of weapon release. The aircraft position is, of course, a consequence of velocity over a time interval, and therefore, the fundamental requirement is for rapid and precise velocity vector control. Rounds from the GAU-8 gun, however, impact at points largely determined by the direction of the pipper line of sight when the round was fired. The gun, therefore, requires that the attitude of the aircraft (and consequently of the gun) be precisely controlled.

The A-10 SAS was originally designed to provide good overall flying qualities, as defined by MIL-F-8785B. During the original deployment and operational utilization of the aircraft, the augmented dynamic response was found to be excellent. As the aggressiveness of the ground attack maneuvers increased, it was determined that a task-oriented SAS was required in order to realize the inherent dynamic performance capabilities of the aircraft in this evolving maneuver environment. The purpose of this paper is to contrast the dynamic performance assessment obtained from application of MIL-F-8785B with the assessment derived from use of a task oriented performance measure. The original lateral-directional SAS is initially defined. The development of the task oriented SAS is then presented.

The response characteristics of the systems are then compared: first, in terms of application of MIL-F-8785B for response evolution, then, in terms of task oriented response. The results of simulation, and, finally, flight test are then presented.

2. Original SAS

The original lateral directional stability augmentation system is presented in Figure 2. This system was selected on the basis of extreme simplicity and capability to satisfy the requirements of the flying qualities specification. Figure 2 shows that the system consists of cancelled yaw rate feedback to provide adequate damping, together with an aileron rudder interconnect to inhibit any adverse yaw tendencies. This system provided level 1 lateral directional flying qualities during the prototype flight test phase and original operational deployment of the aircraft. As the evolving maneuver environment became more aggressive, it became apparent, however, that the response requirements of 8785B did not guarantee optimum air-to-ground gun attack flying qualities. A study was initiated to gain insight into these specific requirements.

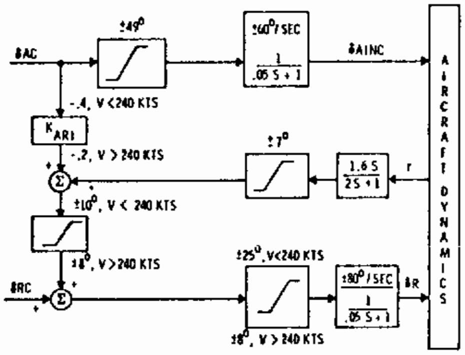

Figure 2. Original Lateral - Directional SAS

3. Kinematic Analysis

Analysis of gun camera film, pilot comments, etc., together with consideration of the functional requirements for CAS presented in the previous section, motivated the selection of indicated hit point steering as the quantity which the SAS should be synthesized to control in a smooth and rapid fashion.

In order to provide control of this vector, it is necessary to derive an analytical expression for it in terms of the aircraft position and orientation.

The required perceived hit point expressions were developed using the vectors and geometry defined in Figure 3. The results are:

$$R_{H_x} = x - z\left[\frac{\cos\theta\cos\psi + \sigma_c\ (\sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi)}{-\sin\theta + \sigma_c\ \cos\phi\cos\theta}\right]$$

$$R_{H_y} = y - z\left[\frac{\cos\theta\sin\psi + \sigma_c\ (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)}{-\sin\theta + \sigma_c\ \cos\phi\cos\theta}\right]$$

Where: x, y, z are the position coordinates in the R-Frame of Figure 3, ψ, θ, and ϕ are the conventional Euler angles, and σ_c is the gun sight depression angle. These expressions will be used as the basis for the task orientated SAS synthesis.

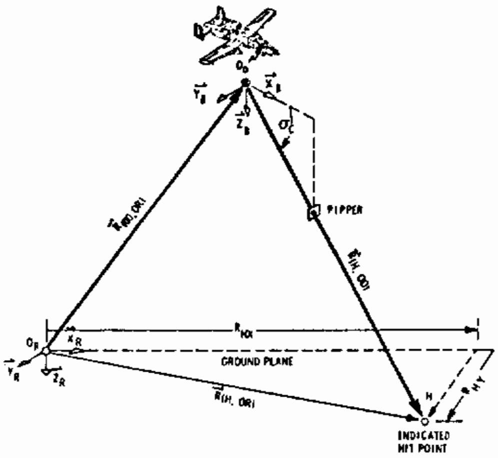

Figure 3. Fixed Reticle Air-to-Ground Weapon Delivery Kinematics

4. Simplified Scenario

The complete kinematic and dynamic analysis of the gunnery scenario presented in the introduction represents a formidable analytical task, and requires simplification in order to gain insight into the problem. Therefore, attention is focused on that portion of the maneuver during which it is most critical to have good control of hit point (pipper) motion, viz. the final portion of the rollout and the track phase.

The simplification shall consider the aircraft at an average slant range of about 4000 feet, velocity of 300 knots, (500 fps), and shall restrict the vehicle motion to a 10-degree inclined plane. This is typical of a low-dive angle rollout maneuver.

Making the usual perturbation analysis assumptions, the linearized expression for the cross track component of the perceived hit point rate can be written as:

$$\dot{R}_{H_y} = V(\psi + \beta - \alpha_0\phi) + \bar{R}(r - \sigma_c p)$$

Where: V is the aircraft velocity, $\bar{R}$ is the average range, α_0 is the trim angle of attack, and β is the sideslip angle.

5. System Synthesis

This section presents the reasoning which led to the control law selection. It was recognized at the outset that control of the perceived hit point (pipper line of sight) should be accomplished in such a way that minimum sideslip angle be maintained, since significant sideslip could cause discrepancies between actual and perceived hit points. The aileron was chosen to be the primary control, since "feet-on-the-floor" maneuvering is desirable. If the target appears through the Head Up Display (HUD) to the right of the pipper, a natural pilot response is to roll to the right. It is desirable to have the gun cross move to the right without any pendulum effect (initial non-minimum phase motion; i.e., motion of the gun cross initially opposite to the desired direction). In order that the perceived hit point move to the right, it is necessary that $\dot{R}_{H_Y} > 0$, whenever $p > 0$.

The derivative of the linearized task oriented control variable, $\dot{R}_{H_Y}$, can be simplified using the simplified scenario. Recall that $V \approx 500$ fps and $\bar{R} \approx 4000$ feet. In addition, ψ and ϕ will be small, and $\beta \approx 0$ is desired. Applying these considerations to the linearized expression for R_{H_Y}, then:

$$\dot{R}_{H_Y} = V(\psi + \beta - \alpha_0 \phi) + \bar{R}(r - \sigma_c p)$$

which leads to the simplified expression:

$$\dot{R}_{H_Y} \approx \bar{R}(r - \sigma_c p)$$

This equation was derived assuming sideslip was zero. It is now of interest to determine the relation of r and p, when $\beta = 0$. Sideslip angle, β, will remain zero if the time derivative, $\dot{\beta}$, is always zero.

The aircraft side acceleration equation can yield this relation. The equation is:

$$\dot{v} + ur - wp = g \sin\phi \cos\theta + Y_A/m$$

Where Y_A = aerodynamic side force, and u, v, and w are aircraft axial, side, and vertical velocities. Using $u \approx V$, $\alpha = w/V$, $\beta = v/V$, dividing through by velocity, and rearranging terms yields:

$$\dot{\beta} = -r + \alpha p + (g \sin\phi \cos\theta/V) + Y_A/mV$$

If $\dot{\beta} = 0$, then:

$$r = \alpha p + (g \sin\phi \cos\theta/V) + Y_A/mV$$

Assuming Y_A/mV is negligible, then:

$$r = \alpha p + g \sin\phi \cos\theta/V$$

For ϕ small, $g \sin\phi/V$ is negligible, and $r \approx \alpha p$.

Substituting this approximation for r into the simplified expression for R_{H_Y}, then:

$$\dot{R}_{H_Y} \approx \bar{R}(\alpha p - \sigma_c p) = \bar{R}p(\alpha - \sigma_c)$$

This indicates that whenever the angle of attack is the same as the gun depression angle, the perceived hit point will not move in the $\vec{Y}_R$ direction, in response to roll rate. In other words, the aircraft would roll about the pipper and the pilot could not make a correction via ailerons. This situation would be desirable if the pilot were able to roll out on the target with no error. A more usual situation is that some initial errors exist, and it is not desirable to roll about the gun line. It is more desirable to roll about an axis which is below the gun line so that a proper initial motion of the perceived hit point (gun line) is generated. In order to accomplish this, a bias is introduced into the $\dot{\beta}$ equation, i.e., if it is required that $\dot{R}_{H_Y} > 0$ when $p > 0$ for all $\alpha > 0$, then it is appropriate to replace the α term in the $\dot{\beta}$ equation by $\alpha + \alpha_\beta$ where $\alpha_\beta = \sigma_c$. This results in:

$$\dot{R}_{H_Y} = \bar{R}\alpha p$$

So far as control of R_{H_Y} is by the use of aileron control for this simplified scenario, the result can be derived based on the one degree-of-freedom (1 DOF). roll rate response as:

$$\dot{R}_{H_Y}(s)/\delta_A = \bar{R}\alpha p(s)/\delta A$$

For the design flight condition:

$$\dot{R}_{H_Y}(s)/\delta_A = 3628/(s + 5.23)$$

This simple and dynamically attractive expression for hit point rate, in terms of aileron input, motivated the decision that candidate SAS systems yielding such a result should be evaluated by simulation studies based on the simplified scenario.

The control law chosen was such that the SAS rudder command is of the form $\delta R = K_{\dot{\beta}} \hat{\dot{\beta}}$, where $K_{\dot{\beta}}$ is the feedback gain and $\hat{\dot{\beta}}$ the sideslip rate estimate derived directly from the sideforce equation. The rationale for this choice of control law is simply to provide a SAS which will maintain $\hat{\dot{\beta}}$ near zero, thereby yielding a dynamic relationship between $\dot{R}_{H_Y}$ and δ_A, which will approximate the favorable one derived above via linearized analysis.

6. Flying Qualities Comparison

The purpose of this section is to provide a brief outline of the differences in flying qualities between the original SAS and the task oriented SAS as obtained from the flying qualities specification. The response of both systems to a maximum roll input is presented in Figure 4. In terms of the response requirements of paragraph 3.3.2.4 Sideslip Excursions of MIL-F-8785B the response of both systems in excellent, i.e., level 1. The results of application of paragraph 3.3.2.4.1 Additional sideslip requirement for small inputs are presented in Figure 5. The results of this Figure also shows both SAS responses to be excellent. These results show that a more discriminating criterion is required for the gun attack problem. The next section describes the selected criterion as well as initial simulation results.

7. Preliminary Simulator Studies

A three degree-of-freedom (3 DOF) lateral/directional flight simulation was set up at Fairchild Republic for extensive analysis of the ground attack mode. The objectives of this simulation were to:

- Validate response criteria selection
- Validate the selection of R_{H_Y} as the task oriented control variable and determine a meaningful aileron test input
- Ascertain the need for the aerodynamic force terms in the $\dot{\beta}$ estimate
- Demonstrate the viability of the $\hat{\dot{\beta}}$ control law for the solution of the air-to-ground targeting problem.
- Optimize the feedback gain, denoted by $K_{\dot{\beta}}$.

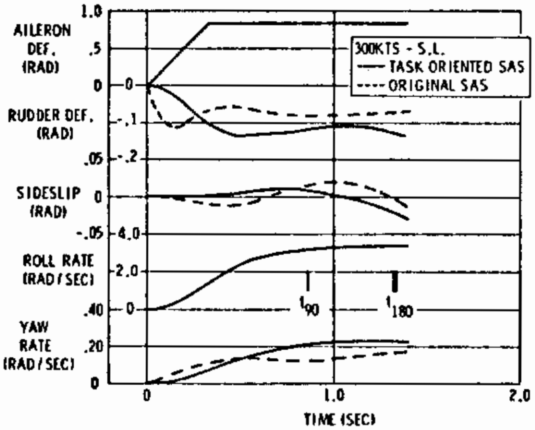

Figure 4. Maximum Roll Comparison

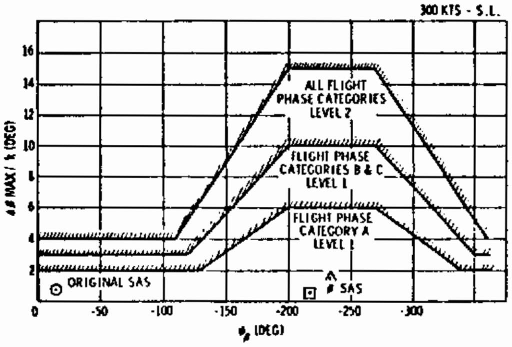

Figure 5. Sideslip Excursion Limitations

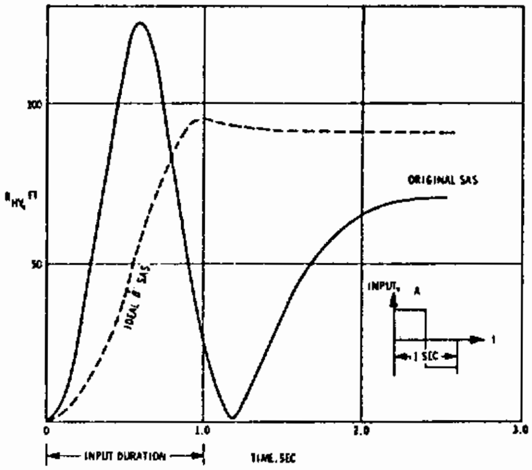

Figure 6. Response to a 1-Second, Half-Stick Aileron Doublet For Tracking Scenario

Based on analysis of the types of control inputs normally seen in the rollout and tracking phases of air-to-ground gunnery, 1- and 2-second aileron doublet input responses in R_{H_Y} were selected as criteria for SAS performance evaluation. These criteria were first applied to the original A-10 SAS for the simplified scenario previously described. The results of a half-stick doublet are shown in Figure 6. The time history, shows that the response of the original SAS for this particular input is both oscillatory and slow, persisting for 2.2 seconds for a 1-second duration input. The original SAS consists of a washed-out yaw rate command to the rudder for "dutch roll" damping, plus an aileron-to-rudder crossfeed to compensate for the inherent adverse yaw of the aircraft. By contrast, the response of an idealized $\dot{\beta}$SAS system is seen to be both much faster and better damped. The idealized $\dot{\beta}$ system response was obtained utilizing a feedback gain of $K_{\dot{\beta}} = -2$ seconds which was found to optimize doublet response at the design flight condition of 300 knots at sea level. This value was used for all manned simulation and flight test evaluation. These results, which

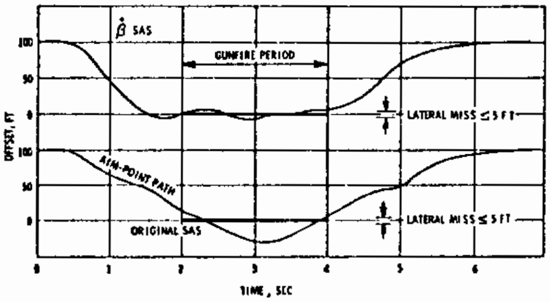

Figure 7. Preliminary Simulation Results for the Original and $\dot{\beta}$SAS Configurations

will later be shown to correlate well with manned simulation and flight test results, validate the utilization of this type of response for SAS performance criteria evaluation.

A comparison of piloted tracking capability is shown in Figure 7, indicating more positive and precise pipper control for the $\dot{\beta}$ SAS than for the original SAS configuration. This task utilized the previously described, simplified scenario. The pilot's task was to make a rapid heading change, maintain the pipper on the target for 2 seconds, then reacquire the original heading.

The preliminary conclusions reached as a result of this simplified simulation effort were:

- The mission oriented variable R_{H_Y} is meaningful for low altitude gun attack
- Response to a 1-second aileron doublet is very useful for judging the relative merits of competitive SAS systems, and correlates well with piloted simulation results
- The piloted runs show that the lateral tracking error for the $\dot{\beta}$ SAS is significantly less than that for the original SAS
- The results of this study were sufficiently encouraging to motivate detailed parameter selection for a manned simulation utilizing a 6-DOF model.

8. System Definition

The viability of an idealized $\dot{\beta}$ SAS for providing good control of the mission oriented control variable, R_{H_Y}, was established, and, therefore, the practicalities of obtaining an acceptable estimate of $\dot{\beta}$ could be considered. The study started with consideration of the possibilities for simplification of the exact expression for $\dot{\beta}$ obtained from the side force equation. (Refer to Appendix for further details.) Consideration of the aerodynamic characteristics of the A-10, as well as mission requirements and flight envelope, led to the selection of the following biased estimate of $\dot{\beta}$:

$$\hat{\dot{\beta}} = -r + (\alpha_\beta + \alpha)\, p + g \quad \sin\phi/\bar{V}$$

Where $\bar{V}$ is an average velocity value, and α_β was chosen to be the pipper depression angle based on the reasoning presented in the system synthesis section. A block diagram for this system is presented in Figure 8.

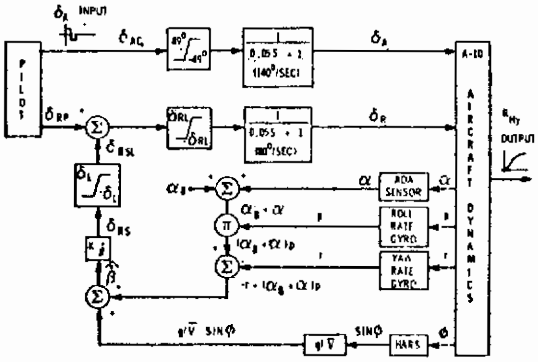

Figure 8. Task-Oriented SAS Block Diagram

9. Manned Simulator Studies

An evaluation of the original and $\dot{\beta}$ configurations for the A-10 SAS was subsequently conducted on the manned flight simulator at the General Electric Company, Binghamton, New York. The tasks for performance evaluation stressed speed of action and pipper control in an environment of expected ground fire. Both Fairchild Republic Company and USAF pilots participated in this evaluation. The two scenarios used were:

1. Gross Maneuver (ψ_0 = 90 degrees): The target was located initially off the left wing at 7000-feet slant range. The task was to rollin to the attack and fire the gun as soon as possible, pulling normal load factors as required. This represented the typical curvilinear maneuver

2. Tracking Maneuver: The target was located initially 400 feet to the right of gun boresight at a slant range of 5000 feet. This represented an error of 80 mils, to be removed by a tracking maneuver in minimum time, followed by a period of gunfire.

Ten runs were made for each system/scenario studied, and key measurements were taken and averaged for each set of runs. The measurements made were as follows:

a. Slant Range at Shoot: An indication of the speed with which the pilot was able to get on the target to initiate weapon delivery. A larger range indicates superior pointing control and enhances survivability. At the longer range, however, better tracking accuracy is required to achieve the same miss distance at the target

b. Trigger Depression Time: The length of time the pilot was confident of a gun firing solution

c. Average Miss Distance: A measure of the projectile average miss distance during the gunfire period

d. Minimum Miss Distance: The smallest miss obtained during the gunfire period.

Run Data and Pilot Evaluations

Average measurements for Pilots 1 and 2 are presented in Table 1, and for Pilot 3 in Table 2. It can be seen that the $\dot{\beta}$ SAS is clearly superior. This conclusion is validated by the much longer ranges at gunfire initiation, combined with longer trigger times and comparable or better miss distances achieved with the $\dot{\beta}$ system. Note that Pilot 3 achieves an average miss distance of less than 10 feet in the tracking task with the $\dot{\beta}$ SAS. Figures 9 and 10 are samples of the two scenarios flown by Pilot 2, and show comparisons of the two configurations. The improved lateral tracking error characteristic of the $\dot{\beta}$ system is clearly indicated, as well as the much longer range at shoot.

Table 1. Original Versus $\dot{\beta}$ SAS Comparisons

Maneuver	Tracking				ψ_0 = 90 Degrees			
Pilot	1		2		1		2	
SAS Type	Original	$\dot{\beta}$	Original	$\dot{\beta}$	Original	$\dot{\beta}$	Original	$\dot{\beta}$
Range at Gunfire (Ft)	2070	3440	2210	3810	3960	5110	2830	4230
Trigger Time (Sec)	0.8	1.3	1.3	2.9	2.0	3.1	2.0	3.2
Minimum Miss (Ft)	15	18	14	12	19	16	9	12

Table 2. Tracking Task Averages for Pilot 3

SAS Type	Original	$\dot{\beta}$
Range at Gunfire (Ft)	3090	3370
Trigger Time (Sec)	1.4	1.3
Average Miss (Ft)	24.5	9.5
Average Error (Mil)	8.9	3.1

Additionally, the simulator was flown by Pilot 3 in a variety of maneuvers at all flight speeds in order to test the $\dot{\beta}$ SAS configuration. These maneuvers included wing-overs, dives, pushovers, landings, and rolling pullups, and were made in the presence of random pitch and side gusts. No undesirable flight characteristics were detected. In fact, flying appeared to be easier, and the pilot's workload less than with the original system. Throughout the test there was consistently more positive, more natural control of the aircraft with the $\dot{\beta}$ system.

Results and Recommendations

The results and recommendation of manned simulator performance evaluation are:

1. The three pilots rated the $\dot{\beta}$ system clearly superior to the original SAS

2. Superior handling qualities were reported by Pilot 3 in nonattack flying tasks for this system

3. The $\dot{\beta}$ system approximates a true, feet-on-the-floor system for attack speeds within 275-350 knots, which should provide near-optimum performance with any aircraft configuration over the attack speed range.

10. Flight Test Performance Evaluation

The real measure of performance of the SAS is the degree of proficiency with which the weapon delivery mission is accomplished. The performance of the SAS is evaluated in this section by a detailed analysis of abrupt heading changes and curvilinear strafes.

Load factor (n_z) and roll rate (p) are the most significant parameters to indicate the degree of aggressiveness with which the pilot accomplishes the curvilinear maneuver, i.e., the pilot sees the target, rolls in, and pulls up increasing the load factor to orient the aircraft toward the target as quickly as possible. During this portion of the maneuver the aircraft is banked at a large roll angle, ϕ, of between 70 and 130 degrees. Thus, the large heading change required to point at the target is accomplished primarily through pitch rate, and large n_z. As the pilot approaches the target in azimuth, the task is to roll out quickly while reducing load factor.

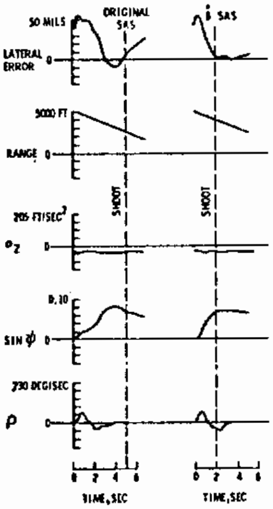

Figure 9. Tracking Scenario Comparisons

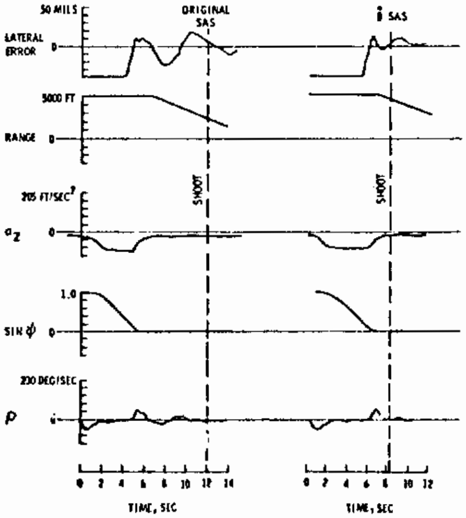

Figure 10. Gross Maneuver Scenario (ψ_0 = 90 Deg) Comparisons

Table 3. Summary of Aircraft Data from Gun Camera Films

SAS Type	At ϕ = 30 Degrees Airspeed (Knots)	Height AGL (Feet)	Pitch Att (Deg)	Range (Feet)	At Break Airspeed (Knots)	Height AGL (Feet)	Pitch Att (Deg)	Range (Feet)
$\dot{\beta}$ SAS	325	1350	-13	5050	345	750	-13	3000
	330	1500	-18	4700	348	900	-17	2550
	305	1500	-19	6100	325	1050	-15	3450
	300	1400	-16	7250	322	750	-12	3200
	320	1400	-19	4450	335	800	-16	2550
Average	316	1430	-17	5510	335	850	-14.6	2950
Original SAS	305	1120	-15	3750	315	570	-13	2500

Subsequent abrupt heading change maneuvers may be required to put the pipper on target and keep it there. The ability of the aircraft to make these changes quickly, as shown by the time required prior to firing, is the true measure of SAS characteristics and performance.

Abrupt Heading Change Data

The abrupt heading change maneuver consisted of stabilizing on one target with a 10-degree dive angle, a velocity of about 300 knots, and a range of about 4000 feet, then shifting to another target as quickly as possible. Maneuver time is measured from start of rollin to shoot. The most significant parameter in evaluating system performance is the maneuver time. However, this should be normalized to account for the varying magnitude of the heading change.

Averaging data over five pilots and many maneuvers for each pilot, the normalized maneuver time is 0.82 seconds per degree of heading change for heading changes of between 4.5 and 8.5 degrees. While no quantitative flight test data is available for the original SAS performance in this maneuver environment, qualitative examination of gun camera film, as well as pilot comments, reveal a large improvement in augmented aircraft response in these aggressive maneuvers. Furthermore, examination of the times required to achieve heading changes implies very aggressive maneuvering.

Curvilinear Strafe Data

The average values for maximum load factor and roll rate during the rollout, maximum bank angle during the turn, and tracking time were:

$$
\begin{aligned}
n_{z_{max}} &= 4.75g \\
p_{max} &= 93 \text{ deg/sec} \\
\phi_{max} &= 93 \text{ degrees} \\
\text{Tracking time} &= 2.33 \text{ seconds}
\end{aligned}
$$

during very aggressive maneuvering. The most important parameter is tracking time, but load factor, bank angle, and roll rate are all indicative of the pilots' confidence in the system.

Again, no quantitative flight test data for the original SAS are available for aircraft maneuvers of this degree of aggressiveness. However, the average tracking time of 2.33 seconds represents a reduction of more than 50 percent when compared with the original SAS, during significantly less aggressive maneuvers. This improvement is, perhaps, the most significant operational benefit derived from utilization of the task-oriented $\dot{\beta}$ SAS.

Gun Camera Film Analysis of Curvilinear Strafes

It was decided to analyze in detail all curvilinear strafes performed by one pilot for a complete flight with the $\dot{\beta}$ SAS, and one typical maneuver by the same pilot with the original SAS.

The gun camera film material is presented in tabular and time history form. Each maneuver is picked up during rollout at the time the roll angle had diminished in magnitude to 30 degrees. The horizontal and vertical offsets represent the angular offset from the pipper to the center of the target. Positive offsets indicate the target is up and to the right.

Table 3 presents approximate airspeed, altitude, pitch angle, and slant range at two points in time for each maneuver. The first time is when the roll angle has been reduced to 30 degrees during the rollout (elapsed time of zero), and at break (when pulling off the target). The airspeed, altitude, and pitch angle readings are HUD indications read from the gun camera film. Height is altitude decreased by 2430 feet, the gunnery range altitude, therefore the table presents height as above ground level (AGL).

The estimated slant range is an average of two calculations. The first is based on aircraft altitude above ground and the gunsight angle with respect to horizontal. The second estimates range from the film, using the known target size, and its apparent size relative to the 50-mil reticle diameter. These parameters are meant to give some feeling for the type of maneuvers which were being used.

Table 4 lists the data obtained from the gun camera film records of the terminal portion of the curvilinear strafe maneuver. The measurements in the table are the criteria for evaluating the SAS/aircraft combination, comprising the weapon delivery system as follows:

1. The time from $\phi = 30$ degrees to lateral offset ≤ 2.5 mils represents the time from the 30-degrees roll angle reference at rollout to when the pipper was stabilized within 2.5 mils of the target, thus indicating the time when gunfire could begin. The shortest time is the most desirable. Within 1 second from $\phi = 30$ degrees the azimuth offset (pipper from target) was held to less than ± 2.5 mils, on the average, with the $\dot{\beta}$ system. The same task could not be accomplished with the original SAS, i.e.,

Table 4. Summary of Curvilinear Strafe Performance Data from Gun Camera Films

SAS Type	Time From $\phi = 30^\circ$ to Lateral Offset ≤ 2.5 Mils (Sec)	Time Within ±2.5 Mils (Sec)	Time From $\phi = 30^\circ$ to ϕ_{SS} (Sec)	Total Maneuver Time (Sec)	% Time Within ±2.5 Mils	Lateral Offset at $\phi = 30^\circ$ (Mils)	Maximum Lateral Offset (Mils)	Time at Maximum Offset (Sec)
$\dot{\beta}$ SAS	1.78	3.6	0.50	5.4	67	0.0	5.0	0.40
	0.05	3.7	1.90	3.7	100	5.0	5.0	0.00
	0.00	3.2	0.20	3.2	100	1.0	2.5	0.40
	2.10	2.9	0.30	5.0	81	11.0	22.5	0.75
	0.58	2.6	0.50	3.6	72	25.0	25.0	0.00
Average	0.90	3.2	0.68	4.2	84	8.4	12.0	—
Original SAS	0.00	0.6	—	3.9	15	3.0	16.0	2.4–2.6, & 3.20

the pipper was offset more than 2.5 mils from the target throughout most of the maneuver

2. The time within ±2.5 mils laterally indicates the total time the pipper was held at less than 2.5 mils of the target in azimuth, and indicates vernier control in the lateral/directional mode. The longest time is the most desirable, and is 3.2 seconds for the $\dot{\beta}$SAS, and 0.6 second for the original SAS

3. The time from $\phi = 30$ degrees to ϕ_{SS} indicates the time taken to rollout, or the aggressiveness and subsequent controllability of the maneuver. The $\dot{\beta}$SAS time is 0.7 second, indicating a high level of controllability during a very aggressive maneuver. A steady-state bank angle did not occur with the original SAS, indicating that the pilot was continually maneuvering

4. The total time measures the time from roll reference (30 degrees) to pulloff from the target. This only indicates the maneuver duration

5. The percentage of time within ±2.5 mils in azimuth, which is the ratio of time within ±2.5 mils to the total time of the maneuver, measures firing opportunity. The $\dot{\beta}$SAS averaged 84 percent of the total time of the maneuver, as compared with only 15 percent for the original SAS. Note also that every maneuver with the $\dot{\beta}$ SAS was within ±2.5 mils for over two-thirds of the total time of the maneuver

6. The lateral offset at $\phi = 30$ degrees averages to 8.4 mils with the $\dot{\beta}$SAS, as compared with 3 mils with the original SAS. However, the maximum lateral offset occurring during the maneuver averages to 12 mils with the $\dot{\beta}$SAS, and is 16 mils with the original. The time to the greatest offset subsequent to the $\phi = 30$ degrees reference point is less than 1 second, indicating accurate control for the remainder of the maneuver with the $\dot{\beta}$SAS. Maximum lateral offset with the original SAS occurred from 2.4 to 2.6 seconds, and again at 3.2 seconds, indicating reduced controllability.

Time histories of typical curvilinear strafes with the original SAS and with the $\dot{\beta}$SAS are presented in Figures 11 and 12. Even though the maneuver with the original SAS is accomplished at a much lower roll rate than with the $\dot{\beta}$SAS, it is clear that the pilot has less control over pipper placement in the original configuration during this task.

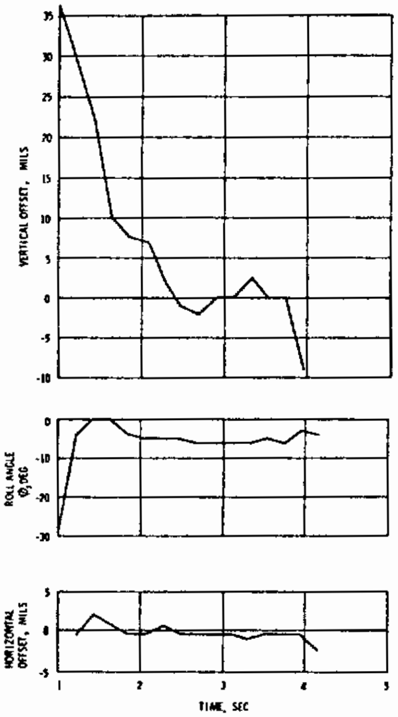

Figure 11. Gun Camera Tracking Data: $\dot{\beta}$ SAS

11. Conclusions

The concept of a task-oriented SAS seems fundamental, in retrospect, so successful was the design and implementation of the A-10 $\dot{\beta}$SAS. However, SAS design previously has been rarely motivated directly by the primary mission requirements of the aircraft, but rather by MIL-F-8785B, the generalized military flying qualities specifications.

The success of the task-oriented A-10 SAS design is indicated by the decision to incorporate the $\dot{\beta}$SAS in all subsequent production A-10 aircraft. Importantly, this success was achieved while adhering to the ground rule

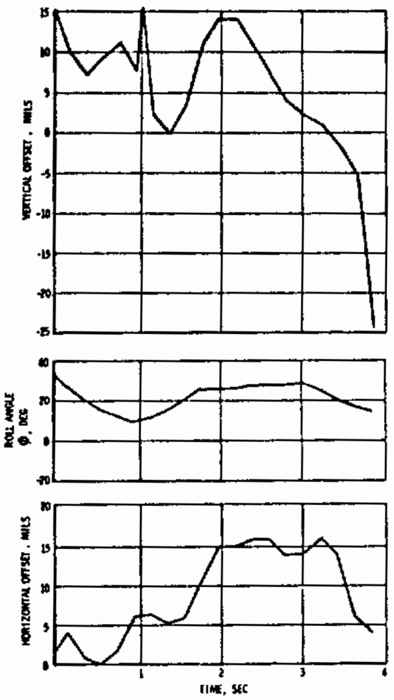

Figure 12. Gun Camera Tracking Data: Original SAS

that any improved SAS must not involve costly modifications, i.e., it must be cost-effective.

12. Acknowledgements

The development effort described in this paper was due to the combined efforts of many individuals, particularly: Mr. Wayne Thor and Capt. Mike Burski of the A-10 SPO; Ron Gague, Dick Quinlivan, and Dick Clark of the General Electric Company; the members of the Flight Dynamics, Avionics, and Flight Test Sections of the Fairchild Republic Company; and the Joint Test Force and Tactical Air Command pilots who participated in this program. The material presented is derived very largely from a paper entitled "Evaluation of a Cost Effective, TASK Oriented, Lateral Directional SAS for the A-10 aircraft" presented at the AIAA Aircraft Systems and Technology Conference in August, 1978.

13. Appendix

This appendix presents a brief outline of the various candidate estimates for $\dot{\beta}$ which were considered during the SAS design. The most complete (and costly) estimate for $\dot{\beta}$ is:

$$\hat{\dot{\beta}} = -r + (\alpha + \alpha_B)p + (g/V)\ \sin\phi\cos\theta + Y_A/mV$$

Cost-effectiveness was a primary goal in the design of this SAS, and thus various means of estimating $\dot{\beta}$ were considered closely so that the most cost-effective $\dot{\beta}$ estimate could be identified. All of the options considered were studied extensively via manned simulation, including both weapon delivery maneuvers and aerobatics.

The first simplification considered was the elimination of the aerodynamic side force term, Y_A. This did not affect significantly dynamic performance, and further eliminated a requirement for an accelerometer. It can also be shown by simple analysis that this result might be anticipated.

The LaPlace transformation of the side force equation can be written as:

$$\dot{\beta}(s) = s/(s + \bar{Y}_\beta)\ \dot{\beta}_0(s)$$

Where: $\bar{Y}_\beta = 0.20$ (at 300 knots, sea level)

$$\dot{\beta}_0(s) = -r(s) + (\alpha + \alpha_B)\ p(s) + (g/V)\ \phi(s)$$

It can be seen, on a linear basis, that the effect of dropping the side force term is to replace the term:

$$F(s) = s/(s + 0.20) = 5s/(5s + 1)$$

by unity. However, F(s) is seen to be a long time constant washout compared with the duration of tactical maneuver elements and will not significantly affect dynamic response during these maneuvers. Then, the estimate for $\dot{\beta}$ becomes:

$$\hat{\dot{\beta}} = -r + (\alpha + \alpha_B)\ p + (g/V)\ \sin\phi\cos\theta$$

Next, it was recognized that, in a low-altitude, tactical maneuver, the pitch angle is rarely large, so that the approximation $\cos\theta = 1$ should be evaluated. This approximation will produce a rudder command in error by $\epsilon_{\delta R}$, where:

$$\epsilon_{\delta R} = K_{\dot{\beta}} g\ \sin\phi(\cos\theta - 1)/V$$

It can be seen that this error will not be significant unless both roll and pitch angles are simultaneously large. This approximation does not have any noticeable effect on the tactical maneuvering simulation results, and did not produce unacceptable dynamic response, even for rolling maneuvers at approximately 90-degree pitch attitude. Based on these results, the estimate for $\dot{\beta}$ was taken to be:

$$\hat{\dot{\beta}} = -r + (\alpha + \alpha_B)\ p + g\ \sin\phi/V$$

The replacement of the g/V term with the piecewise constant $\bar{V}$ is described in the text. This approximation leads to the final form for the $\dot{\beta}$ estimate of:

$$\hat{\dot{\beta}} = -r + (\alpha + \alpha_B)\ p + g\ \sin\phi/\bar{V}$$

with which excellent flight test results were obtained. Other, still simpler, estimate schemes involving the replacement of the term $(\alpha + \alpha_B)$ p with a term $\bar{\alpha}$p, where $\bar{\alpha}$ is a constant, were also considered, but pilot preference led to the selection of the estimate presented above. This estimate is the simplest and least costly estimate which led to consistently good dynamic performance and pilot acceptance, and therefore was deemed to be the most cost-effective.

QUESTIONS AND ANSWERS

1. Dwight Schaefer - Boeing:

Question: $\dot{\beta}$ includes an a_y term. Was the effect of this term examined? What were the Dutch Roll stability characteristics for the two systems? Were the problems associated with the first yaw damper due to turn coordination, not Dutch Roll.

Answer: The effect of the a_y term was studied in detail. Both analytical and simulator studies were conducted. The conclusion was that, for the rapid maneuvers being considered, a_y feedback did not make any significant difference in dynamic response, i.e., β feedback was not required. The problems associated with the first yaw damper were caused by the nature of the sideslip response caused by the ARI and not due to Dutch Roll damping.

2. Chick Chalk, Calspan:

Question: You changed the phase of the sideslip, do pilots use the rudder?

Answer: Yes they generally still use the rudder but to a much smaller extent than they previously did. In fact, the dominant pilot comment in this area was that they had to relearn rudder technique and use much less rudder and furthermore to use it in a pulsed mode, i.e., get on and off the pedals very quickly.

3. Wayne Thor, ASD:

Question: Did the pilots rate the original SAS as level 1?

Answer: The lateral-directional SAS met 8785B level 1 for attack flight conditions. It did not meet level 1 for this scenario.

4. Bill Lamar, AFWAL:

Question: Have you considered additional degrees of freedom?

Answer: Yes, control of additional degrees of freedom has been and is being considered in order to enhance air-to-ground attack. Preliminary studies have shown that direct force can be very useful for enhancing this attack mode.

5. Tom Twisdale, AFFTC:

Question: Why didn't the problem with rapidly acquiring the target after a flight path correction surface in early simulation studies? Why did you have to wait till flight test to see it?

Answer: Early simulation studies focused on the originally planned tactical maneuvers which were satisfactorily accomplished. It was only as the maneuvers became very aggressive that the problem surfaced.