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A Piloted Simulation Investigation of the Normal Load Factor and Longitudinal Thrust Required for Air-to-Air Acquisition and Tracking

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ABSTRACT

A piloted simulation study was performed by the U.S. Army Aeroflightdynamics Directorate to develop insight into the maneuverability requirements for aggressive helicopter maneuvering tasks such as air-to-air combat. Both a conventional helicopter and a helicopter with auxiliary thrust were examined. The aircraft parameters of interest were the normal and longitudinal load factor envelopes. Of particular interest were the mission performance and handling qualities tradeoffs with the parameters of interest. Two air-to-air acquisition and tracking tasks and a return-to-cover task were performed to assess mission performance. Results indicate that without auxiliary thrust, the ownship normal load factor capability needs to match that of the adversary in order to provide satisfactory handling qualities. Auxiliary thrust provides significant handling qualities advantages and can be substituted to some extent for normal load factor capability. Auxiliary thrust levels as low as 0.2 thrust/weight can provide significant handling qualities advantages.

NOTATION

L_p	roll damping coefficient, 1/sec
M_q	pitch damping coefficient, 1/sec
N_x	longitudinal load factor, g
N_z	normal load factor, g
u_{body}	longitudinal airspeed, ft/sec
V	total airspeed ft/sec
x	inertial position, ft
y	inertial position, ft
z	vertical position, ft (+down)
γ	climb angle, rad
ϕ	roll attitude, rad
ψ	heading, rad

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INTRODUCTION

The primary objective of this simulation experiment was to develop insight into the maneuverability requirements for aggressive helicopter maneuvering tasks such as air-to-air combat. Maneuverability and agility (MA) has been a topic of research for many years in both the fixed and rotary wing communities (Refs. 1-18). It is generally agreed that maneuverability is some measure of the maximum achievable time-rate-of-change of the velocity vector and that agility is the measure of the maximum achievable time-rate-of-change of the acceleration vector. It is also agreed that good MA is a key requirement for success in highly dynamic missions such as air-to-air combat. Unfortunately, that's where the agreement stops. A precise definition of MA and a quantification of the amount required have never been agreed upon. Regrettably, this author believes it unlikely that there will be agreement at any time in the near future.

To change the magnitude and direction of the velocity vector one has to apply a force. Obviously, then, the major contributor to good maneuverability is the ability to generate normal, longitudinal, and lateral load factor. In a conventional helicopter, acceleration is generated by changing the magnitude and direction of the main rotor thrust. In a compound helicopter, acceleration is generated by using a combination of the magnitude and/or the direction of the main rotor thrust and the magnitude of the auxiliary thrust. Maneuverability was examined in the context of these facts during this experiment. Namely, the effects that variations in the load factor envelope have on handling qualities and mission performance for some representative "aggressive" tasks were investigated. By taking this approach, it was expected that a set of data would be generated from which information regarding the relationship between maneuverability, mission performance, and handling qualities could be obtained.

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DESIGN AND CONDUCT OF THE EXPERIMENT

To accomplish the stated objectives, a five week piloted simulation investigation was conducted on the NASA Ames Research Center (ARC) Vertical Motion Simulator (VMS) (Refs. 19, 20). This section contains a detailed description of the experiment, including the experimental facility, ownship and adversary aircraft, experimental variables, evaluation tasks, evaluation pilots, and collection of experimental data.

Facility Description

The investigation was conducted using the six-degree-of-freedom VMS with the NCAB cockpit (Fig. 1). The VMS is unique among flight simulators in its large range of motion (Table 1). This large motion capability provides cues to the pilot that are critical to the study of handling qualities.

The primary inputs to the motion base are the translational and rotational accelerations calculated by the math model for the pilot position. These signals are filtered by second-order washout filters characterized by a gain and a washout frequency. The motion system parameters used for this experiment were tuned to minimize the phase error between the accelerations generated by the model and those generated by the motion base while at the same time providing the largest possible motion envelope within the software limits.

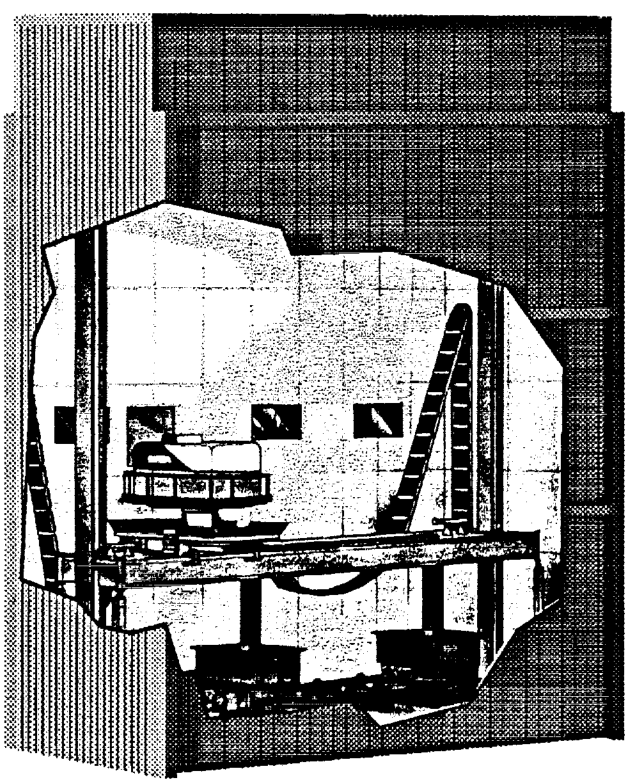

Figure 1. NASA Ames Research Center Vertical Motion Simulator.

Table 1. Vertical Motion Simulator motion limits.

	Displ. (ft)	Rate (ft/sec)	Accel. (ft/sec^2)
Long.	±4	±4	±10
Lat.	±20	±8	±16
Vert.	±30	±16	±24
	(deg)	(deg/sec)	(deg/sec^2)
Pitch	±18	±40	±115
Roll	±18	±40	±115
Yaw	±24	±46	±115

The NCAB was configured as a single pilot cockpit with a three window computer generated imagery (CGI) display. The field of view is shown in Figure 2. The CGI database used for this experiment contained an 8-kilometer-by-16-kilometer gaming area consisting of mountains, rivers, and roadways. There was a ground pattern but no ground texturing.

Conventional helicopter controllers were used. A summary of the force characteristics of the controllers is contained in Table 2. Stick force per g was provided by scaling the cyclic pitch stick gradient with load factor:

$$\text{pitch gradient (lb/in.)} = 2.0\,N_z - 0.5.$$

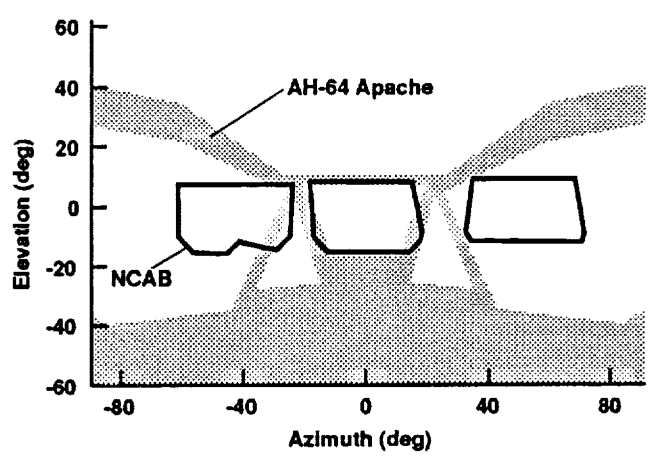

Figure 2. NCAB field of view.

Table 2. Controller characteristics.

	Pitch	Roll	Yaw	Heave
Range (in.)	±6.15	±6.10	±3.40	0 - 10.0
Deadzone (in.)	±0.15	±0.10	±0.15	0
Breakout (lb)	1.5	1.0	4.0	0
Gradient (lb/in.)	1.5[a]	1.0	2.5	0
Damp. (lb/in./sec)	0.8	0.5	1.0	0
Friction (lb)	1.0	1.0	2.0	3.0

[a] at 1.0 g

Four inceptors for the control of the auxiliary thruster were examined during the early stages of the simulation (Fig. 3). The four were: 1) a thumbwheel on the cyclic grip that contained a center detent but no spring gradient; 2) a thumb joystick on top of the cyclic grip; 3) a twist grip on the collective that contained only friction; and 4) a beep switch on the collective head. The thumbwheel and the collective twist grip were used as either direct X-force-command or u_{body}-command. The collective beep switch and the cyclic thumb joystick were used as either X-force-rate-command or u_{body}-rate-command. This gave eight auxiliary thruster control possibilities.

The instrument panel included a horizontal situation indicator (HSI), an airspeed indicator, a barometric altimeter, a vertical speed indicator, a turn and slip indicator, a torque meter, and a load factor meter. Also included was a moving map display which showed the relative position, altitude, and heading of the ownship and adversary.

Figure 4 shows the heads-up display (HUD) symbology. Included on the HUD were a torque meter, a radar altitude tape, a horizon bar, a heading tape, a sideslip ball, and digital readouts of torque, load factor, airspeed, radar altitude, and range to target. In the center of the display was a vector indicating the horizontal direction and range to the adversary, relative to the ownship nose. On the bottom of the display was an adversary position display that showed the azimuth and elevation of the adversary relative to the ownship nose. A floating pipper was used to track the target during the air-to-air task. The azimuth and elevation offset of the pipper from the boresight was computed in order to provide the proper lead angle required for a hypothetical fixed-forward-firing gun. Specifically, when the pipper was

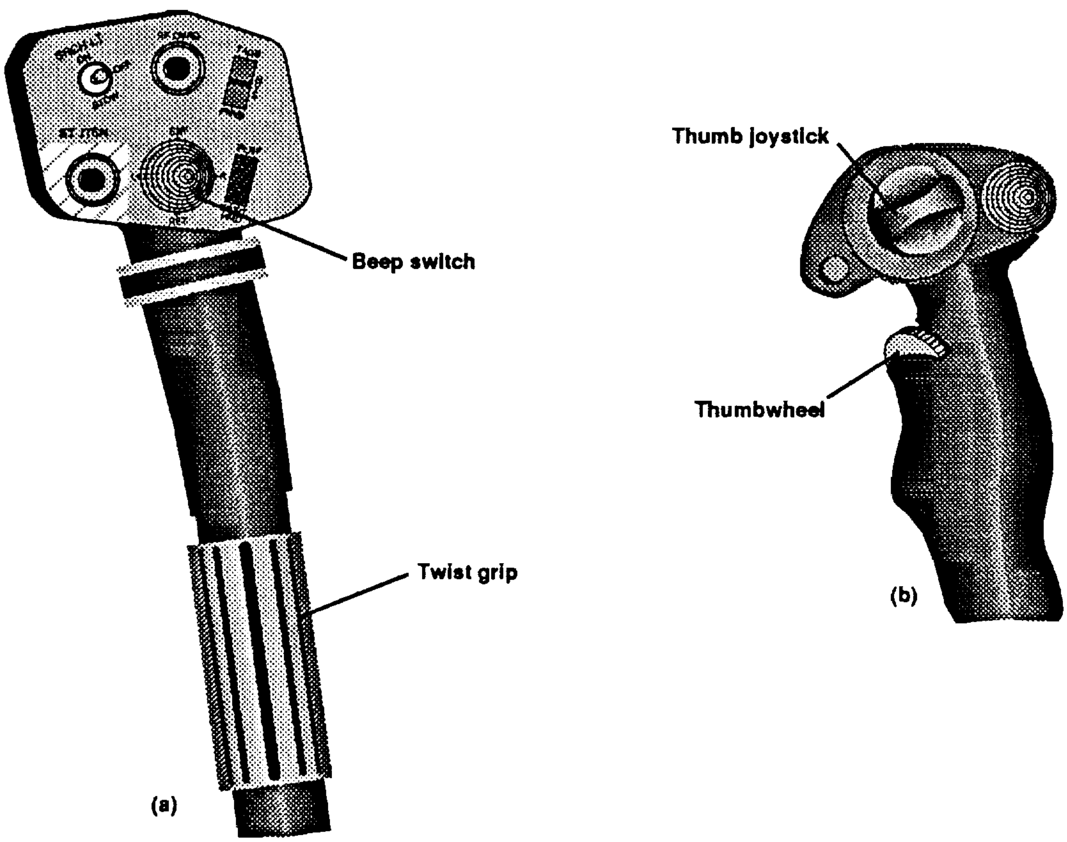

Figure 3. Location of auxiliary thrust control inceptors. (a) collective grip; (b) cyclic grip

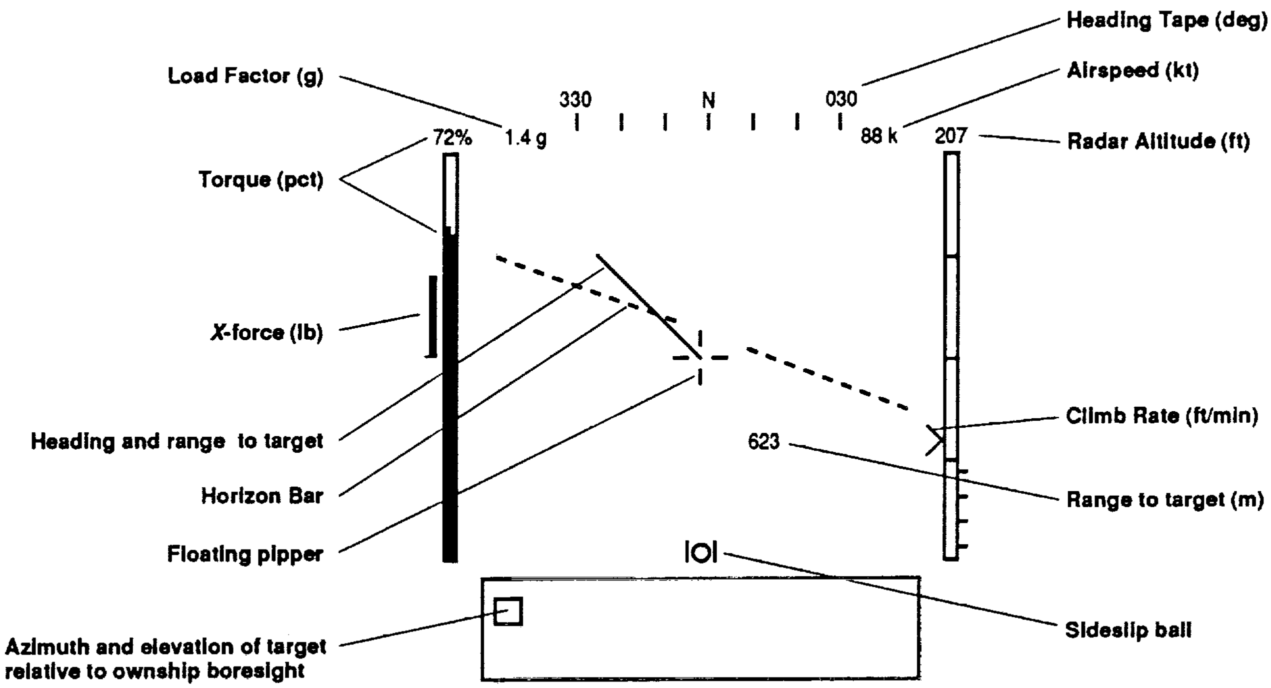

Figure 4. Heads-up display symbology

overlaid on the target, the boresight of the aircraft was pointing at the predicted target location one bullet time-of-flight into the future.

Rotor, engine, and transmission noises were simulated using a Wavetek Helicopter Sound Simulation System. Warning tones and weapon noises were simulated using a Mirage sound system generator.

A seat shaker simulated aircraft vibration. The vibration math model was based on the vibration model developed for a high-fidelity UH-60A Blackhawk simulation (Ref. 21). The amplitude and frequency of vibration were calculated as functions of rotor speed, collective stick position, load factor, and airspeed.

The stick-to-visual throughput time delay was 74.5 milliseconds. No visual time delay compensation was used because the stick-to-visual time delay already closely matched the stick-to-motion time delay in the pitch and roll axes.

AUTOMAN

The air-to-air adversary used during this experiment was the AUTOmated MANeuvering (AUTOMAN) opponent developed by Grumman Corporation under contract to the U.S. Army Aeroflightdynamics Directorate (Refs. 22, 23). In the past, air-to-air simulation experiments have relied on either a second pilot flying the adversary aircraft, or simple pre-programmed flight paths for the adversary aircraft. Both of these approaches can have drawbacks. Using a piloted target can lead to undesirable variations in the aggressiveness of the engagements, because the target pilot cannot always employ consistent maneuvering logic. In addition, a piloted target requires the use of one of the CGI channels, thus degrading the visual presentation to the ownship pilot. Preprogrammed flight paths can lead to skewed results because the pilot is able to memorize the flight path of the target and anticipate its movement. The AUTOMAN program was therefore developed to alleviate these problems.

The AUTOMAN computer program generates automated maneuvering decisions for helicopters during air-to-air combat at low altitude in hilly terrain. Maneuvers are selected by employing simple game theory (Ref. 24). Capabilities of AUTOMAN include a guidance law for target acquisition when a firing opportunity arises; fire-control sequence logic; low-flying capabilities; line-of-sight computations for the cockpit field-of-view; air-to-air collision avoidance maneuvers; decisions on and adjustable levels of simulated pilot experience.

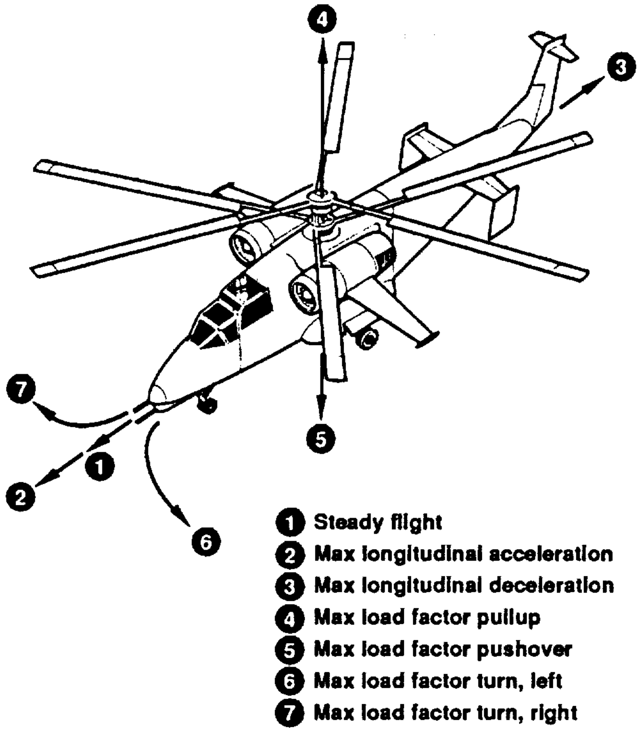

Figure 5. AUTOMAN elemental maneuvers

To determine the best maneuver choice, the consequences of performing various maneuvers are evaluated. It is assumed that each aircraft selects one of the seven elemental maneuvers shown in Figure 5. While the maneuvers shown are maximum-performance turns, climbs, etc., there are first-order lags, typical of the actual responses of the aircraft, between the command and control variables; consequently, the maneuvers are achieved gradually. Since maneuver choices are updated frequently, moderate maneuvers can occur as the average of a sequence of short-duration, maximum-performance maneuvers.

The helicopter math model used by AUTOMAN is a simple point mass model which performs coordinated turns. The equations of motion are as follows:

$$\dot{x} = V\cos\gamma\cos\psi$$
$$\dot{y} = V\cos\gamma\sin\psi$$
$$\dot{z} = -V\sin\gamma$$
$$\dot{V} = g(N_x - \sin\gamma)$$
$$\dot{\gamma} = \frac{g}{V}(N_z\cos\phi - \cos\gamma)$$
$$\dot{\psi} = \frac{gN_z\sin\phi}{V\cos\gamma}$$

Table 3. AUTOMAN time constants and angular rate constraints

N_x time constant	1.0 sec
N_z time constant	0.2 sec
$\dot{\phi}$ time constant	.2375 sec
maximum $\dot{\phi}$	57.3 deg/sec
maximum $\dot{\gamma}$	120 deg/sec
maximum $\dot{\psi}$	40 deg/sec

The control variables are the roll rate $\dot{\phi}$ and the longitudinal and normal load factors, N_x and N_z, and the corresponding commands are $\dot{\phi}_c$, N_{xc}, and N_{zc}. A first order lag is assumed between the commanded values and the response. A summary of the time constants and angular rate constraints used in AUTOMAN for this experiment is given in Table 3. Figure 6 shows the AUTOMAN load factor, longitudinal acceleration, and turn rate capabilities.

Ownship Math Model

A stability derivative helicopter math model termed the Enhanced Stability Derivative Model (ESD) was used as the ownship. The ESD model is a derivative

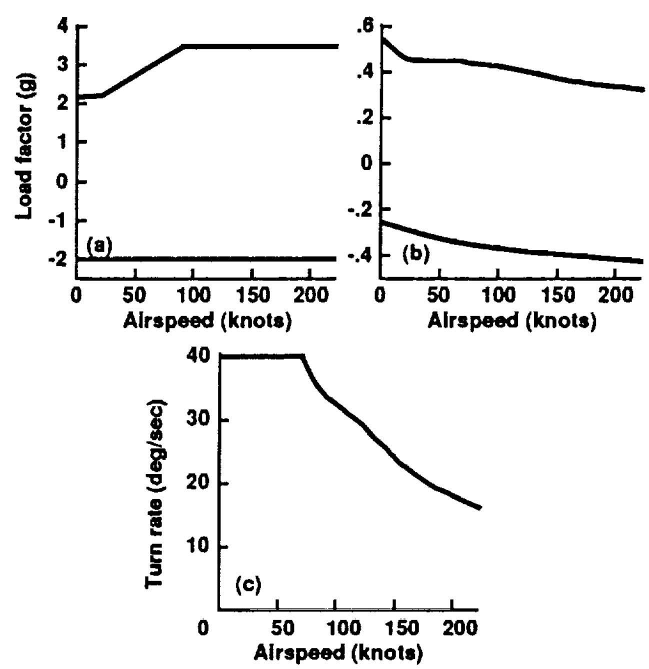

Figure 6. Performance capabilities of AUTOMAN (from Reference 22). (a) maximum and minimum normal load factor; (b) maximum and minimum longitudinal load factor; (c) maximum turn rate.

of the TMAN model developed for the Helicopter Air Combat (HAC) simulation experiments (Refs. 25-27). Earlier versions of the ESD model have been used for other handling qualities experiments (Refs. 28,29). The ESD model is a simple, non-linear, generic helicopter math model intended for use as a handling qualities research tool. The response dynamics are easily modified thus allowing a wide range of handling qualities to be studied. It includes the effect of load factor on the pitch and roll rate damping derivatives, the effect of forward speed on the force derivatives, a collective trim curve, and a ground effect model. The attitude response is rate-type in pitch, roll, and yaw with automatic turn coordination above fifty knots. The total aerodynamic forces and moments required for the six-degree-of-freedom equations of motion are generated as the summation of reference and first-order terms of a Taylor series expansion about a reference trajectory. The model does not include control or response coupling.

Auxiliary Thruster — An auxiliary thruster with a selectable force or u_{body} command system was added for this experiment. Table 4 shows a summary of the various control-inceptor/control-response types. The math model assumed axial flow through a 10 ft diameter propeller and included the effects of both power and stall limitations. Figure 7 shows a pitch trim sweep for a configuration with a 3.5 g normal load factor capability and auxiliary thrust/weight ratios of 0.1, 0.2, and 0.33. The solid lines indicate the maximum nose-up and nose-down attitudes that the configuration can trim at in level flight. The dashed line indicates the trim pitch attitude for the same configuration with no auxiliary thruster.

Experimental Variables

Normal and longitudinal load factor envelope were varied during this experiment. Maximum

Table 4. Auxiliary thruster control system gains.

Inceptor	Response Type
cyclic joystick	force rate
cyclic joystick	u_{body} rate
cyclic thumbwheel	force
cyclic thumbwheel	u_{body}
collective beep switch	force rate
collective beep switch	u_{body} rate
collective twist grip	force
collective twist grip	u_{body}

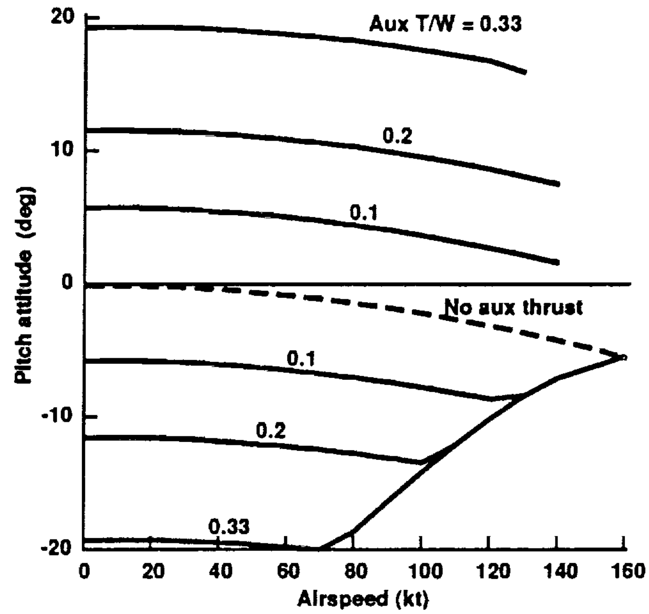

Figure 7. Pitch trim sweep of configuration with auxiliary thruster

continuous normal load factor capability was varied from 1.5 to 5.0 g (at 80 kt). Maximum longitudinal load factor capability was varied only for the thrust augmented cases and was varied from 0.1 to 1.0 auxiliary thrust/weight ratio. The transient load factor limit was set equal to 1.33 times the maximum continuous load factor capability at 80 kt. Table 5 shows the configurations matrix.

Tasks

Three tasks were flown during the experiment — the abeam air-to-air task, the mountain air-to-air task, and the return-to-cover task. The intent was to obtain handling qualities and mission performance data with respect to variations in the load factor envelope and auxiliary thrust level.

Air-to-air tasks — Both of the air-to-air tasks were taken from the RATAC experiment (Ref. 29). The objective of both tasks was the same; to track the AUTOMAN for as long as possible using the ownship pipper on the HUD. The position of the pipper on the HUD was driven by a set of equations such that the proper lead angle for a fixed-forward-firing gun was displayed. As mentioned earlier, when the pilot overlaid the pipper on the target, the nose of the ownship was pointed at the estimated location of the target one bullet-time-of-flight into the future. In addition, the pilot was required to

Table 5. Configuration test matrix

	Auxiliary thrust/weight					
N_z (g)[a]	0	0.1	0.2	0.33[b]	0.6	1.0
1.5	AMM_2R			AM		
1.75	AMR			AM		
2.0	AMM_2R	A		AM		
2.5	AMR			AM		
3.0	AMR	AM	AM	AMR	AMR	AR
3.5	AMM_2	M	M	AM		
4.0	AMR			AM		AM
5.0	AMR			AM		

A - Abeam air-to-air task
M - Mountain air-to-air task
M_2 - Mountain air-to-air task, low capability adversary
R - Return-to-cover task
[a] Maximum continuous capability at 80 knots.
[b] This level of thrust/weight represents the average value of several compound helicopters surveyed.

maintain less than 0.2 g lateral acceleration, two ball widths, while tracking. Pilots were encouraged to maintain airspeed above forty-five knots. Each run was limited to 25 seconds.

The initial conditions for the abeam air-to-air task are shown in Figure 8. The target was positioned 2000 feet in front of, and 100 feet below the ownship with a heading 135 degrees away to the left or right. The ownship was initialized at its maximum maneuvering speed, 80 knots, while the target was initialized at 120 knots. Line-of-sight existed for both aircraft over hilly terrain. The initial target heading was randomly set to either the left or right before each run to introduce some variability to the task. A typical run of the abeam task is shown in Figure 9.

The initial conditions for the mountain air-to-air task are shown in Figure 10. This task began with a mountain preventing line of sight between the two aircraft. The ownship was initialized at its maximum maneuvering speed, 80 knots, while the target was initialized at 140 knots. The initial target heading was randomly set to either the left or right before each run. A typical run of the mountain task is shown in Figure 11.

Task performance standards were based on the longest continuous tracking period measured during the run. Tracking time accumulated whenever the AUTOMAN cg was within 30 feet of a vector defined by the ownship pipper, azimuth and elevation < $\tan^{-1}$(30/range), and the ownship lateral acceleration was less than 0.2 g. Performance for the longest tracking period was categorized as unsatisfactory (< 2.0 seconds), adequate (>= 2.0, < 4.0 seconds), or desired (>= 4.0 seconds). These levels ensured a baseline level of aggression among the pilots. Task performance was indicated to the pilot via audio tones in the headset; i.e., a low, continuous tone meant that he was within the tracking constraints, a high continuous tone meant that he had met the constraints for 2.0 seconds, and a high, intermittent tone meant that he had met the constraints for

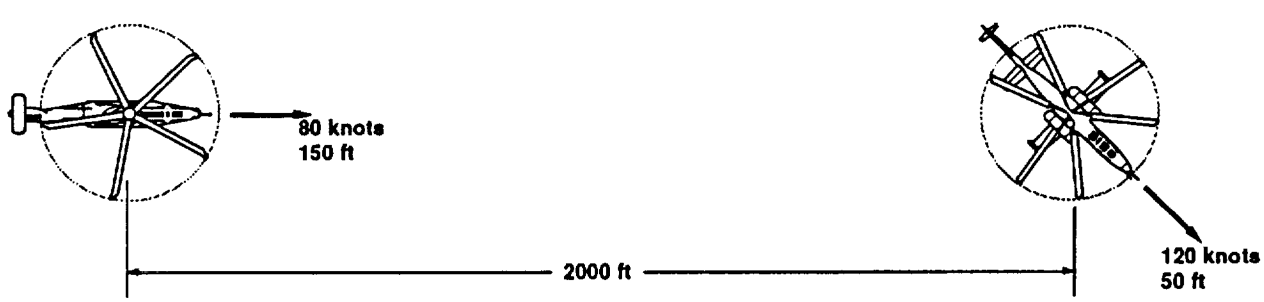

Figure 8. Abeam air-to-air task initial conditions.

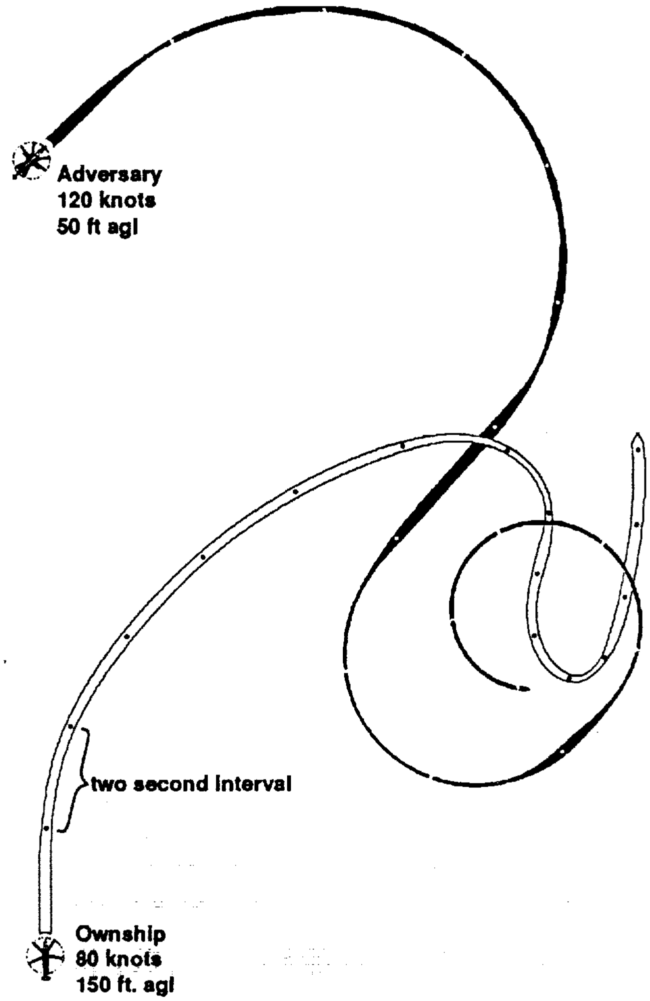

Figure 9. Typical run of the abeam air-to-air task

4.0 seconds. Pilots were encouraged not to assign CHR's based solely on their performance relative to these standards, but to assess the overall handling qualities of the vehicle.

To prevent the pilots from employing the stand-off techniques characteristic of missile engagements, the tracking cone was configured to only allow tracking within a thirty foot radius circle at the target range. This made distant engagements more difficult than close ones, resulting in more dynamic close-in maneuvering.

The run length was limited to twenty-five seconds because that was the point at which the engagements typically degraded into a "furball." Under those conditions, the generation of useful handling qualities data was difficult.

During the experiment, similar tactics for the air-to-air task emerged for all of the pilots. Task initial conditions created the opportunity for the ownship pilot to immediately begin tracking by using an aggressive lateral input. As the engagement progressed, tracking opportunities became clustered at ranges of less than 1000 feet. Given the dimensions and orientation of the tracking cone, a close-in, tail chase position provided the greatest performance potential, making it the tactical objective. A tail chase position also offered an advantage in maintaining situational awareness. Pilots found that it was essential to keep the target in sight, to maintain airspeed, and to establish a slight altitude advantage if they expected to perform well and to remain oriented.

During the experiment, the AUTOMAN usually tried to overcome the initial tactical disadvantage by performing a maximum performance turn towards the ownship culminating in a head-on engagement. Once the AUTOMAN had closed in on the ownship, it would continue to perform turns and roll reversals in an attempt to achieve a gun solution. Occasionally, the AUTOMAN

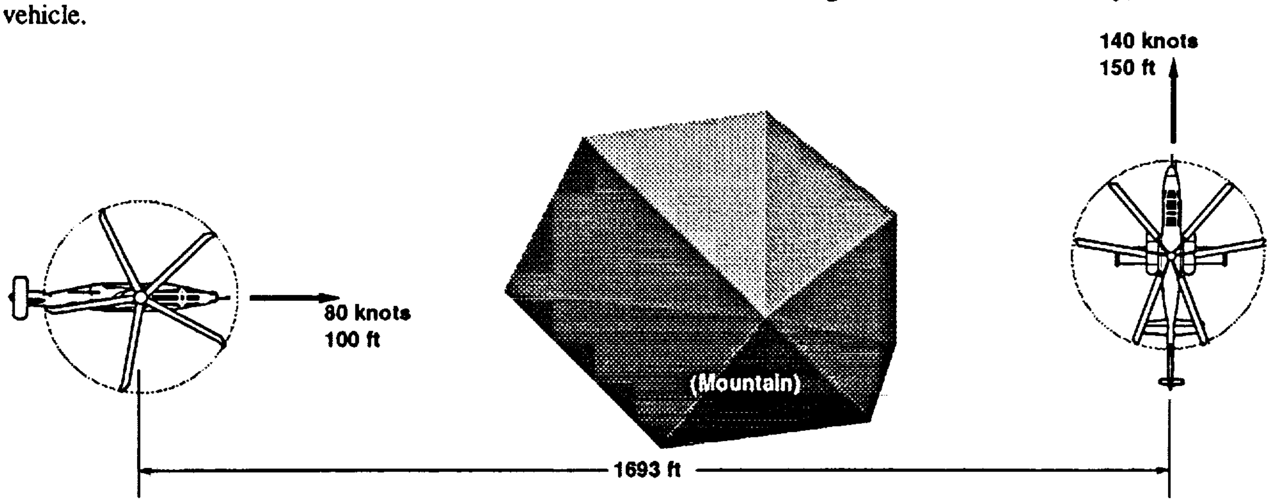

Figure 10. Mountain air-to-air task initial conditions

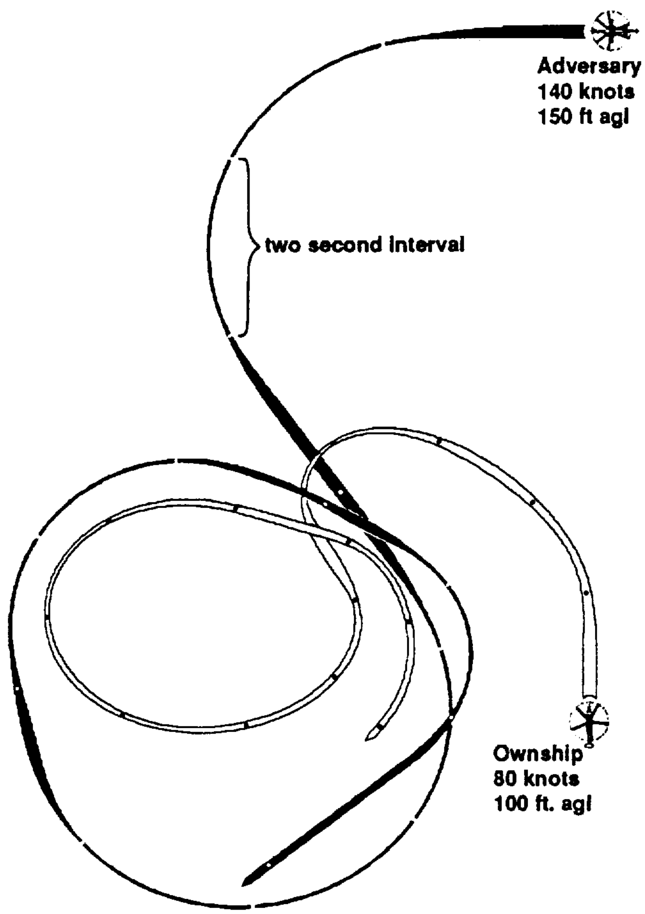

Figure 11. Typical run of the mountain air-to-air task

would turn away from the ownship in what appeared to be an attempt to disengage. Engagements usually concluded with the ownship having either improved or lost the advantage enjoyed at the outset. On rare occasions, the AUTOMAN had enough time to reverse its tactical disadvantage and place the ownship on the defensive.

Return-to-cover task — Figure 12 shows the return-to-cover task. The objective of the task was to return to the cover of the treeline as quickly as possible. The task was initialized with the ownship flying 80 kt at 100 ft above ground level (AGL). After the ownship passed over the treeline and the tank, the pilot was signaled to initiate a maneuver and return to the cover of the treeline as soon as possible.

Pilots

One U.S. Army/Ames test pilot, two NASA/Ames test pilots and one U.S. Army/AQTD test pilot participated in the experiment. All four pilots have had extensive handling qualities evaluation experience in

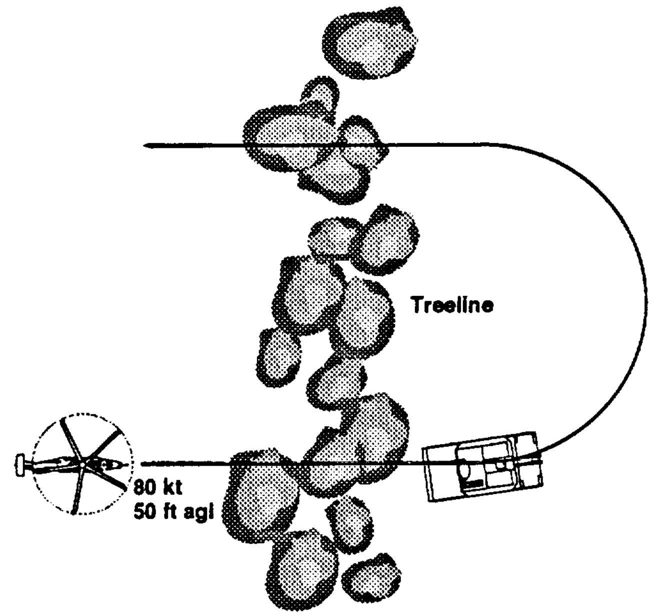

Figure 12. Return-to-cover task initial conditions.

a wide range of fixed and rotary wing aircraft.

Data Collection

Four types of data were collected during this experiment. Real time variables of interest such as position, attitude, and rates were digitally recorded. Performance measures such as time-on-target were recorded and printed out at the end of each run. Qualitative pilot opinion was gathered for each configuration in the form of commentary and a Cooper-Harper rating (CHR) (Ref. 31).

To minimize the effects of training, each pilot was given several hours to practice the tasks. During this time, task performance was communicated to the pilot at the end of each run. Data were not collected until both the pilot and the investigator were convinced that the pilot had achieved the necessary skill level.

Collection of data proceeded as follows. The helicopter was initialized in the test configuration and task. The pilot was not informed of which configuration he was flying. The pilot was allowed to practice the task until he was satisfied that his performance would not improve substantially with additional practice. At that point, the data collection equipment was turned on and the pilot proceeded to perform the task. After a minimum of three representative runs were completed, the pilot gave commentary and assigned a CHR.

RESULTS

This section contains the qualitative and quantitative data gathered during the experiment. The results from variations in load factor capability and auxiliary thrust level are presented in the form of task performance, CHRs, and pilot commentary. The data shown are a summary of the data gathered for all four pilots who participated unless otherwise noted.

The level of confidence in the data was measured. The range within which the true mean will occur with a ninety percent probability has been calculated using the *t*-test (Ref. 32). This confidence interval is indicated using error bars on the task performance plots and CHR summary plots. More simply stated, the true mean of the entire pilot population has a ninety percent chance of occurring within the error bars shown. This type of deviation calculation is useful in that it reflects both the spread and quantity of data collected.

Load Factor

Figure 13 shows a summary of the CHR data plotted versus load factor capability for the air-to-air task versus the 3.5 g adversary. Figure 14 shows a summary of the task performance data plotted versus load factor capability. The error bars indicate the ninety percent confidence interval for the data. The CHR data have been averaged together for the two air-to-air tasks because of the great similarity in tactics, control strategy, and workload. The performance data have been separated because the different initial conditions for the two tasks led to slightly different time-on-target results. The performance data for the abeam task do not include the first ten seconds of each run because the pilots found the tracking task to be relatively easy during this portion of the task and did not feel it was relevant to their evaluation of the configuration.

The CHR summary data indicate that a minimum load factor capability of 2 g is required for Level 2 handling qualities and a load factor capability of 3.5 g is required for Level 1 handling qualities. The performance data support the CHR data. There is a general improvement in performance out to 3.5 g and then a tapering off.

The pilot commentary strongly indicates that the Level 3 configurations lacked adequate maneuvering capability. For a 1.5 g configuration, pilot A states,

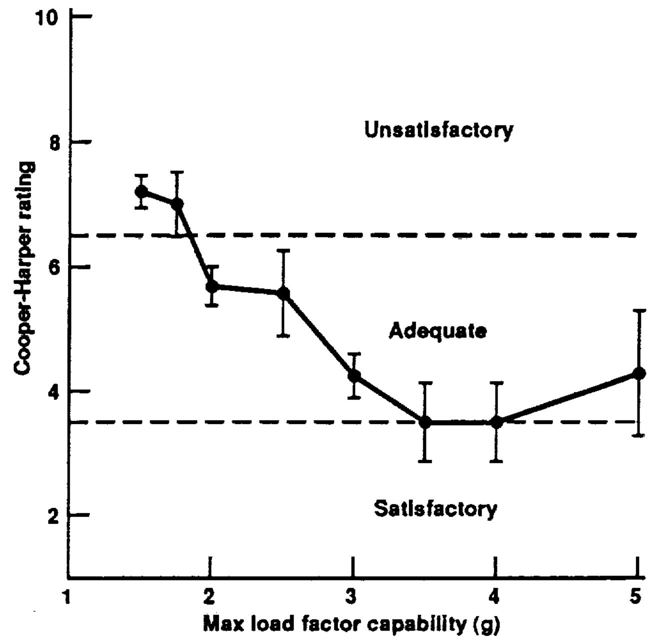

Figure 13. Cooper-Harper pilot ratings versus load factor capability.

"I think there was an inability to meet adequate performance standards. It was almost an inability to remain in flight. The primary reason was that you just didn't have anything to maneuver with. There was just no performance to gain out of the helicopter."

For a 1.75 g configuration, pilot A states,

"You just can't turn. You find yourself sinking down to the ground into the trees or into the hillside. It seemed like when you did get on the target you could stabilize pretty well, but it didn't stay on the target very long and it was difficult to track the target with the pipper. ... I would give this major deficiencies in that you can't achieve adequate performance, and there may even be a question of considerable pilot compensation to retain control."

Pilot comments for the Level 2 configurations indicate some improvement in the overall handling qualities but still not enough maneuverability to perform the task satisfactorily. Pilot C states that with the 2.0 g configuration,

"I think that it is shown that given this set of tactics and this level of capability on the aggressors part, that you can, in fact, get some reasonable tracking time on the guy But you can't expect to have immediate gratification. If you have to keep flying the aircraft and keep working it

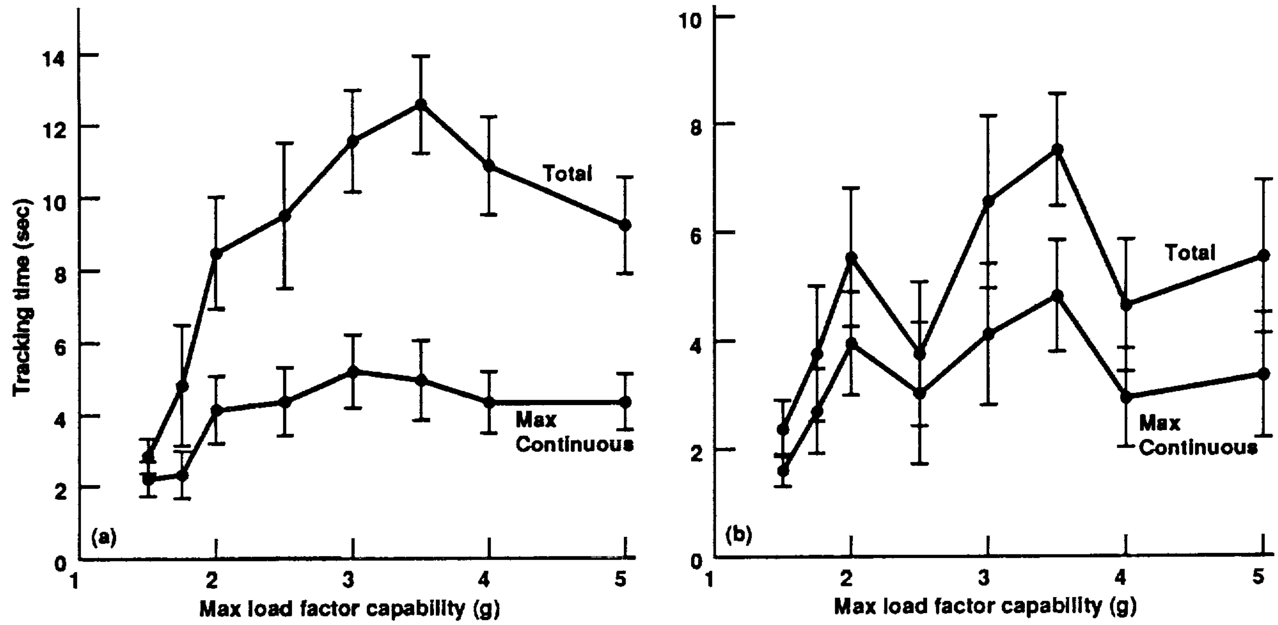

Figure 14. Task performance versus load factor capability. (a) mountain task; (b) abeam task.

into a position, you can not just pull the aircraft into position and expect to be able to ride there. The load factor does not allow that. ... You really do have to look at the load factor and the airspeed, make sure that you have the power all the way in, and be very careful with the controls. You keep telling yourself, 'don't pull any harder,' and see what happens."

The commentary for the Level 1 configurations indicate satisfaction with the maneuver capability. For a 3.5 g configuration Pilot E states,

"I would say that we definitely got desired performance for the most part. ... It was a pretty aggressive run, I didn't feel like I was limited in the aircraft in any way."

It is interesting to note the degradation in CHRs which occurred when the load factor capability was increased to 5.0 g. The pilot commentary indicated that the pitch and roll axes became more "ratchety" and "oscillatory." Pilot A stated,

"It seemed like it was a little bit more difficult to stabilize on the target with the high g load. It had a tendency to oscillate back and forth off the target and out of the cone. ... I'd say that there is a slightly objectionable control oscillation and slightly objectionable number of control reversals."

Pilot E stated,

"I found the oscillations to be something that is actually kind of interesting. I don't know why it is that I should be walking the target as badly — but it happened over and over again. I'm not sure if that is from trying too hard, or if there is some artifact of having a lot of power on the rotor system. Something makes it a little bit more goosey than I would expect from past experience."

What the pilots were probably experiencing was a result of the way the pitch and roll damping derivatives were scheduled with load factor. Figure 15 shows a plot of pitch and roll damping versus load factor as was implemented in the math model for this experiment. It can be seen that at 5.0 g the damping derivatives were approximately -12.0 and -14.0 1/sec in pitch and roll respectively. At this level, the pitch and roll response of the math model may have excited CGI and motion system dynamics that could be characterized as objectionably abrupt or ratchety as was seen during the RATAC experiment (Ref. 29).

Figure 16 shows a histogram of load factor usage for each of the eight different load factor configurations examined. The data shown are a summary of all runs flown of both air-to-air tasks by all of the pilots. It can be seen that for the configurations which had less than 3.0 g capability, the pilots were using all of the continuous load factor capability available and encountering the transient limit a significant amount of the time. For the configurations at or above 3.0 g capability the pilots were

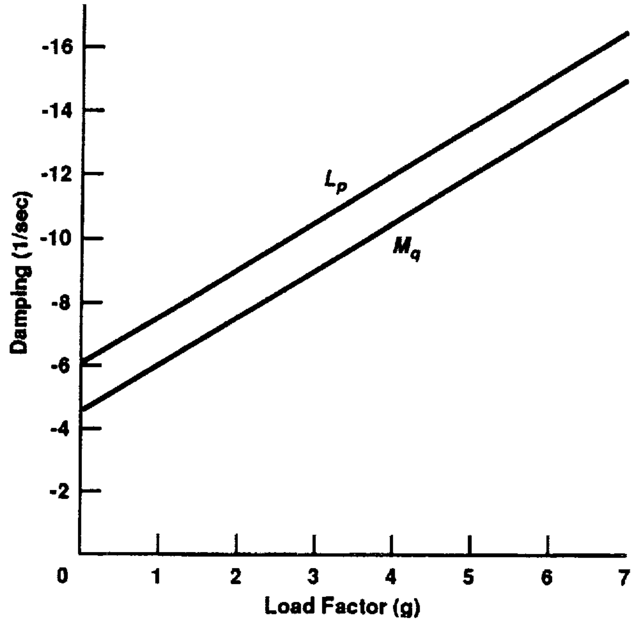

Figure 15. Variation of pitch and roll damping with load factor.

not encountering the transient limit at all. For the 4.0 and 5.0 g cases the pilots were rarely making use of the continuous capabilities of the configuration, if at all. These data support the previous commentary which indicated the pilots dissatisfaction with the maneuver capability of the Level 2 and Level 3 configurations.

It is important to note that all of the data presented so far are from air-to-air engagements against an adversary which had a continuous load factor capability of 3.5 g (Fig. 6). It is reasonable to expect that an adversary with a different maneuvering capability would change the maneuverability required of the ownship to successfully engage him air-to-air combat. Figure 17 shows CHR and performance data that was gathered for the same air-to-air tasks but against a low-capability adversary (only 2.0 g continuous load factor capability). Only two pilots participated in this portion of the experiment and only the 1.5, 2.0, and 3.5 g configurations were evaluated.

As one would expect, the 2.0 g adversary did not demand as much maneuvering capability from the ownship. The CHRs indicate that the pilots required a load factor capability only comparable to that of the adversary in order to successfully engage him. The performance data supports the CHR results. Pilot B states that for the 2.0 g ownship configuration,

"It was fairly easy to meet desired performance standards both in getting on to his tail and staying on his tail. ... You didn't have to perform the task too aggressively, because the target aircraft wasn't very aggressive. ... Minimal pilot compensation required for desired performance."

Figure 18 shows a plot of the mean time that was required during the return-to-cover task versus the load

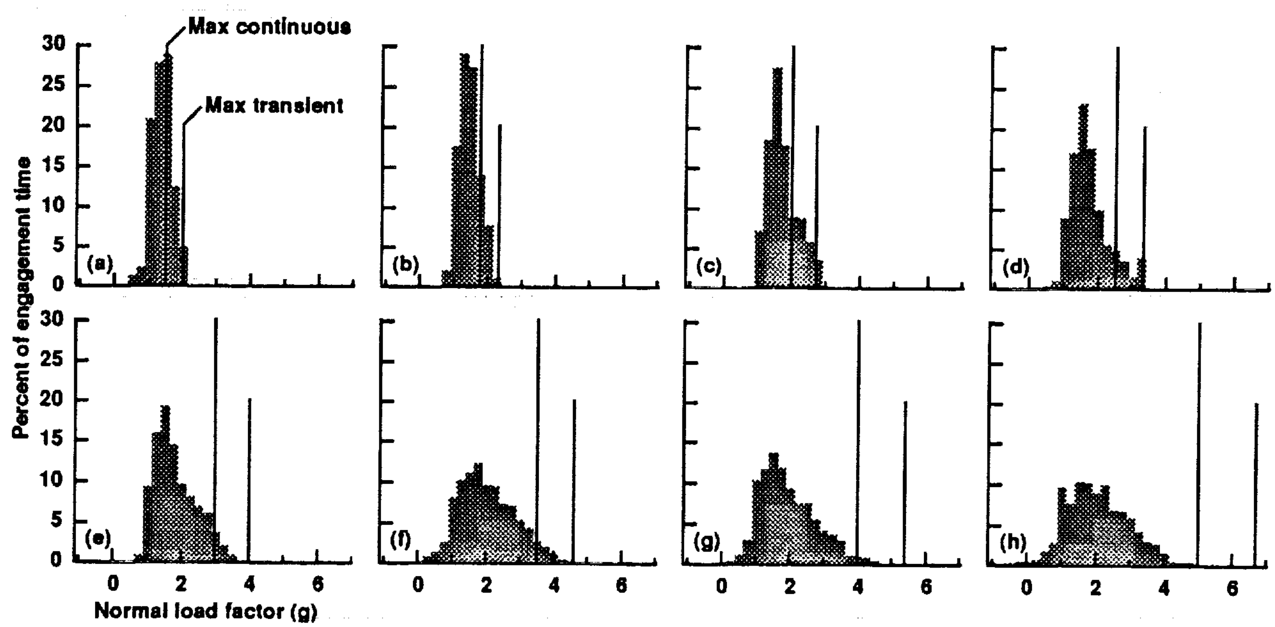

Figure 16. Load factor histogram for the mountain task. (a) 1.5 g config.; (b) 1.75 g config.; (c) 2.0 g config.; (d) 2.5 g config.; (e) 3.0 g config.; (f) 3.5 g config.; (g) 4.0 g config.; (h) 5.0 g config.

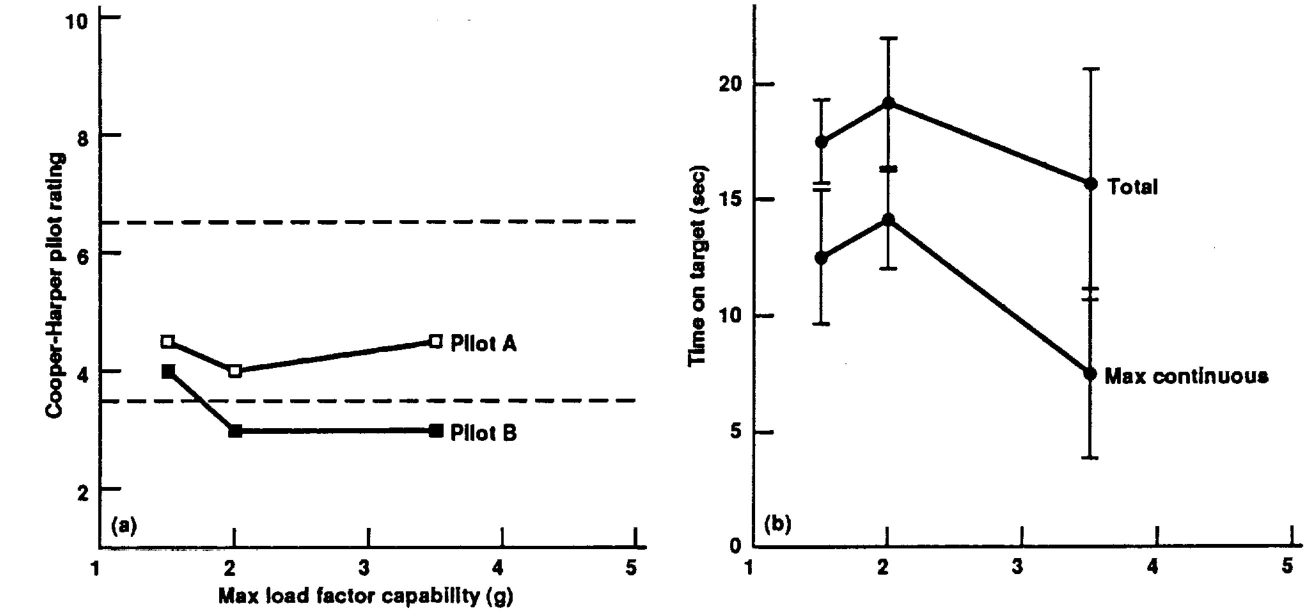

Figure 17. Results from abeam air-to-air engagements against low capability (2.0 g) adversary. (a) Cooper-Harper pilot ratings; (b) task performance.

factor configuration. The error bars indicate the ninety percent confidence interval. The dashed line on the plot shows the ideal time to turn 180 degrees in a steady turn versus load factor. No CHR data or pilot comments were gathered for this task

The trend of decreased time to regain cover with increased load factor capability is clearly shown. The trend neatly parallels that of the optimum time to turn 180 degrees with only a small time offset associated with rolling in to and out of the maneuver. This information might be useful to the designer or specification writer who has some estimate of the acceptable length of time an aircraft could be safely exposed.

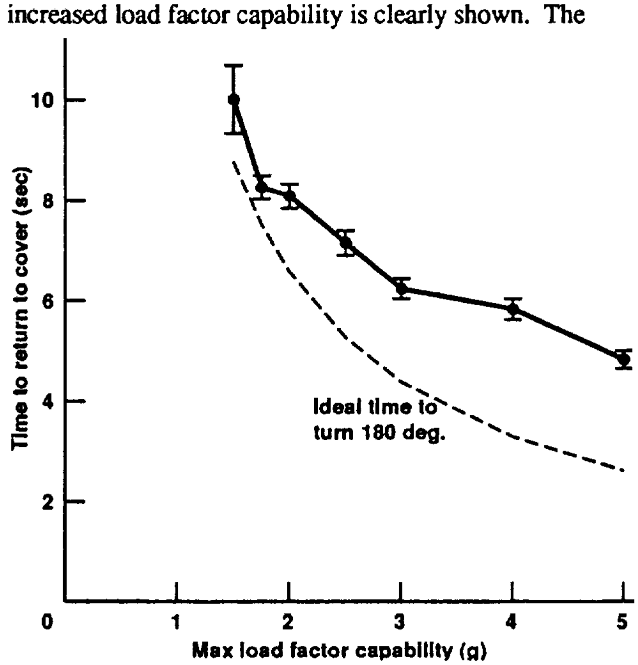

Figure 18. Time to return to cover versus maximum load factor capability.

Auxiliary Thrust

This section contains a discussion of the results from the auxiliary thruster.

Initially, the eight different auxiliary thruster inceptor/control response types were examined to determine the best candidate for the remainder of the experiment. The mean CHRs from the abeam air-to-air task for each of the eight different combinations are shown in Table 6. The pilots expressed a preference for

Table 6. Mean CHRs for auxiliary thrust inceptors.

Inceptor	Response force	Response u_{body}
cyclic joystick	5.5	2.9
cyclic thumbwheel	5.0	5.8
collective beep switch	4.8	3.5
collective twist grip	6.0	5.5

[a] Maximum N_z capability = 3.0, auxiliary thrust/weight = 0.33

the cyclic joystick with the u_{body}-rate command system. It is interesting to note though that one pilot favored the collective beep switch because of its location on the left side. He said he felt that the auxiliary thruster was a "power-type" control and should therefore be grouped with the collective. The cyclic joystick with the u_{body}-rate command system was used to generate the rest of the data presented in this section.

Figure 19 shows the CHRs and task performance results for the air-to-air tasks with and without the auxiliary thruster. Figure 19a shows the mean CHRs from both the air-to-air task and the abeam task. Figure 19b shows the task performance results for the mountain task only. The data shown for the auxiliary thruster were for a thruster which had a maximum thrust/weight capability of 0.33. The results shown for no auxiliary thruster are the same as those shown in Figures 13 and 14a.

The results indicate a significant improvement in both handling qualities and task performance when the auxiliary thruster was added. In general, there was 1.0 to 1.5 CHR improvement with the auxiliary thruster. The CHRs also indicate that the pilots were satisfied with an approximately 3.0 g configuration with the auxiliary thruster as compared to a 3.5 to 4.0 g configuration without the auxiliary thruster.

The pilot commentary indicates that the improved speed control that the auxiliary thruster afforded was a major factor in the improved CHRs. Pilot B stated,

"You could use [the auxiliary thruster] quite easily to slow yourself down, increase your turn rate or to speed yourself up to get into a better position without having to sort of lower the collective and bring the nose up so that your tracking has gone to worms."

Pilot A commented,

"During the initial part of this run, it looks like since the target is so far away from you that you can go ahead and use positive x-force to increase your speed quickly to get it up to a desired velocity for rate of closure. Once the adversary started turning, you could increase your rate of turn in an attempt to track him by using the negative X-force."

Figure 20 shows a summary of the mean CHRs given for all of the auxiliary thrust configurations. The data shown represent the average of both air-to-air tasks. The data have been shaded to indicate the CHR Level: Level 3 ratings are black, Level 2 rating are gray, and Level 1 ratings are unshaded.

The data indicate that some load factor capability can be traded for auxiliary thrust capability without significantly degrading handling qualities. It can be seen that a 3.0 g configuration with an auxiliary thrust/weight

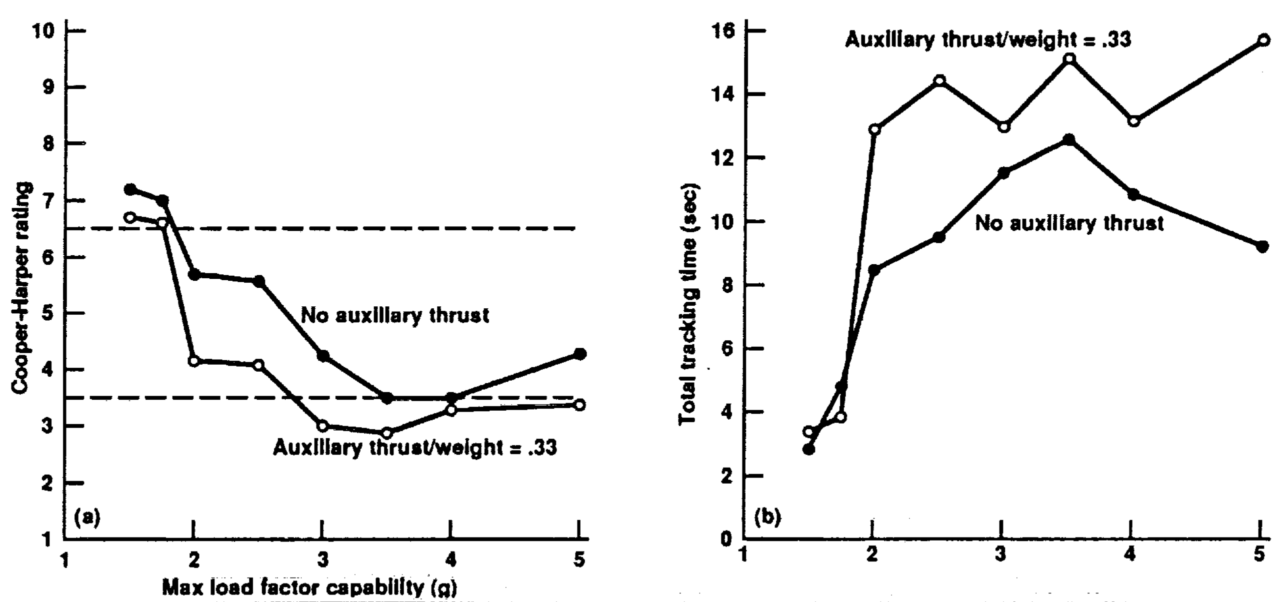

Figure 19. Air-to-air task results with and without auxiliary thrust. (a) mean CHRs for both tasks; (b) task performance for the mountain air-to-air task.

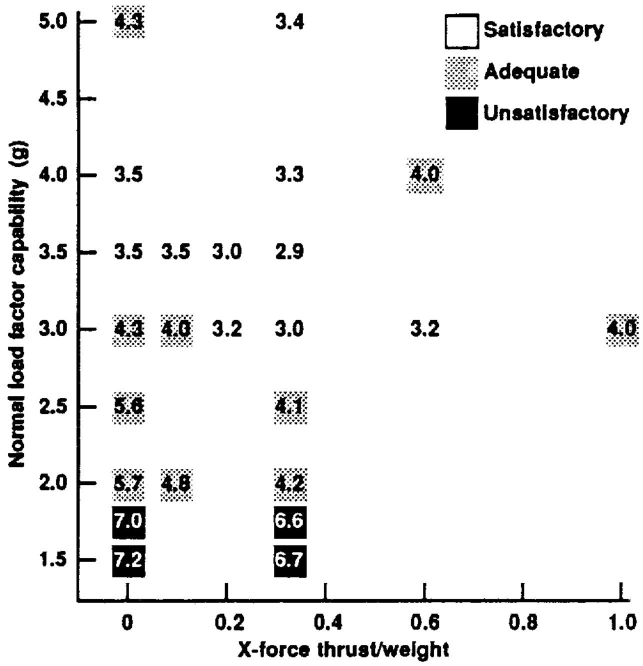

Figure 20. Mean CHRs versus load factor capability versus auxiliary thrust capability.

of 0.33 achieved better CHRs than a 4.0 g configuration without auxiliary thrust. Configurations with auxiliary thrust/weight levels as low as 0.2 are seen to possess significant handling qualities advantages over those without.

The data in Figure 20 indicate that the configurations with auxiliary thrust/weight levels of 0.6 and 1.0 did not have significant handling qualities advantages over those with 0.33 thrust/weight levels. This can be seen even more clearly in Figure 21 which shows a histogram of auxiliary thrust usage. The data in Figures 21a, b, and c show the pilots using all of the auxiliary thrust available as compared to Figures 21d and e where they do not.

Figure 22 shows a plot of the mean times that were required during the return-to-cover task versus the auxiliary thrust/weight configuration. The error bars indicate the ninety percent confidence interval. No CHR data or pilot comments were gathered for this task.

The data in Figure 22 can be compared to the data shown in Figure 18. The effect on time-to-turn of auxiliary thrust is not nearly as significant as the effect of load factor.

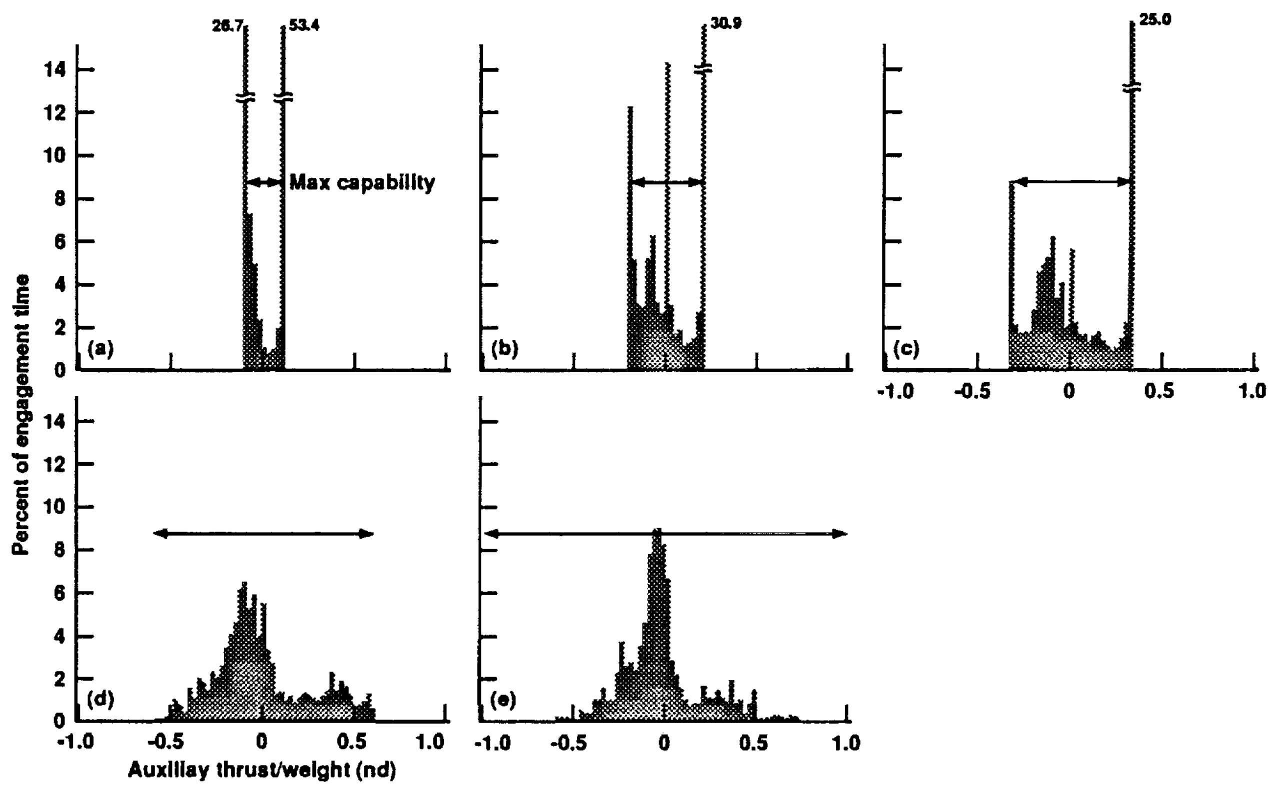

Figure 21. Auxiliary thrust histogram. (a) 0.1 thrust/weight config.; (b) 0.2 thrust/weight config.; (c) 0.33 thrust/weight config.; (d) 0.6 thrust/weight config.; (e) 1.0 thrust/weight config.

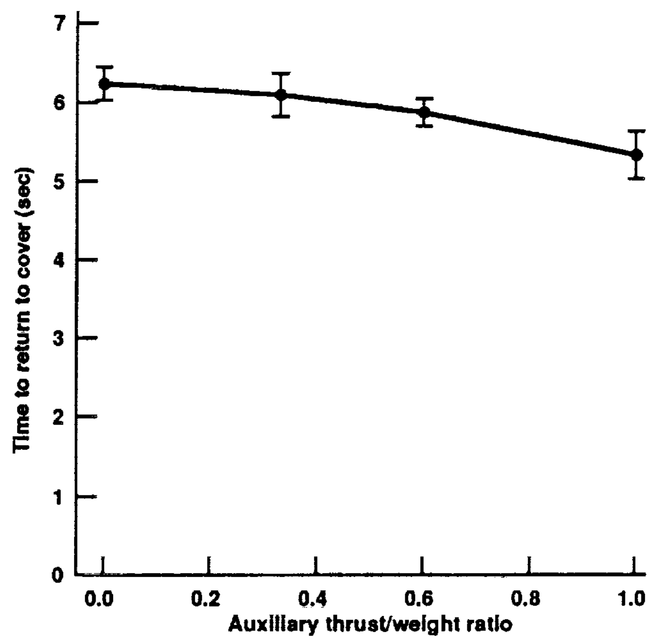

Figure 22. Time to return to cover versus auxiliary thrust capability (3.0 g maximum load factor capability).

CONCLUDING REMARKS

The U.S. Army Aeroflightdynamics Directorate performed a piloted simulation study on the NASA Ames Research Center's Vertical Motion Simulator to develop insight into the maneuverability requirements for aggressive helicopter maneuvering tasks such as air-to-air combat. Both a conventional helicopter and a helicopter with auxiliary thrust were examined. The aircraft parameters of interest were the normal and longitudinal load factor envelopes. Of particular interest were the effects of these load factor envelopes on mission performance and handling qualities. Two air-to-air acquisition and tracking tasks and a return-to-cover task were performed to assess these effects.

In general, CHRs, task performance, and pilot commentary indicated that without auxiliary thrust, the ownship normal load factor capability needed only to match that of the adversary in order to provide satisfactory handling qualities. This meant that against a 3.5 g adversary, the ownship needed 3.5 g normal load factor capability for Level 1 handling qualities and against a 2.0 g adversary, the ownship needed 2.0 g normal load factor capability.

At high levels of normal load factor capability (5.0 g) the CHR data and pilot commentary indicated some problem with pitch axis oscillations in tracking. This was probably due to the higher levels of pitch and roll damping generated by the math model at higher load factors.

The data gathered for the return-to-cover task show a clear improvement in task performance with increased load factor capability.

Of the auxiliary thruster/control systems examined, a u_{body}-rate command/u_{body}-hold system with a cyclic joystick inceptor was found to provide the best handling qualities. This system was successfully demonstrated to provide significant handling qualities advantages over configurations without auxiliary thrust.

Auxiliary thrust levels as low as 0.2 thrust/weight were shown to have significant handling qualities and mission performance advantages over those configurations without auxiliary thrust. Some normal load factor capability could be traded for auxiliary thrust capability without sacrificing satisfactory handling qualities. Increasing auxiliary thrust levels to 0.6 thrust/weight and higher did not yield further improvement.

REFERENCES

[1] Wells, C. D. and Wood, T. L., "Maneuverability — Theory and Application." Proceedings of the 28th Annual Forum of the American Helicopter Society, May 1972.

[2] Merkley, "An Analytical Investigation of the Effects of Increased Installed Horsepower on Helicopter Agility in the Nap-of-the-Earth Environment." USAAMRDL-TN-21, Dec. 1975.

[3] Attlfellner, S. and Sardanowsky, W., "Meeting the Maneuverability Requirements of Military Helicopters." Proceedings of the 2nd Annual European Rotorcraft Forum, Bückeburg, Germany, Sep. 1976.

[4] Tomlinson, B. N. and Padfield, G. D., "Piloted Simulation Studies of Helicopter Agility." Proceedings of the 5th European Rotorcraft Forum, Amsterdam, Sep. 1979.

[5] Vause, R., Harris, M., Falco, M., Shaw, D. and McDaniel, R., "The Utility of Speed, Agility, and Maneuverability for an LHX Type Mission." Proceedings

of the 39th Annual Forum of the American Helicopter Society, May 1983.

[6] Lappos, N. D., "Insights into Helicopter Air Combat Maneuverability." Proceedings of the 40th Annual Forum of the American Helicopter Society, May 1984.

[7] Curtiss, H. C. Jr. and Price, G., "Studies of Rotorcraft Agility and Maneuverability." Proceedings of the 10th Annual European Rotorcraft Forum, Aug. 1984.

[8] Houston, S. and Caldwell, A. E., "A Computer-Based Study of Helicopter Agility, Including the Influence of an Active Tailplane." Proceedings of the 10th Annual European Rotorcraft Forum, Aug. 1984.

[9] Levine, L. S., Wharburton, F. W. and Curtiss, H. C. Jr., "Assessment of Rotorcraft Agility and Maneuverability with a Pilot-in-the-Loop Simulation." Proceedings of the 41st Annual Forum of the American Helicopter Society, Fort Worth, Texas, May 1985.

[10] Thomson, D. G., "An Analytical Method of Quantifying Helicopter Agility." Proceedings of the 12th European Rotorcraft Forum, Garmisch-Parteenkirchen, Germany, Sep. 1986.

[11] Thomson, D. G., "Evaluation of Helicopter Agility through Inverse Solutions of the Equations of Motion." PhD dissertation, University of Glasgow, Nov. 1986

[12] Olson, J. R. and Scott, M. W., "Helicopter Design Optimization for Maneuverability and Agility." Proceedings of the 45th Annual Forum of the American Helicopter Society, Boston, Mass., May 1989.

[13] Scott, W. B., "Air Force, NASA Conduct Tests to Define Fighter Aircraft Agility." Aviation Week & Space Technology, Jan. 9, 1989.

[14] Bitten, R., "Qualitative and Quantitative Comparisons of Government and Industry Agility Metrics." Proceeding of the AIAA Atmospheric Flight Mechanics Conference, Boston, Mass., Aug. 1989.

[15] Drajeske, M. H. and Riley, D. R., "An Experimental Investigation of Roll Agility in Air-to-Air Combat." AIAA-90-2809-CP, 1990.

[16] Cliff, E. M., Lutze, F. H., Thompson, B. G. and Well, K. H., "Toward a Theory of Aircraft Agility." AIAA-90-2808-CP, 1990.

[17] Liefer, R. K., Valasek, J., Eggold, D. P. and Downing, D. R., "Assessment of Proposed Fighter Agility Metrics." AIAA-90-2807-CP, 1990.

[18] Schaefer, C. G. and Lutze, F. H., "Enhanced Energy Maneuverability for Attack Helicopters using Continuous, Variable (C-V) Rotor Speed Control." Proceedings of the 47th Annual Forum of the American Helicopter Society, May 1991.

[19] Danek, G., "Vertical Motion Simulator Familiarization Guide." NASA TM-103923, Jan. 1993.

[20] Jones, A. D., "Operations Manual, Vertical Motion Simulator (VMS) S.08." NASA TM-81180, May 1980.

[21] Plonsky, J. G., "Development of Equations to Improve Deficiencies in the GENHEL UH-60A Math Model." Aircraft Division, United Technologies Corporation, NAS2-11058, 1989.

[22] Austin, F. and George, D., "Automated Control of an Adversary Aircraft for Real-Time Simulation of Air-to-Air Combat." Grumman Corp. Report RE-786, Aug. 1991

[23] Austin, F., George, D. and Bivens, C., "Real-Time Simulation of Helicopter Air-to-Air Combat." Proceedings of the 47th Annual Forum of the American Helicopter Society, Phoenix, Arizona, May 1991.

[24] Von Neumann, J. and Morgenstern, O., Theory of Games and Economic Behavior, Princeton University Press, 1944, p 112.

[25] Lewis, M. S. and Aiken, E. W., "Piloted Simulation of One-on-One Helicopter Air Combat at NOE Flight Levels." NASA TM-86686, Apr. 1985.

[26] Lewis, M. S., Mansur, M. H. and Chen, R. T. N., "A Piloted Simulation of Helicopter Air Combat to Investigate Effects of Variations in Selected Performance and Control Response Characteristics." NASA TM-89438, Aug. 1987.

[27] Lewis, M. S., "A Piloted Simulation of One-on-One Helicopter Air Combat in Low Level Flight." J. AHS, Volume 31, No. 2, pp. 19—26, Apr. 1986.

[28] Whalley, M. S., "Development and Evaluation of an Inverse Solution Technique for Studying Helicopter Maneuverability and Agility." NASA TM-102889, USAAVSCOM TR 90-A-008, Jul. 1991.

[29] Whalley, M. S. and Carpenter, W. R., "A Piloted Simulation Investigation of Pitch and Roll Handling Qualities Requirements for Air-to-Air Combat." Proceedings of the 48th Annual Forum of the American Helicopter Society, Jun. 1992.

[30] Anon., "Handling Qualities Requirements for Military Rotorcraft, U. S. Army AVSCOM Aeronautical Design Standard, ADS-33C." Aug. 1989.

[31] Cooper, G. E. and Harper, R. P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities." NASA TN-5153, Apr. 1969.

[32] Bethea, R. M. and Rhinehart, R. R., Applied Engineering Statistics. Marcel Dekker, Inc., New York, 1991, pp 63-65.