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Moving-Base Simulation Evaluation of Thrust Margins for Vertical Landing for the NASA YAV-8B Harrier Aircraft

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Summary

A simulation experiment was conducted on Ames Research Center's Vertical Motion Simulator to evaluate the thrust margin for vertical landing required for the YAV-8B Harrier. Two different levels of ground effect were employed, representing the aircraft with or without lift improvement devices installed. In addition, two different inlet temperature profiles were included to cover a wide range of hot gas ingestion. For each ground effect and hot gas ingestion variant, vertical landings were performed at successively heavier weights, with the pilot assessing the acceptability of the operation in each case. Results are presented as a function of hover weight ratio and a metric of the mean ground effect and ingestion that reflect the increase in thrust margin required to provide acceptable control of sink rate during the descent to touchdown with increasing suck down and hot gas ingestion.

Nomenclature

a_z	normal acceleration, g
F_G	corrected gross thrust, lbs
g	acceleration due to gravity, ft/sec^2
h	landing gear wheel height above ground, ft
HGI	hot gas ingestion
IGE	in ground effect
JPT	jet pipe temperature, °C
LIDS	lift improvement devices
m	aircraft mass, slugs
N_F	corrected fan rpm, %
N_f	actual fan rpm, %
OGE	out-of-ground effect
rcs	reaction control system
T	vertical thrust, lbs; ambient temperature, °C or °K
T_o	standard temperature, °C or °K
W	gross weight, lb
W_H	maximum hover weight, lbs
ΔL	increment in jet-induced aerodynamic lift, lbs
$\Delta L/T$	normalized jet-induced aerodynamic ground effect
$(\Delta L/T)'$	normalized lift increment due to ground effect and hot gas ingestion
ζ	damping ratio
θ	temperature ratio T/T_o as a function of wheel height
ω	natural frequency, rad/sec

Introduction

Recent work on design criteria for STOVL fighter aircraft has included simulation experiments on conceptual aircraft designs to determine the requirements for thrust margin during vertical landing to cater for the influences of jet-induced aerodynamic ground effect and ingestion of engine exhaust flow on control of sink rate during the descent to touchdown. Results of these experiments (ref. 1) present a boundary of acceptable thrust/weight ratio as a function of mean ground effect and ingestion that account for hover control out of ground effect, arrestment of a nominal sink rate at decision height, and the avoidance of excessive sink rates at touchdown.

Since these results are based on a hypothetical aircraft design, the method cannot be verified by comparison with flight data from an actual aircraft. A great deal of information does exist on the ground effect and hot gas ingestion characteristics of the Harrier aircraft and their influence on its vertical landing capability. NASA Ames Research Center is currently operating the YAV-8B prototype of the operational AV-8B Harrier. The YAV-8B aircraft and its Pegasus engine are also modeled for use in moving-base piloted simulation. It was appropriate to capitalize on this experience and capability to substantiate the generalized requirement for thrust margin to control a STOVL aircraft in vertical landing. Accordingly, a simulation experiment was devised to define the thrust margins required for the YAV-8B. Two different levels of ground effect were employed, representing the aircraft with or without lift improvement devices installed. In addition, two different inlet temperature profiles were included to cover a wide range of hot gas ingestion. For each ground effect and hot gas ingestion variant, vertical landings were performed at successively heavier weights, with the pilot assessing the acceptability of the operation in each case. Results are presented as a function of hover weight ratio and the mean ground effect and ingestion metric devised in reference 1.

The paper that follows includes a description of the characteristics of the Pegasus engine, of the different jet-induced aerodynamic ground effects and hot gas ingestion characteristics, and the organization of the simulation experiment and details of results.

Simulation Model

The mathematical model of the YAV-8B aircraft on which this simulation was based is described in detail in references 2 and 3. Aerodynamic characteristics in hover and forward flight, including jet-induced contributions and ground effects were obtained from reference 3. Pegasus engine characteristics, including the reaction control system, and documentation of the flight control system, including features of the stability augmentation system were extracted from reference 2. To accomplish this program, it was necessary to modify dynamic response characteristics of the Pegasus engine to more accurately represent those obtained from ground tests, and to provide the desired jet-induced aerodynamic ground effects and inlet temperature rise associated with hot gas ingestion. These modifications are described in the following sections.

Pegasus Engine Characteristics

The baseline model of the Pegasus engine was obtained from reference 2 and is based on the Rolls-Royce YF402-RR-404 derivative of the F402-RR-402 that is used in the YAV-8B. Initial comparisons of the dynamic response from the model of reference 2 with those of unpublished transient data taken from test stand runs of the F402-RR-402 engine revealed discrepancies that were necessary to correct before a valid simulation of the aircraft could be obtained for hover and vertical landing. Modifications were made to the model that relate to:

1. transient rpm response
2. dynamic jet pipe temperature response at the thermocouple
3. rpm change due to compressor bleed flow
4. gross thrust change with compressor bleed flow
5. acceleration schedule

The first modification introduced a second-order filter into the relationship between fan rpm and fuel flow to quicken the rpm response from that represented by the model of reference 2 and to represent the dynamic overshoot evidenced in test stand results. The second-order filter is given by:

$$\frac{\omega^2}{(s^2 + 2\zeta\omega s + \omega^2)}$$

where $\zeta = 0.9$ and $\omega = 15$ rad/sec. The second modification involved defining the true jet pipe temperature response to power-spindle angle also by a second-order equation, where $\zeta = 0.5$ and $\omega = 10$ rad/sec, in order to properly represent the transient response of temperature to throttle inputs.

The third modification altered the schedule of rpm variation with bleed flow, by changing the scale factor from 0.089 to 0.033%/lb/sec to match steady-state rpm droop in response to bleed flow demand. The fourth modification deleted the direct correction to gross thrust from rcs bleed flow. Now the only variation in gross thrust with bleed comes about through the variation in rpm. The last modification increased the acceleration rate at high thrust settings to achieve times to accelerate from 55% to 100% rpm that meet high power acceleration criteria for the aircraft. Examples of the simulated engine response are presented in figures 1–4. Data for acceleration from idle to maximum thrust and deceleration from maximum to idle are shown in figures 1(a) and (b), involving time histories of fuel flow, jet pipe temperature thermocouple output, and corrected fan rpm in response to a step power spindle input. The character of the acceleration reflecting operation on acceleration limits is evident, and the time from 55% to 100% satisfies the high power acceleration requirement of 2–2.4 sec. The deceleration to idle thrust is similarly well matched. Responses to transient step commands at a high initial thrust setting for thrust increase or decrease are illustrated in figures 2(a) and (b). The rise time and the transient overshoot of the steady state conditions are comparable to test stand measured characteristics. In the example shown in figure 3, a transient thrust increase at high thrust setting that invoked the jet pipe temperature limiter shows the overshoot in thermocouple temperature followed by cutback to the maximum thrust limiter value of 610°C. The same character of cutback is experienced for the short lift dry or wet limits associated with the vertical landing. Finally, reaction of the indicated variables to a step change in compressor bleed is shown in figure 4. The level of bleed is the maximum allowed for the Pegasus engine, and the adjustment in the bleed flow to rpm scale factor noted previously was made to match the steady-state change in rpm.

As a consequence of these modifications in the Pegasus model, pilot comments indicated that engine responses during hover were representative, with one exception, of those experienced in the aircraft. The exception was a concern that thrust degradation due to reaction control activity was not of a magnitude comparable to the aircraft. Some further adjustments in this characteristic were made during the experiment to determine the sensitivity of maximum acceptable vertical landing weight to bleed flow effects.

Ground Effect and Hot Gas Ingestion Characteristics

Variations in jet-induced aerodynamic lift in proximity to the ground were modeled for the YAV-8B for the configuration with and without under fuselage flow fences known as lift improvement devices (LIDS). The aerodynamic characteristics are shown in figure 5, where the lift increment ΔL is referenced to the out-of-ground effect lift and is normalized by the vertical component of thrust from the engine. The LIDS-on data were derived initially from reference 4, but were modified by reducing the peak lift increment to produce sink rate characteristics considered to be representative of the actual aircraft. The resulting aircraft behavior during landing was represented by an initial sink rate of 3–4 ft/sec that reduced to 1–2 ft/sec at touchdown due to the lift increment produced by the LIDS. For initial sink rates less than 3 ft/sec, the aircraft's descent would be arrested before ground contact and a modest climb rate would be induced. Lift increments from the LIDS greater than that shown in figure 5 (comparable to the increments of ref. 4) resulted in the descent being arrested at nominal landing sink rates of 4–5 ft/sec. Subsequent flights with the YAV-8B yielded a pilot assessment of response characteristics that was closer to those associated with ground effects of reference 4 than those as modified for this experiment.

LIDS-off data were obtained from reference 5 and confirmed by earlier wind tunnel tests of the Harrier prototype whose results are published in reference 6. Behavior of the aircraft in landing descent with LIDS off was considered to be representative of an AV-8A configuration. Consequently, the lift data from these references were used without modification.

Three temperature profiles due to recirculation of the exhaust gases from the engine that were employed in the simulation are shown in figure 6. The YAV-8B LIDS-off profile was based on AV-8A data from flight measurements of ambient temperature at the engine inlet. With the LIDS on, the temperature rise is the same as that for LIDS off but with an onset that occurs at a lower altitude. The third profile represented an arbitrary temperature variation with height that reflected a more severe hot gas ingestion environment and that was independent of LIDS configuration.

Simulation Experiment

The simulation experiment was structured around variations in ground effect due to LIDS, hot gas ingestion, ambient temperature, and wind conditions for landings on the runway or aboard an LPH class amphibious assault ship. The test matrix is shown in table 1. The range of ambient temperatures was selected to cover cold to hot day conditions and, specifically, to establish conditions where either engine rpm limits or the jet pipe temperature limits would be invoked during the landing at heavy weight. Operations were conducted without water injection, which, for this simulation, resulted in a short lift dry JPT limit of 705°C and a corrected rpm limit of 106%. Typically, the rpm limit would dominate at the coldest temperature and the JPT limiter would govern for all other test cases. Winds were chosen either to be calm or 15 knot cross wind conditions with rms turbulence of 6 ft/sec. Shipboard landings took place in sea state 3 with light winds of 5 knots.

For each combination of conditions in the test matrix, an initial hover gross weight was chosen and the landing was performed to obtain the pilot's assessment of its acceptability. Gross weight was held constant during the test run and did not vary to account for fuel burn. During airfield operations, each run was initiated from a stabilized hover over the landing point at a wheel height of 43 ft (50 ft c.g. height), a steady descent rate of approximately 4 ft/sec was established, and sink rate and hover position was controlled to touchdown. Shipboard recoveries began from a stabilized hover off the port side of the LPH abeam the landing spot just aft of the ship's superstructure. The aircraft was translated at constant altitude into a hover position over the landing spot, deck motion was assessed, and the descent to touchdown was initiated at a nominal sink rate of 4 ft/sec. Evaluation of the acceptability of the operation was based on three factors: (1) control of height and sink rate out of ground effect, (2) the ability to arrest a nominal rate of descent with an application of the remaining thrust starting at a representative decision height, and (3) the ability to control sink rate acceptably to touchdown in the presence of control activity required for attitude and hover position control without encountering thrust limits or cutbacks imposed by the engine's controls. Gross weight was increased progressively until the pilot determined that insufficient thrust margin was available for the landing to be accomplished successfully. Maximum hover weights out of ground effect were determined for the ambient temperature conditions of 0, 5, 25, and 30°C to be 19847, 19347, 17447, and 16847 lb respectively. These weights were established by trimming the aircraft at increasingly heavier conditions until the JPT or rpm operating limits were reached. Test condition gross weights are normalized by maximum hover weight to produce the hover weight ratio W/W_H.

The experiments were conducted on the Vertical Motion Simulator at Ames Research Center. This simulator provides six degree-of-freedom motion with large excursions in the vertical and longitudinal axes, and large acceleration bandwidths in all axes that encompass the bandwidths of motion that are expected to be of primary

Table 1. Matrix of test conditions

Ground effect	Temperature profile	Ambient temperature, °C	Wind/sea condition
LIDS on	LIDS on	0	Calm
		5	Calm
			15 knots, 6 ft/sec rms turbulence
		25	Calm
			15 knots, 6 ft/sec rms turbulence
		30	Calm
LIDS off	LIDS off	0	Calm
			5 knots, sea state 3
		5	Calm
			15 knots, 6 ft/sec rms turbulence
		25	Calm
			15 knots, 6 ft/sec rms turbulence
		30	Calm
			5 knots, sea state 3
LIDS on	Increased HGI	0	Calm
			5 knots, sea state 3
		5	Calm
			15 knots, 6 ft/sec rms turbulence
		25	Calm
			15 knots, 6 ft/sec rms turbulence
		30	Calm
			5 knots, sea state 3
LIDS off	Increased HGI	0	Calm
			5 knots, sea state 3
		5	Calm
			15 knots, 6 ft/sec rms turbulence
		25	Calm
			15 knots, 6 ft/sec rms turbulence
		30	Calm
			5 knots, sea state 3

importance to the pilot in vertical flight tasks. A three-window, computer-generated image system presented the external view to the pilot. The visual scene consisted of either an airfield scene, or a shipboard scene of an LPH assault ship. An overhead optical combining glass projected the HUD for the pilot. Control inceptors consisted of a center stick, rudder pedals, and a left-hand quadrant that contained throttle and thrust vector deflection handles.

Five experimental test pilots participated in the experiment. Of this group, three were research pilots from NASA Ames' staff with current operational experience in the YAV-8B Harrier. One pilot came from the U. S. Marine Corps and was assigned as a test pilot at the Naval Air Test Center, Patuxent River, Maryland. The fifth pilot was a member of Rolls-Royce's test staff at Bristol, UK. The latter two pilots were current in the AV-8B/GR Mk 5 models of the Harrier.

Discussion of Results

Assessments of acceptable vertical landing weights for the different aircraft configurations and ambient temperature conditions are presented in figure 7. Each pilot's evaluation of the landing at a particular ratio of landing weight to maximum hover weight (hover weight ratio) is shown as either clearly acceptable, unacceptable, or borderline. Each evaluation typically was the result of 3–4 landings to insure the pilot had a representative view of sink rate control and the effects of significant variations in control technique. Also, for each case, the pilot would normally determine the ability to check the initial sink rate with an application of maximum thrust starting at different decision heights ranging from 10 to 20 ft. Results for each configuration are also presented in appendix A.

For the YAV-8B with LIDS on (fig. 7(a)) and for ambient temperatures for which the JPT limiter was invoked, maximum hover weight ratios of approximately 0.975 were consistently identified by the pilots. A slight trend of increasing hover weight ratio with increasing temperature is observed from 5–30°C, but the total variation is 0.7% and is considered to be within the normal variability of the pilots' assessments. When the rpm limit governs, the maximum hover weight ratio is reduced by about 1.5% to 0.957. The more conservative landing weight is apparently related to operation of a heavier aircraft associated with cold day conditions. The individual pilot's assessments were consistently in agreement and were based on the thrust margin required for height control out of ground effect. Variations in wind and turbulence did not alter the results.

With LIDS off (fig. 7(b)), the YAV-8B maximum hover weight ratio is reduced to 0.946 when the JPT limit is imposed, and a further 1.4% to 0.932 when rpm limiting is encountered. While there is not the unanimity among pilots in this set of evaluations that existed for the LIDS-on case, the majority of pilots agreed on these maximum weights, with only one pilot in significant disagreement. The primary factor in the pilots' assessments was the ability to control sink rate at touchdown without encountering the JPT limit. When shipboard operations are considered, the JPT-limited hover weight ratio is reduced by about 1.5% to 0.93, while the rpm-limited case aboard ship is reduced by 2.5% to 0.907. Operations were performed in light winds with deck motion associated with sea state 3 conditions.

For the YAV-8B with LIDS but with the hypothetical elevated hot gas ingestion profile (fig. 7(c)), the maximum hover weight ratio with JPT limiting is approximately 0.94, and is unchanged for the case of rpm limiting. The evaluations are reasonably tightly grouped across the temperature range. Again, the primary factor in the pilots' assessments was the ability to control sink rate at touchdown without encountering the JPT limit. For shipboard landings, JPT-limited hover weight ratio is reduced by 2% to 0.92; the rpm-limited condition is reduced to 0.93.

When the LIDS are removed for the case of increased HGI (fig. 7(d)), the limiting condition could be reasonably considered to be a hover weight ratio of 0.89 for either the JPT or rpm limiting cases. The one pilot's assessment for the 5°C case was only slightly heavier than for the other two conditions. Once more, the primary factor in the pilots' assessments was the ability to control sink rate at touchdown without encountering the JPT limit. In the case of shipboard landings, hover weight ratio for the JPT-limited case is reduced 3% to 0.86, while that for the rpm-limited condition is reduced to 0.87.

In the course of performing the airfield landings, some of the pilots felt that the influence on height control of control activity to stabilize pitch, roll, and yaw was not of the magnitude experienced in the Harrier. Specifically, reaction control bleed did not appear to degrade engine thrust to the degree encountered in flight. Consequently, an alternative condition was investigated for the YAV-8B, with and without LIDS, to determine the sensitivity of maximum acceptable vertical landing weight to increased thrust loss with bleed. This condition included a decrement in engine gross thrust that amounted to 80 lb per lb/sec of bleed flow. Figure 8 provides a comparison of the pilots' evaluations of this increased bleed effect with the baseline condition. With LIDS on or off, for either the JPT or rpm limiting cases, this increase in bleed effect on thrust reduces the maximum hover weight ratio about 2.5%.

Interpretation of Results

In order to provide guidance for STOVL aircraft design, it is necessary to generalize, if possible, the results of these thrust margin experiments with the Harrier. An experiment was conducted previously on the VMS where generic variations in ground effect and hot gas ingestion were made on a representative STOVL aircraft concept and their influence on vertical landing was assessed (ref. 1). Results of that experiment were presented in terms of (1) a measure of the total vertical force imposed on the aircraft by the combination of jet-induced aerodynamic force and thrust variations due to changes in temperature at the inlet, and (2) the thrust margin existing in hover out of ground effect that was available to counter the effect of the vertical force variations during the descent to landing. Mean ground effect and ingestion are defined by the impulse of vertical force (normalized by vertical thrust) over the altitude range of interest, divided by that altitude range to obtain a mean value of the impulsive force,

$$\frac{1}{43}\int_0^{43} (\Delta L/T)'\, dh$$

where $(\Delta L/T)'$ incorporates jet induced aerodynamic ground effect as well as thrust variations with inlet temperature. It is derived from the normal force equation as follows:

$$(1 + \Delta L/T)T - W = ma_z$$

where, to account for the thrust variation due to change in ambient temperature,

$$T = W + (\Delta F_G/\Delta N_F)\,(\Delta N_F/\Delta\theta)\,\Delta\theta$$

After collecting terms, the normal force equation reduces to

$$[1+ \Delta L/T][1+ (\Delta F_G/\Delta\theta)\,(\Delta\theta/W)] - 1 = a_z/g$$

and the term on the left side of the equation is $(\Delta L/T)'$. The altitude range over which the mean ground effect and ingestion is based is 0 to 43 ft, and represents the range of wheel heights over which ground effect exists for the Harrier. The term $\Delta L/T$ is obtained from the jet-induced aerodynamic ground effects of figure 5. The effect of inlet temperature variation on thrust is determined from

$$(\Delta F_G/\Delta\theta)\Delta\theta = (\Delta F_G/\Delta N_F)\,(\Delta N_F/\Delta\theta)\Delta\theta$$

where $(\Delta F_G/\Delta N_F)$ as extracted from the curve of corrected gross thrust to corrected rpm is 426.7 lb/% over the range of thrust from 95–100% rpm, and the variation in corrected fan rpm with temperature ratio $(\Delta N_F/\Delta\theta)\Delta\theta$ can be found from the relationship $N_F = N_f/\sqrt{\theta}$ to be $-N_F\left(1 - 1/\sqrt{\theta}\right)$. For each of the experiment configurations, the variations of $(\Delta L/T)'$ with height are shown in figure 9. The values for mean ground effect and ingestion (integral of $(\Delta L/T)'$ over the reference height) are

Configuration	Mean Ground Effect and Ingestion g's
LIDS On—Baseline Temperature Profile	– 0.0037
LIDS Off—Baseline Temperature Profile	– 0.0249
LIDS On—Elevated Temperature Profile	– 0.0279
LIDS Off—Elevated Temperature Profile	– 0.0447

Results based on this interpretation of ground effect and ingestion and thrust margin are presented in figure 10. The boundary shown defines acceptable and unacceptable regions for combinations of mean ground effect and ingestion and hover weight ratio. The YAV-8B data correspond to the configurations with and without LIDS and for two levels of hot gas ingestion. Results are shown for airfield and shipboard landings and for the case with the decrement in thrust due to reaction control bleed flow. These data represent the collective assessment of the pilots for the JPT limiting cases noted in the previous section. They reflect the increase in thrust margin required to provide acceptable control of sink rate during the descent to touchdown with increasing suck down and hot gas ingestion.

Conclusions

A simulation experiment was conducted on Ames Research Center's Vertical Motion Simulator to evaluate the thrust margin for vertical landing required for the YAV-8B Harrier. Two different levels of ground effect were employed, representing the aircraft with or without lift improvement devices installed. In addition, two different inlet temperature profiles were included to cover a wide range of hot gas ingestion. For each ground effect and hot gas ingestion variant, vertical landings were performed at successively heavier weights, with the pilot assessing the acceptability of the operation in each case. Results are presented as a function of hover weight ratio and a metric of the mean ground effect and ingestion that reflect the increase in thrust margin required to provide acceptable control of sink rate during the descent to touchdown with increasing suck down and hot gas ingestion.

Maximum hover weight ratios for airfield landings ranged from 0.975 for the aircraft with LIDS on and nominal hot gas ingestion to 0.89 for the LIDS-off case and elevated hot gas ingestion. Shipboard recovery typically reduced the maximum hover weight ratio by 1.5 to 3%. Increasing the sensitivity of thrust response to reaction control bleed by 80 lb per lb/sec reduced the maximum hover weight ratio by 2.5%.

Appendix A

Experiment Configurations and Pilot Ratings

Configuration	Ambient Temperature °C	Gross Weight lbs	W/W_H	Pilot Rating of Vertical Landing Acceptability Pilot A	B	C	D	E
LIDS Off	0	18000	0.907			Acceptable		
Baseline HGI		18300	0.922		Acceptable		Borderline	
Airfield Landing		18500	0.932	Borderline	Borderline		Unacceptable	
Shipboard Landing		18000	0.907	Acceptable			Borderline	
		18300	0.922	Unacceptable				
Bleed Effects		17700	0.892					Acceptable
		18000	0.907				Borderline	Borderline
		18200	0.917					Unacceptable
Airfield Landing	5	17500	0.905			Acceptable		
		18000	0.93	Acceptable	Acceptable	Unacceptable	Acceptable	
		18300	0.946	Borderline	Borderline		Borderline	
		18500	0.956				Unacceptable	
Bleed Effects		17500	0.905					Acceptable
		17700	0.915					Borderline
		18000	0.93					Unacceptable
Airfield Landing	25	15500	0.888				Acceptable	
		16000	0.917	Acceptable		Acceptable	Acceptable	
		16200	0.929			Unacceptable		
		16500	0.946	Borderline	Borderline	Unacceptable	Acceptable	
		16700	0.957		Unacceptable		Borderline	
		17000	0.974				Unacceptable	
Shipboard Landing		16000	0.917				Acceptable	
		16200	0.929				Acceptable	
		16500	0.946				Unacceptable	
Bleed Effects		15500	0.888					Acceptable
		15800	0.906					Borderline
		16000	0.917					Unacceptable
		16200	0.929				Acceptable	
		16500	0.946				Unacceptable	
Airfield Landing	30	15500	0.92	Acceptable	Acceptable	Acceptable		
		16000	0.95	Borderline	Borderline	Acceptable	Borderline	
		16200	0.962		Unacceptable	Unacceptable		
Shipboard Landing		15500	0.92	Acceptable				Acceptable
		15700	0.932	Unacceptable				Borderline

Configuration	Ambient Temperature °C	Gross Weight lbs	W/W_H	Pilot Rating of Vertical Landing Acceptability Pilot A	B	C	D	E
LIDS Off Baseline HGI Bleed Effects	30	15500	0.92					Borderline
LIDS On Baseline HGI Airfield Landing	0	19000	0.957	Borderline		Borderline	Borderline	
		19300	0.972	Unacceptable		Unacceptable	Unacceptable	
Bleed Effects		18500	0.932				Borderline	Borderline
		18700	0.942					Unacceptable
		19000	0.957					Unacceptable
Airfield Landing	5	18500	0.956			Acceptable	Acceptable	
		18800	0.972	Borderline		Borderline	Borderline	
		19000	0.982	Unacceptable				
Airfield Landing	25	16000	0.917	Acceptable				
		16500	0.946	Acceptable		Acceptable	Acceptable	
		17000	0.974	Borderline		Borderline	Borderline	
		17200	0.986	Unacceptable		Unacceptable	Unacceptable	
Bleed Effects		16500	0.946	Acceptable			Acceptable	Borderline
		16700	0.954	Unacceptable				Unacceptable
Airfield Landing	30	16000	0.95			Acceptable		
		16500	0.979	Borderline		Borderline	Borderline	
		16700	0.991	Unacceptable				
Bleed Effects		16000	0.95					Acceptable
		16200	0.962					Borderline
		16300	0.967					Unacceptable
LIDS Off Increased HGI Airfield Landing	0	17500	0.882	Acceptable		Acceptable	Acceptable	
		17700	0.892	Borderline		Borderline		
		18000	0.907	Unacceptable			Unacceptable	
Shipboard Landing		17300	0.872	Borderline			Acceptable	
		17500	0.882	Unacceptable			Unacceptable	
Airfield Landing	5	17200	0.889		Acceptable			
		17500	0.904		Borderline			
		17700	0.915		Unacceptable			

Configuration	Ambient Temperature °C	Gross Weight lbs	W/W_H	Pilot Rating of Vertical Landing Acceptability Pilot				
				A	B	C	D	E
LIDS Off Increased HGI Airfield Landing	30	14700	0.873			Acceptable		
		15000	0.89	Borderline	Borderline	Acceptable	Borderline	
		15200	0.902	Unacceptable	Unacceptable	Borderline	Unacceptable	
		15500	0.92	Unacceptable		Unacceptable		
Shipboard Landing		14500	0.86	Borderline				Borderline
		14600	0.867				Acceptable	
		14700	0.873	Unacceptable				Unacceptable
		14800	0.879				Acceptable	
		15000	0.89				Unacceptable	
LIDS On Increased HGI Airfield Landing	0	18000	0.907	Acceptable				
		18500	0.932	Acceptable		Borderline		
		18700	0.942			Unacceptable		
		19000	0.957	Unacceptable				
Shipboard Landing		18500	0.932	Borderline			Acceptable	
		18700	0.942				Borderline	
		19000	0.957				Unacceptable	
Airfield Landing	25	15500	0.888				Acceptable	
		16000	0.917				Acceptable	
		16300	0.935				Acceptable	
		16500	0.946				Borderline	
		16700	0.957				Unacceptable	
		17000	0.974				Unacceptable	
Airfield Landing	30	15700	0.932			Borderline		
		15800	0.938	Borderline			Borderline	
		16000	0.95	Unacceptable		Unacceptable	Unacceptable	
		16300	0.967				Unacceptable	
Shipboard Landing		15300	0.908	Acceptable				
		15500	0.92	Borderline				Borderline

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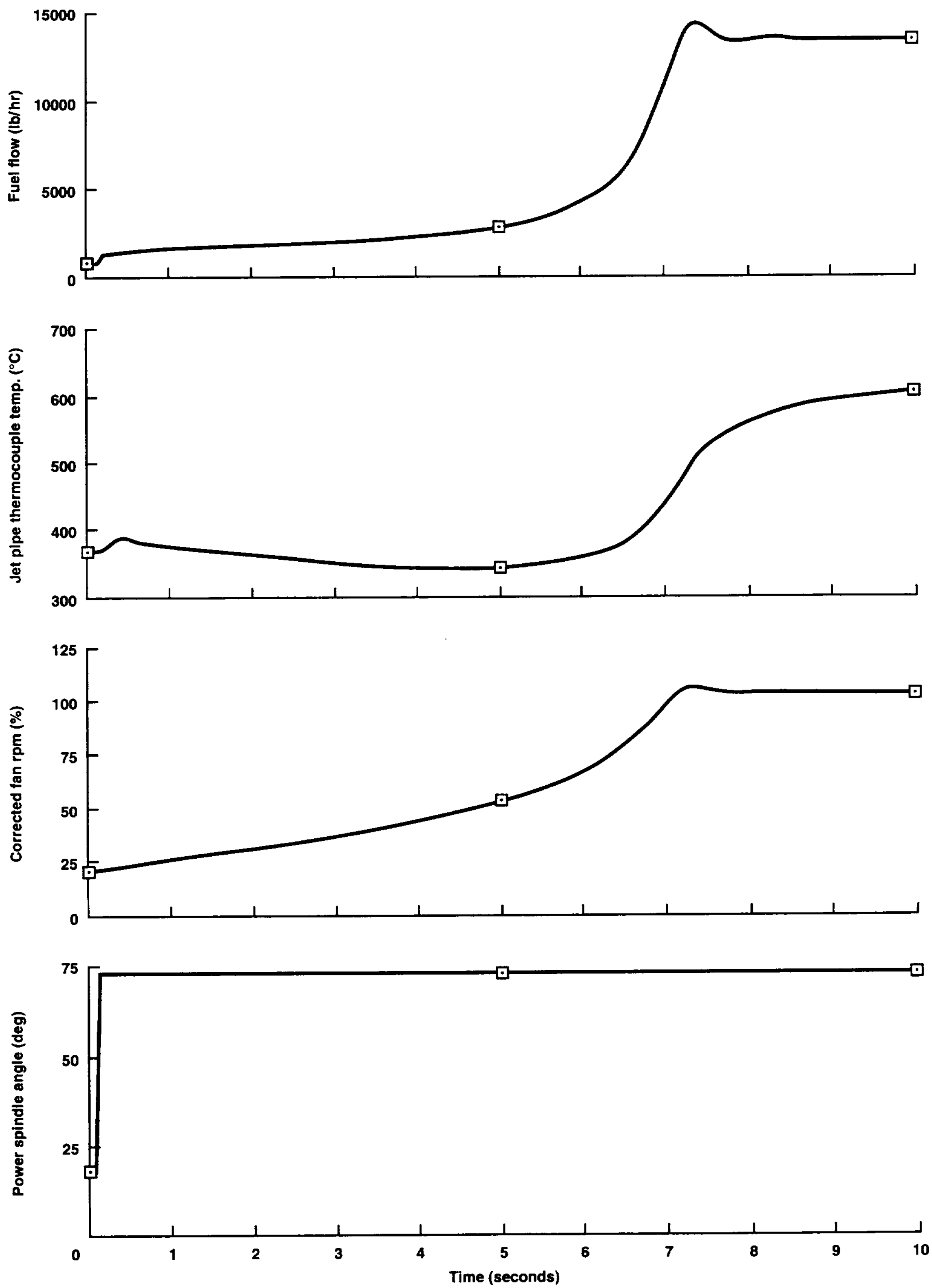
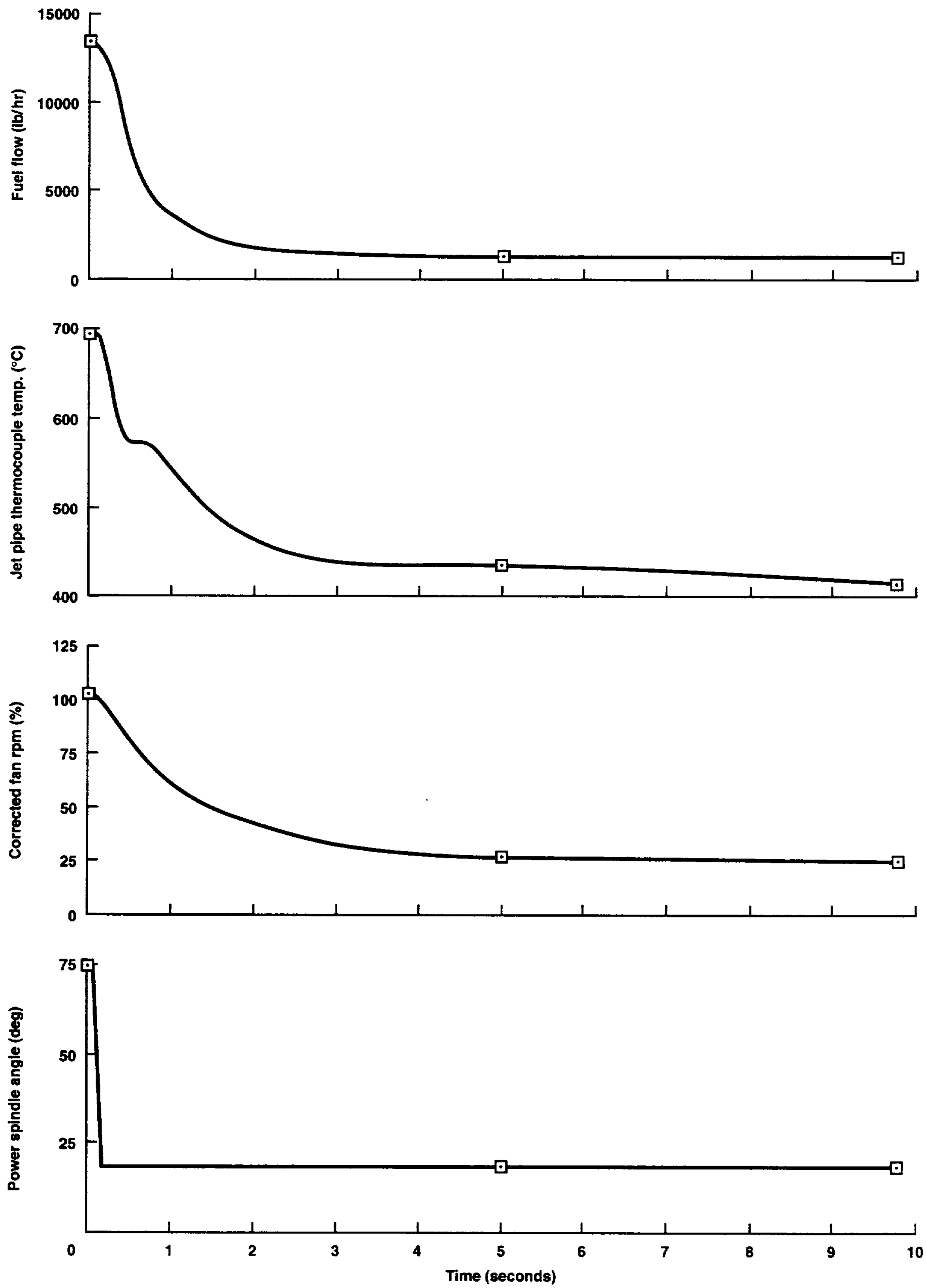


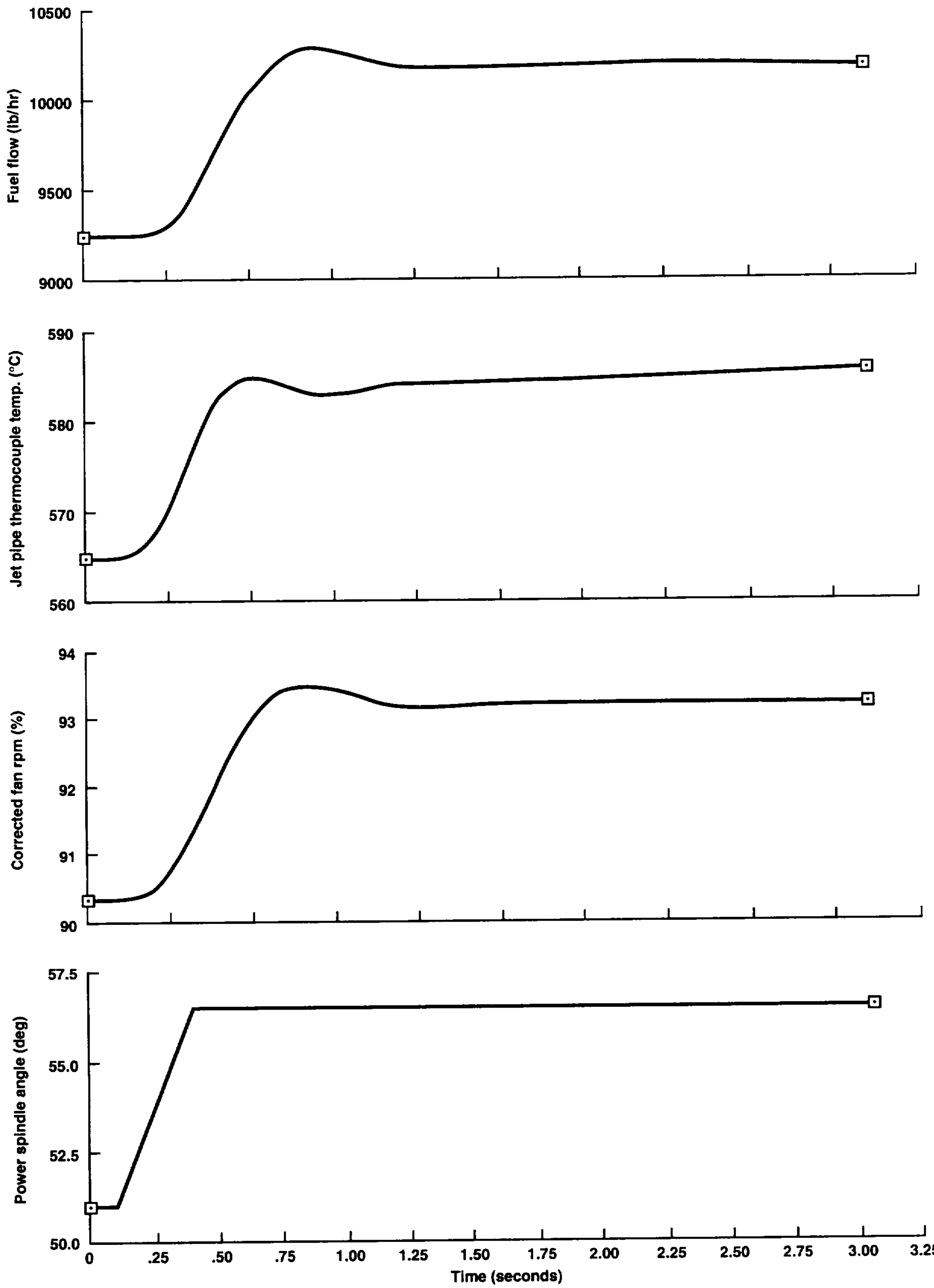
(a) Idle to normal lift thrust.

Figure 1. Engine transient response to throttle slams.



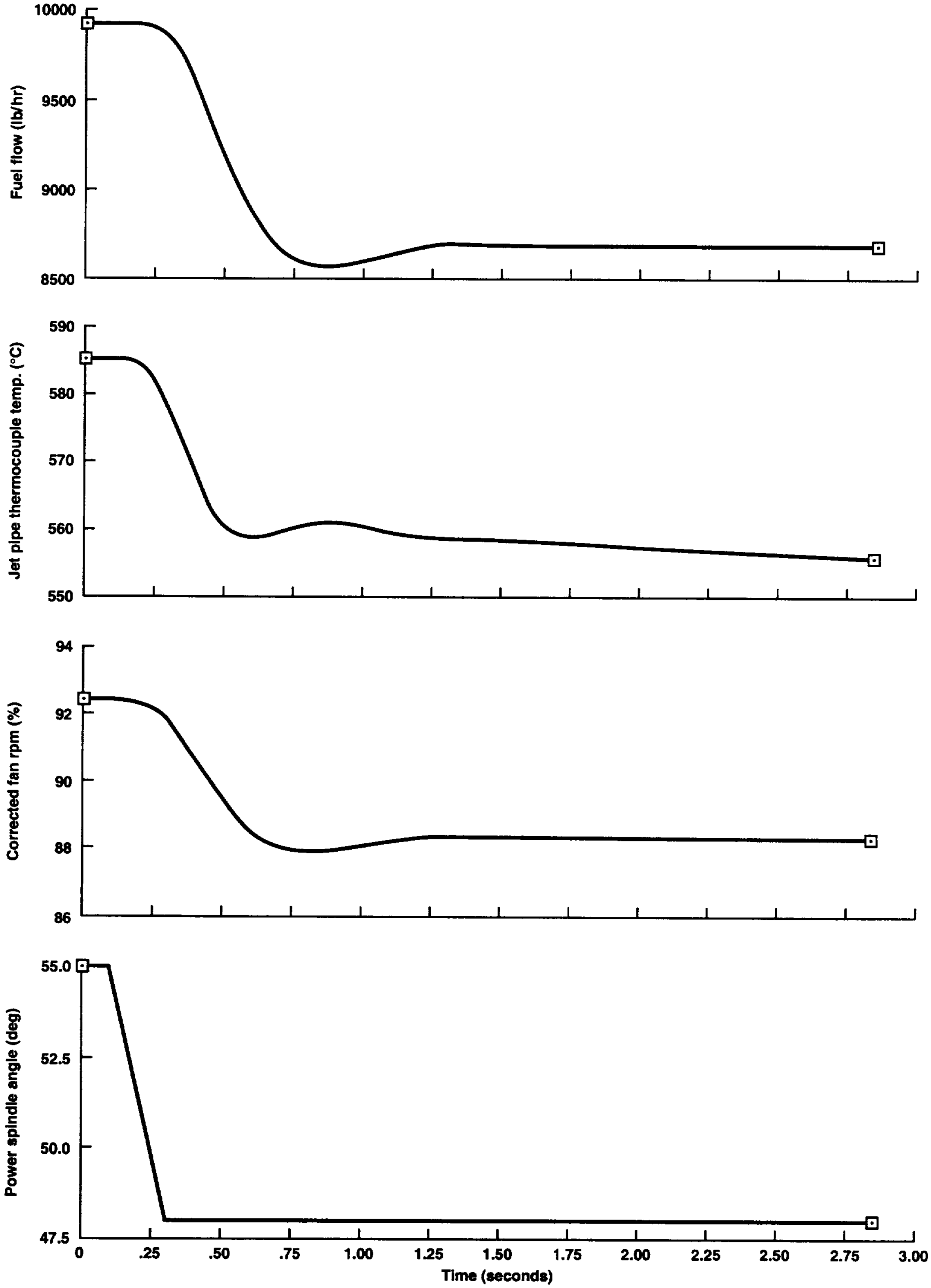
(b) Normal lift to idle thrust.

Figure 1. Concluded.



(a) Thrust increase.

Figure 2. Engine transient response at hover thrust settings.



(b) Thrust decrease.

Figure 2. Concluded.

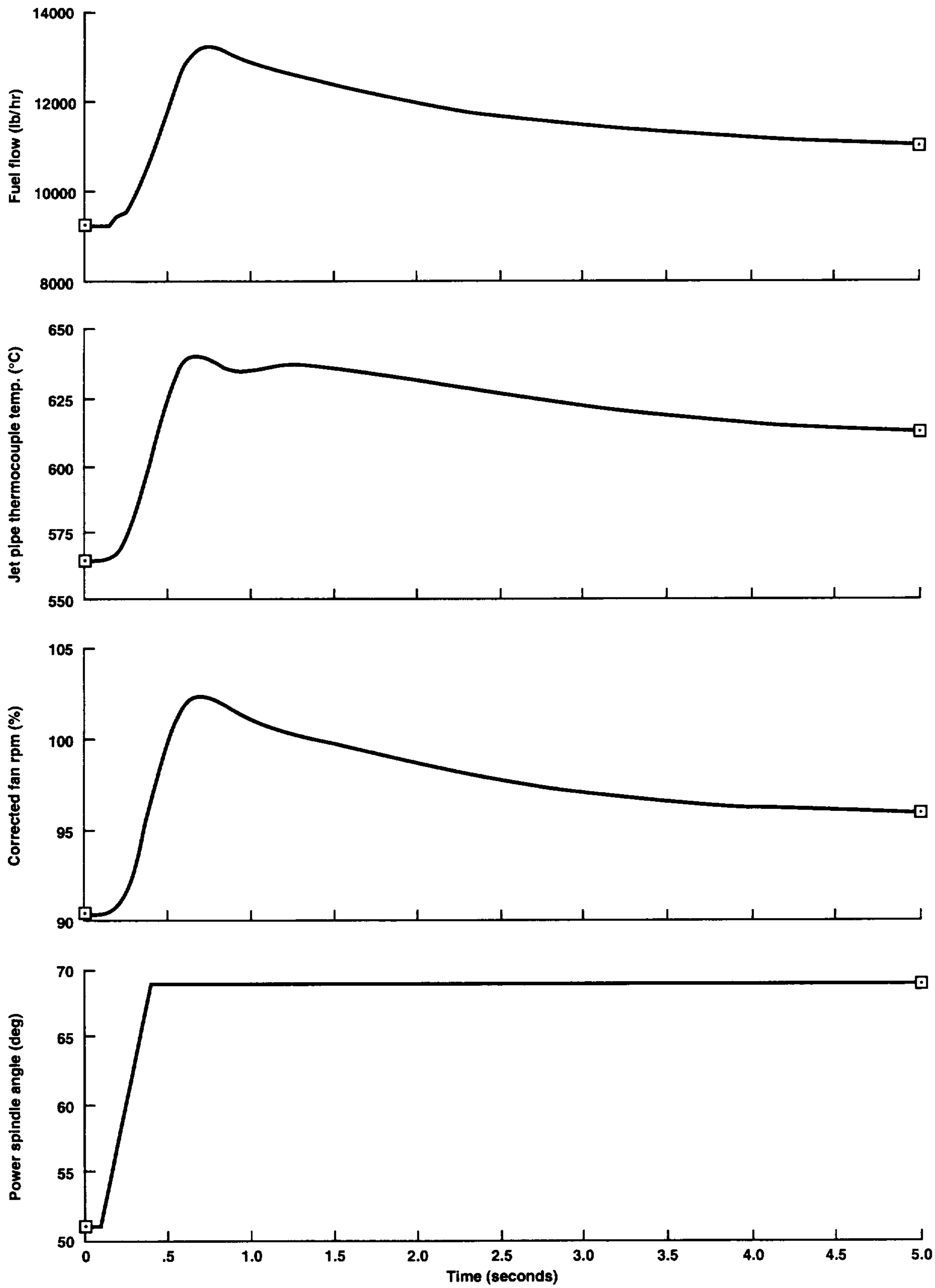


Figure 3. Effect of jet pipe temperature limiter on engine transient response.

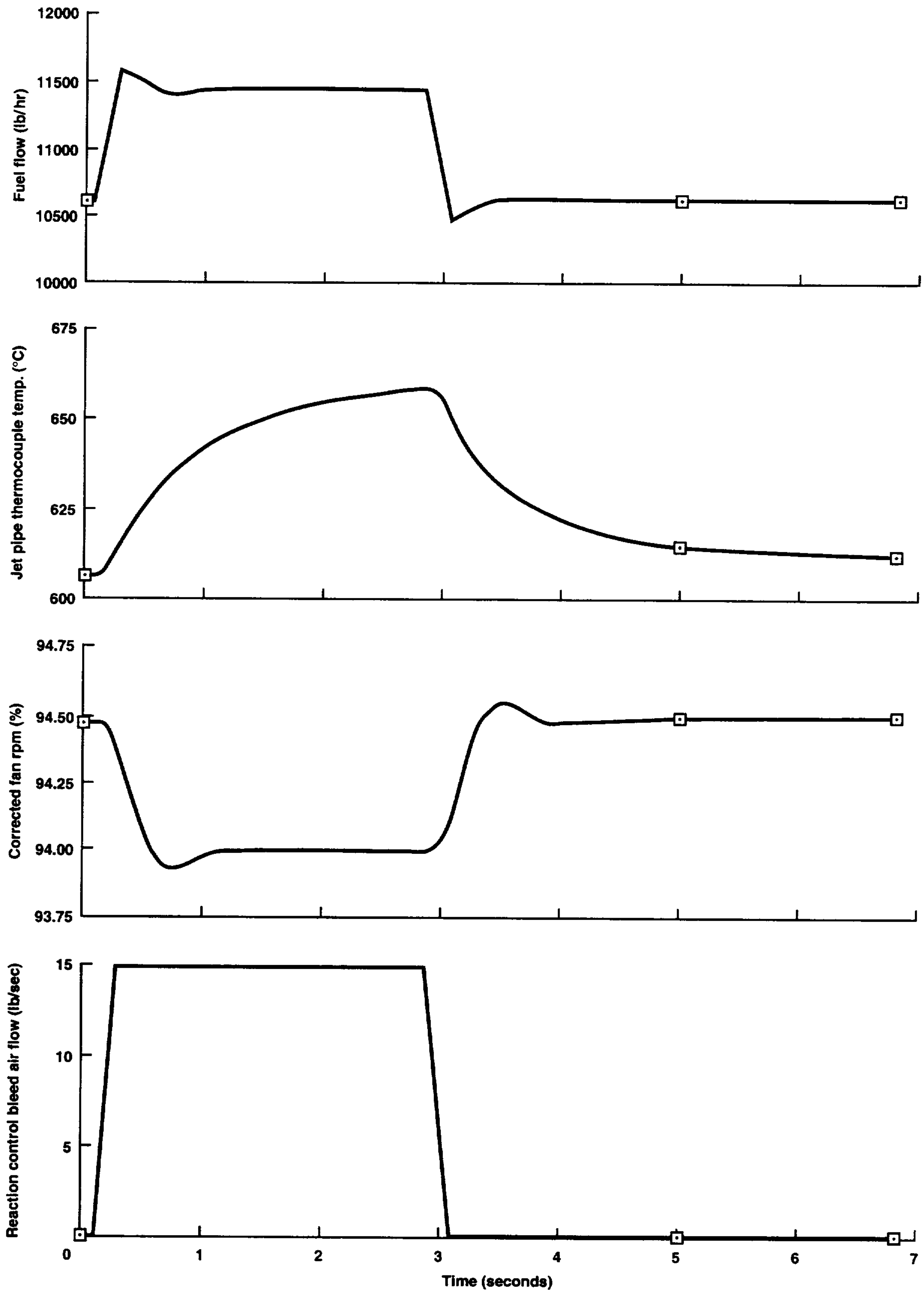


Figure 4. Engine response to maximum bleed demand.

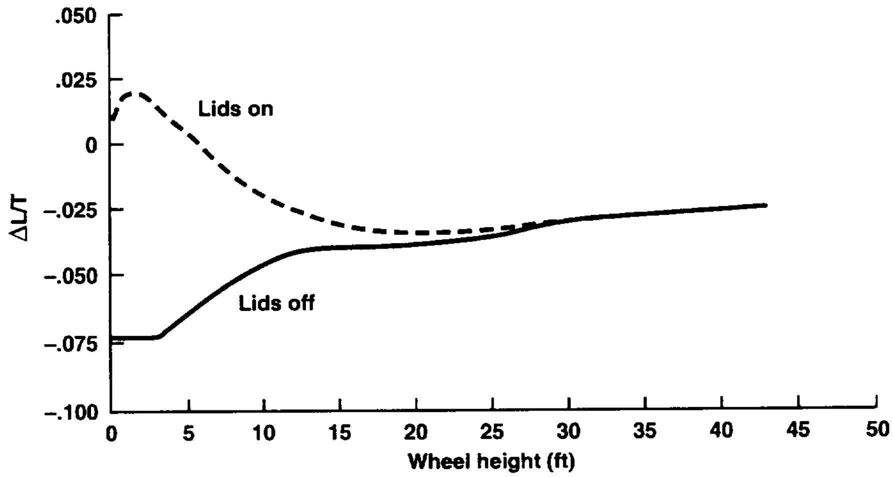


Figure 5. Jet-induced aerodynamic lift in ground proximity.

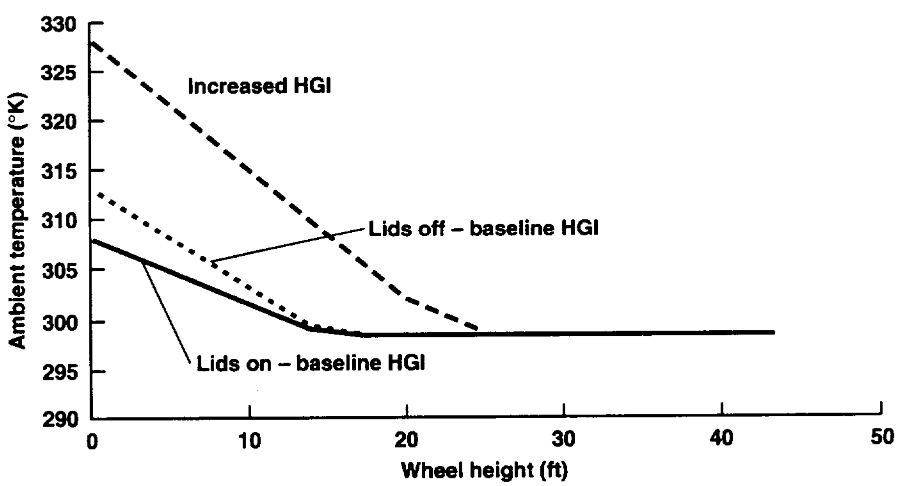
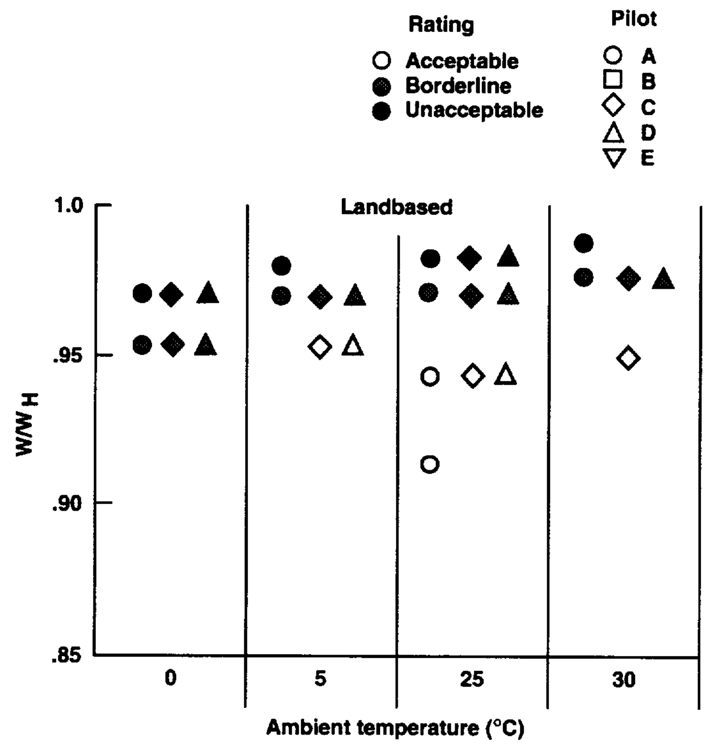
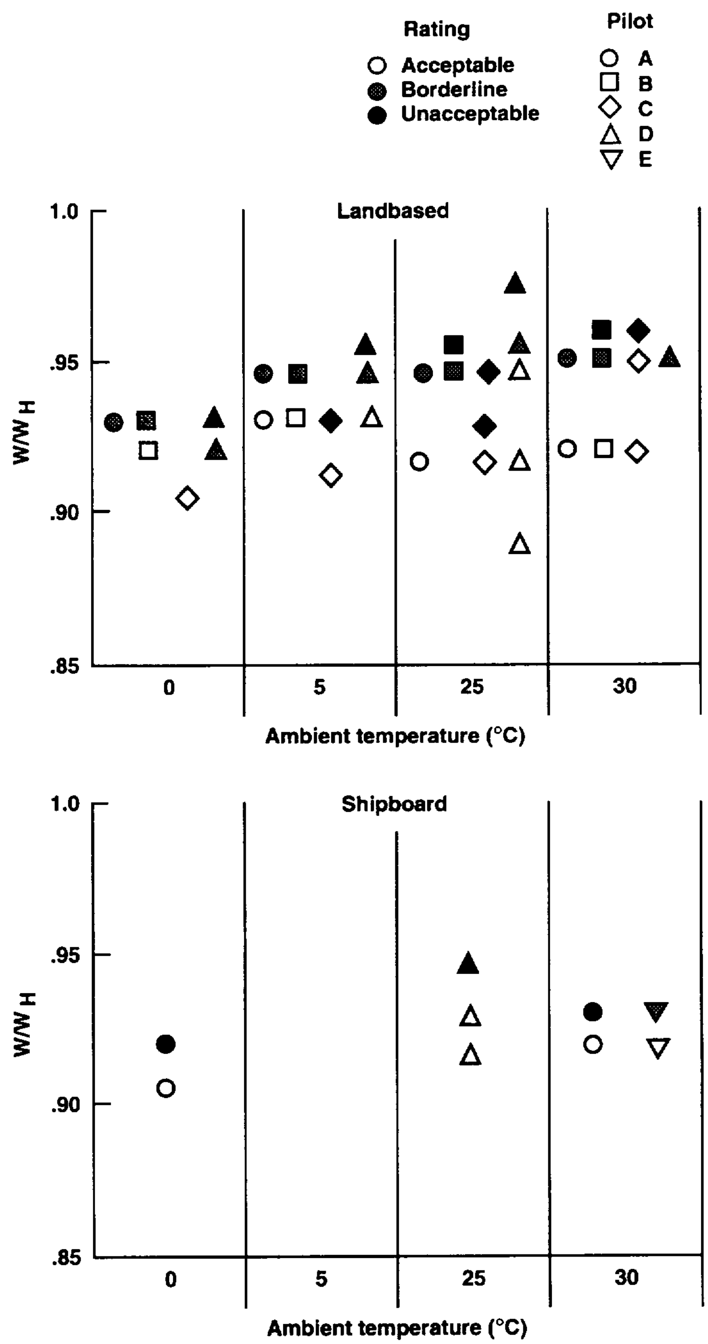


Figure 6. Ambient temperature profiles due to exhaust gas recirculation.



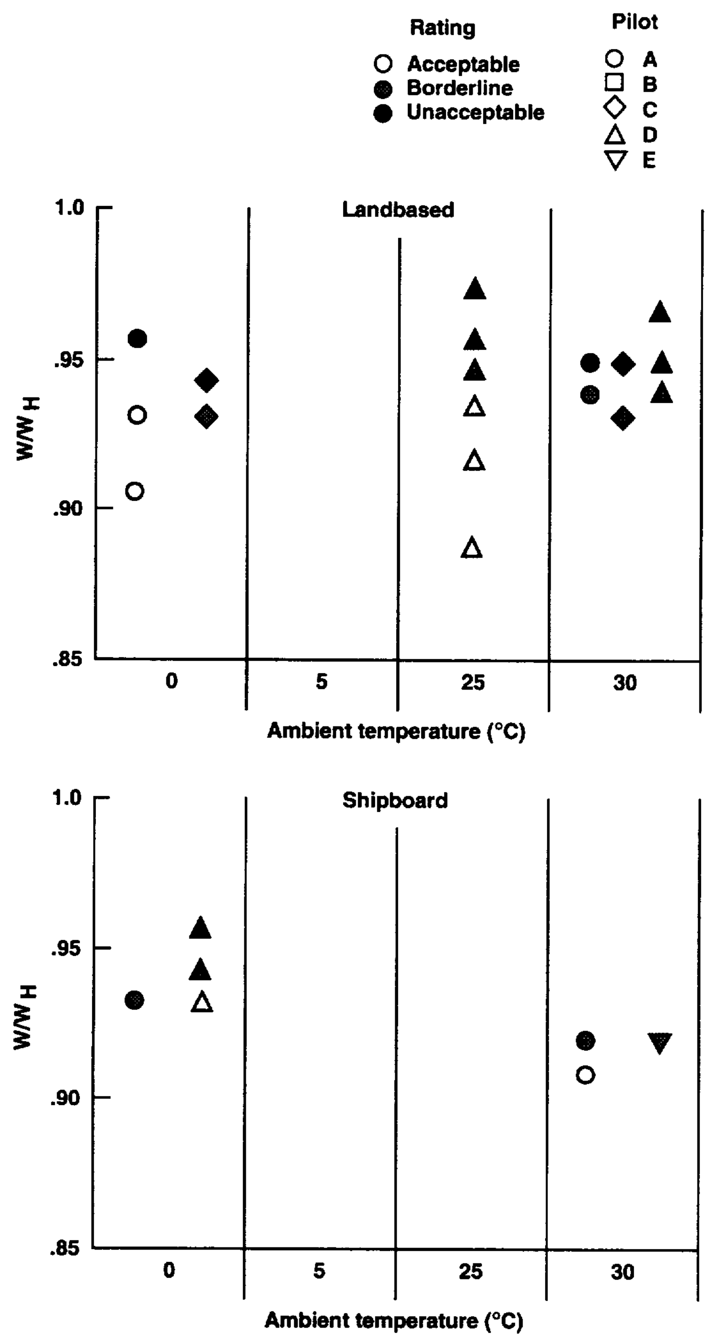
(a) LIDS On - baseline hot gas ingestion.

Figure 7. Evaluation of acceptable vertical landing weight for the YAV-8B Harrier.



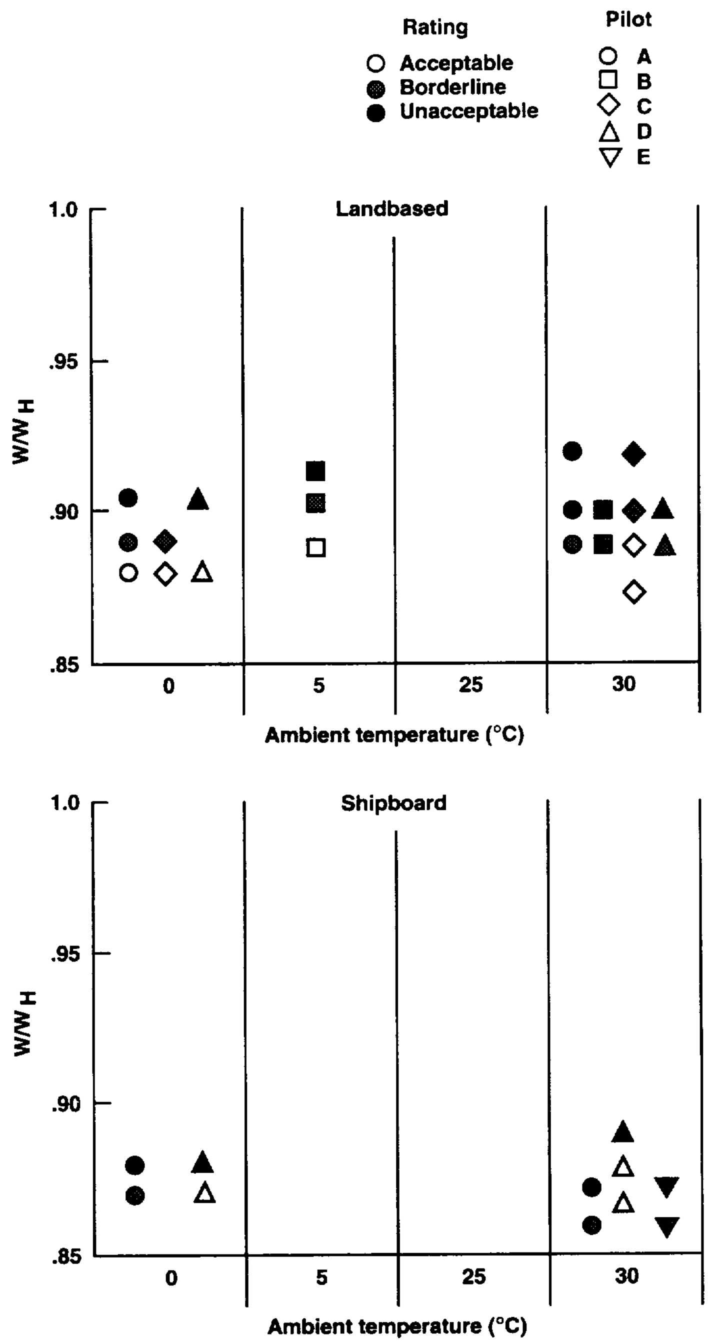
(b) LIDS Off - baseline hot gas ingestion.

Figure 7. Continued.



(c) LIDS On - increased hot gas ingestion.

Figure 7. Continued.



(d) LIDS Off - increased hot gas ingestion.

Figure 7. Concluded.

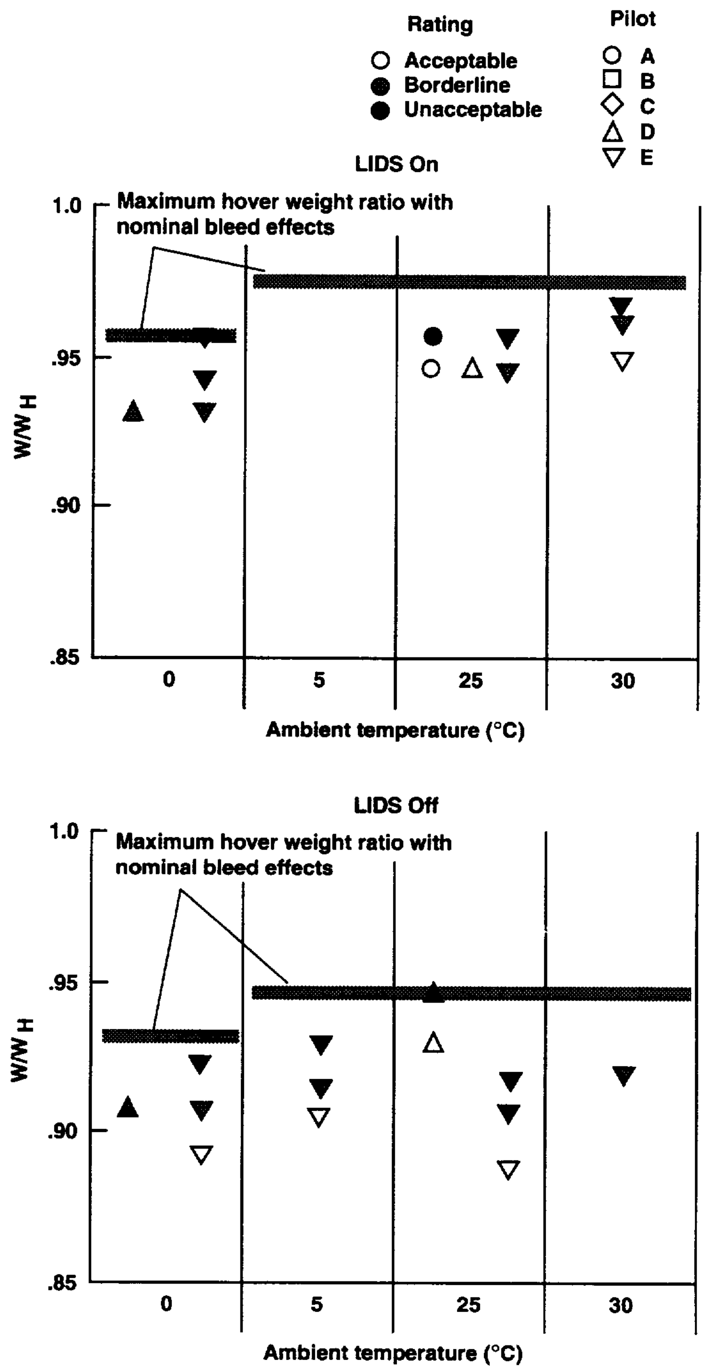


Figure 8. Effect of increased thrust sensitivity to bleed on maximum hover weight ratio.

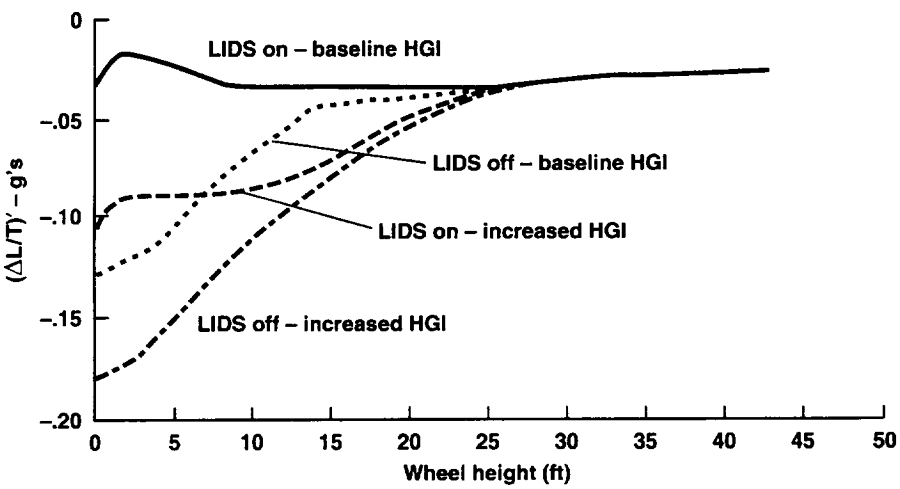


Figure 9. Variation of ground effect and ingestion with wheel height.

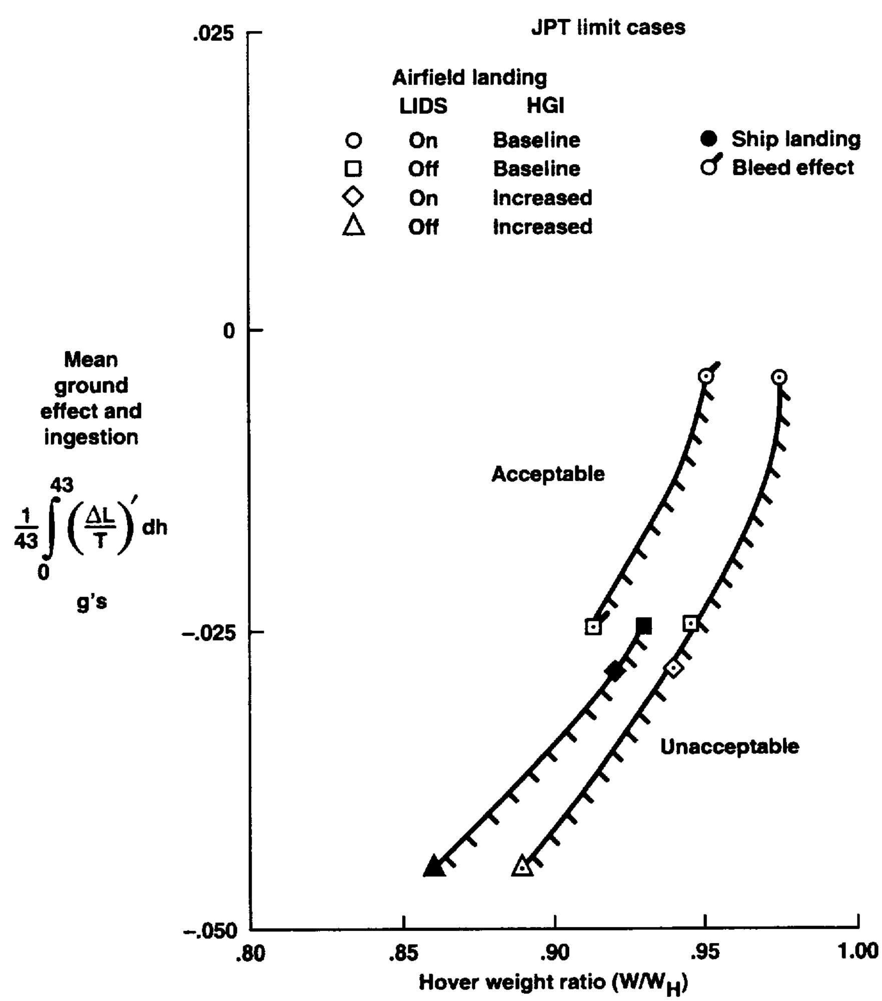


Figure 10. Influence of mean ground effect and ingestion on acceptable hover weight ratio for vertical landing for the YAV-8B Harrier.

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13. ABSTRACT ***(Maximum 200 words)***

A simulation experiment was conducted on Ames Research Center's Vertical Motion Simulator to evaluate the thrust margin for vertical landing required for the YAV-8B Harrier. Two different levels of ground effect were employed, representing the aircraft with or without lift improvement devices installed. In addition, two different inlet temperature profiles were included to cover a wide range of hot gas ingestion. For each ground effect and hot gas ingestion variant, vertical landings were performed at successively heavier weights, with the pilot assessing the acceptability of the operation in each case. Results are presented as a function of hover weight ratio and a metric of the mean ground effect and ingestion that reflect the increase in thrust margin required to provide acceptable control of sink rate during the descent to touchdown with increasing suck down and hot gas ingestion.

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