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Effect of Lift-to-Drag Ratio in Pilot Rating of the HL-20 Landing Task

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A man-in-the-loop simulation study of the handling qualities of the HL-20 lifting-body vehicle was made in a fixed-base simulation cockpit at NASA Langley Research Center. The purpose of the study was to identify and substantiate opportunities for improving the original design of the vehicle from a handling qualities and landing performance perspective. Using preliminary wind-tunnel data, a subsonic aerodynamic model of the HL-20 was developed. This model was adequate to simulate the last 75–90 s of the approach and landing. A simple flight-control system was designed and implemented. Using this aerodynamic model as a baseline, visual approaches and landings were made at several vehicle lift-to-drag ratios. Pilots rated the handling characteristics of each configuration using a conventional numerical pilot-rating scale. Results from the study showed a high degree of correlation between the lift-to-drag ratio and pilot rating. Level 1 pilot ratings were obtained when the L/D ratio was approximately 3.8 or higher.

Nomenclature

$C_{D,o}$ = minimum drag coefficient
L/D = lift-to-drag ratio
$(L/D)_{max}$ = maximum lift-to-drag ratio

Introduction

A DESIGN team at NASA Langley Research Center is in the conceptual design phase of a proposed vehicle for the personnel launch system. The passenger-carrying portion of the personnel launch system proposal, designated the HL-20 (see Figs. 1 and 2), is a 20,000-lb lifting-body vehicle, similar to earlier lifting-body designs[1-4] (M2-F2, M2-F3, HL-10, and X-24).

It is desirable in the early stages of the design process to identify areas of needed or possible improvement in the flight characteristics of the vehicle. A primary performance metric for a flight vehicle that performs unpowered horizontal landings is the maximum lift-to-drag ratio [$(L/D)_{max}$]. The maximum L/D ratio, an invariant quantity for a given aerodynamic shape, is a strong indicator of the vehicle's approach speed, descent rate, glideslope angle, and horizontal flare deceleration in the approach and landing phases of flight. $(L/D)_{max}$ is important because it affects the time available for the pilot to successfully perform the landing flare. (This time is inversely proportional to the rate of deceleration during the final flare maneuver.) Previous studies performed in flight demonstrated successful landings in vehicles with $(L/D)_{max}$ as low as 2.7 in the landing configuration.[5] Other references, citing flight results from the M2-F2 series, suggested that a $(L/D)_{max}$ of 3.0 was the minimum value (landing gear up) for successful landings.[6,7]

A study was performed to ascertain the difficulty of performing a flared horizontal landing in the HL-20 vehicle and to identify the effect of variations in the peak lift-to-drag ratio on pilot opinion of the vehicle's landing characteristics. Since this was to be the first manned simulation of the HL-20 configuration, several questions needed to be addressed: could the HL-20 vehicle be landed unpowered; how would variations in $(L/D)_{max}$ affect pilot opinion in the approach and landing task; and what minimum value of $(L/D)_{max}$ was needed to make satisfactory (Level 1) landings?

Experimental Approach

An experiment was conducted using a fixed-base simulator. A mathematical model of the preliminary HL-20 vehicle was developed, and simulated landings were performed by several different pilots in which $(L/D)_{max}$ was varied about the nominal value of 3.2. Each pilot was asked to provide a subjective handling qualities numerical rating[8] and to comment on the task and rating following a set of landing attempts with a

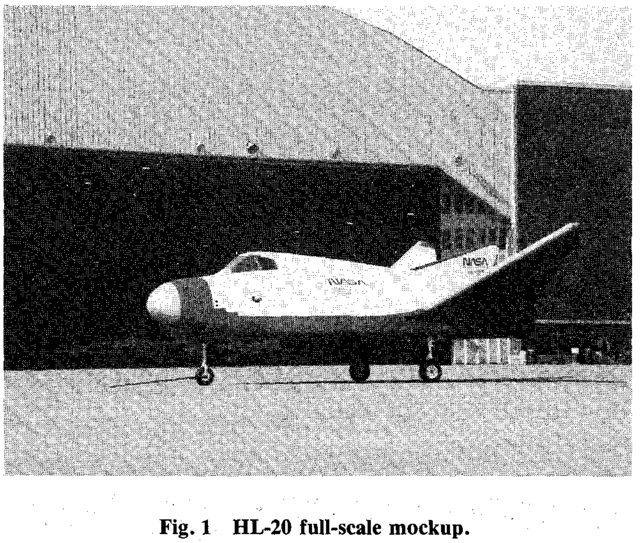

Fig. 1 HL-20 full-scale mockup.

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particular lift-to-drag configuration. Several performance parameters were recorded to support the pilots' opinions.

Vehicle Math Model

An aerodynamic model of the HL-20 was developed from initial wind-tunnel tests of scaled models.[9] This model was limited to subsonic regimes and had simplified linear-control effects. These approximations were regarded to be adequate for the purposes of this study. The trimmed $(L/D)_{max}$ for the baseline preliminary HL-20 configuration (landing gear up) was determined by wind-tunnel tests to be approximately 3.2 at an angle-of-attack of 12.8 deg. During this study, $(L/D)_{max}$ was varied by adding a constant value to (or subtracting from) $C_{D,o}$ in the simulator aerodynamic model coefficient buildup equation. $(L/D)_{max}$ was, thereby, varied from 2.7 to 5.2 for this study (see Fig. 3).

The control system used during this experiment consisted of a rate-feedback stability-augmentation system, an aileron-to-rudder interconnection, and a control mixer.[10] The control mixer served to separate the augmented pitch, roll, and speedbrake commands into appropriate body- and wing-flap commands. In addition, the mixer assured roll-control priority over pitch control and provided nearly pure longitudinal axis-force modulation in response to pilot speedbrake handle inputs. At higher angles of attack, upper body flaps were used as pitch controllers instead of speedbrakes. Angle of attack was fed back to the mixer and used to schedule the speedbrake compensation and to utilize the upper body flaps as pitch controllers during the flare. As shown in Fig. 4, differential body flaps were used for roll control, and symmetric wing flaps were used for pitch control. Symmetric extension of all four body flaps provided a speedbrake capability. The stability-augmentation system caused the aircraft to behave in a well-damped, stable manner and allowed the pilot to control

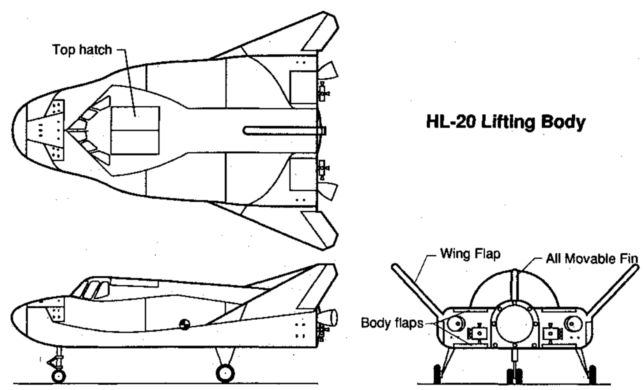

Fig. 2 HL-20 (three views).

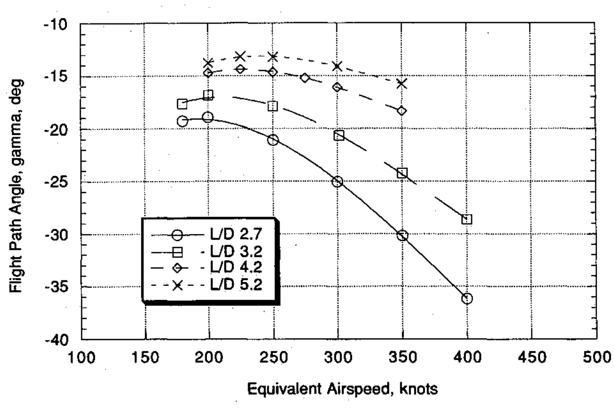

Fig. 3 Trimmed airspeed for different maximum L/D ratios.

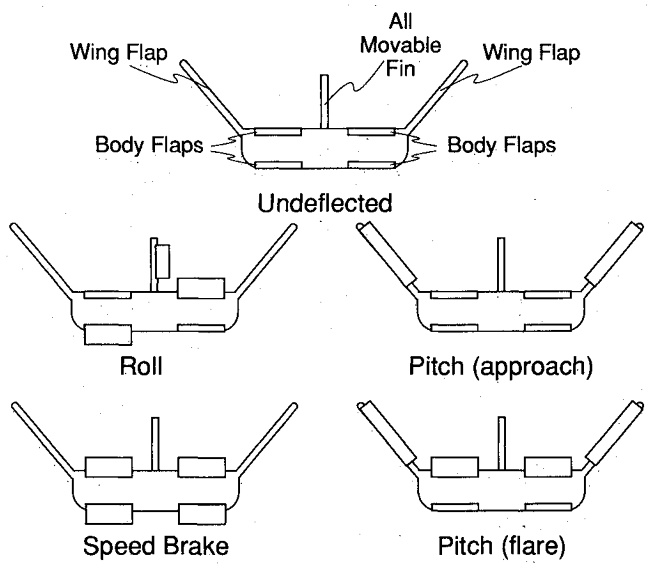

Fig. 4 Control surface deflections for various control commands.

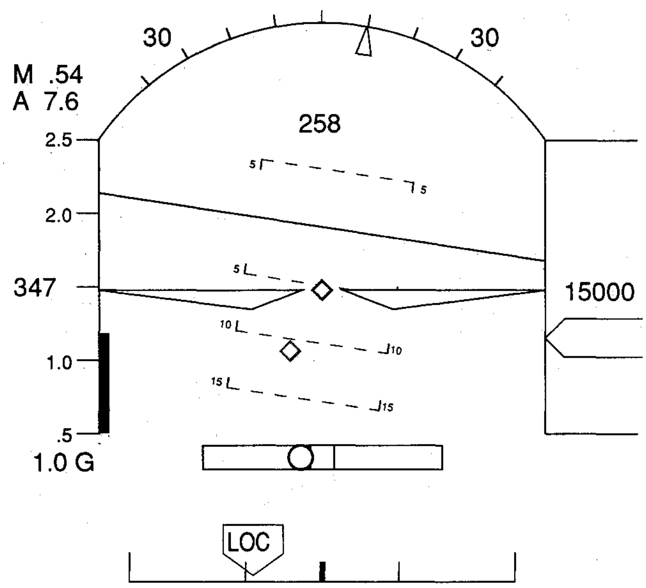

Fig. 5 Electronic attitude display.

the vehicle as though it were an aircraft possessing conventional flight dynamics. A pitch and roll trim button was provided on the control stick; the control system did not provide any autotrim capability. Actuators were modeled as a first-order lag, with a time constant of 0.016 s (10-Hz bandwidth), a rate limit of $\pm$ 200 deg/s, and a position limit of $\pm$ 40 deg. No hinge-moment limiting or hydraulic system-power limiting was modeled, since actuator performance was not a part of this study.

Simulator Cockpit

The simulator cockpit used in this study was a fixed-base transport category cockpit. The cockpit included, at the left pilot's station, a left-hand side-stick controller similar to that used in recent fly-by-wire transport aircraft. Speed modulation was performed using a right-hand speedbrake handle. This arrangement was backward from the left-hand throttle/right-hand stick arrangement found in most fighter aircraft, but most pilots seemed to be able to adapt to it after a short period of time. A head-down display (Fig. 5) provided the pilot with attitude, altitude, airspeed, and trajectory

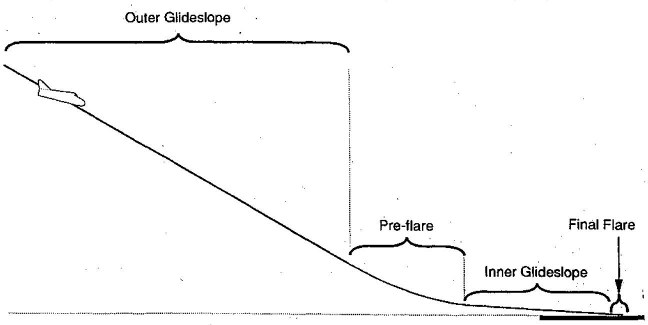

Fig. 6 HL-20 landing trajectory.

Table 1 Trajectory parameters

Max L/D ratio	V, KEAS[a]	Outer glideslope, deg	Preflare altitude, ft	Preflare pull, Δg
2.7	380	− 35	1930	1.0
3.2	347	− 25	1820	0.5
4.2	298	− 16	670	0.5
5.2	286	− 13.75	490	0.5

[a]Knots equivalent airspeed.

information. This information was displayed on a cathode-ray tube (CRT) mounted on the control panel in front of the pilot where attitude indicators are traditionally mounted. A glideslope marker and a localizer marker on the display showed deviations from the preplanned nominal trajectory. A perspective view of the runway, a pitch ladder, and an instantaneous flight-path marker provided the pilot with velocity vector and runway orientation information. The flight-path marker remained fixed in the center of the display whereas the pitch ladder and runway outline moved in response to vehicle motion. An out-the-window scene was generated with an image generation system on an interlaced video monitor operating at an update rate of 50 Hz. The scene was presented to the pilot through simulated forward and side windows which used conventional mirror-beam-splitter displays.

The simulation operated at 33.3 Hz (30 ms frame rate) and was operated asynchronously from the visual system. Pure transport delay (neglecting digital integration effects) from stick input to visual system response was on the order of 150 ms.

Task Definition

The two-part nominal trajectory shown in Fig. 6 was predetermined for all approaches. A steep outer glideslope was joined to a shallow inner glideslope by a parabolic preflare segment. Since the vehicle decelerates in the preflare, a parabolic preflare shape was chosen over a circular shape to keep the steady-state load factor constant. Each approach began at sufficient altitude and distance from the approach end of the runway in order to be on the extended runway centerline and on the outer-glideslope portion of the nominal approach trajectory. To provide a consistent environmental challenge to the pilot, the winds were fixed at 10 kts (direct headwind) with moderate turbulence. The turbulence time history was the same for all runs. The outer-glideslope aimpoint, flight-path angle, equivalent airspeed, preflare initiation altitude, and preflare load factor were adjusted for each L/D configuration to provide approximately 15 s between initiation of preflare and the point at which nominal touchdown speed was reached. For all approaches, the inner glideslope segment had the same angle (-1.5 deg). Table 1 summarizes the initial conditions and trajectory parameters for each L/D configuration; the term "preflare pull" indicates the additional normal acceleration needed to perform the preflare maneuver. A preflare pull of 1.0 means the preflare maneuver required 2 g normal acceleration. The initial condition for each configuration was at "constant dynamic pressure" or "stabilized equivalent airspeed," that is, the vehicle was decelerating (in an inertial sense) at the initial condition such that equivalent airspeed was held constant. A decelerating initial condition was necessary to compensate for the relatively rapid increase in atmospheric density at a descent rate on the order of 10,000 ft/min. If the initial state of the simulation had been an "inertially trimmed" condition, equivalent airspeed would rise rapidly

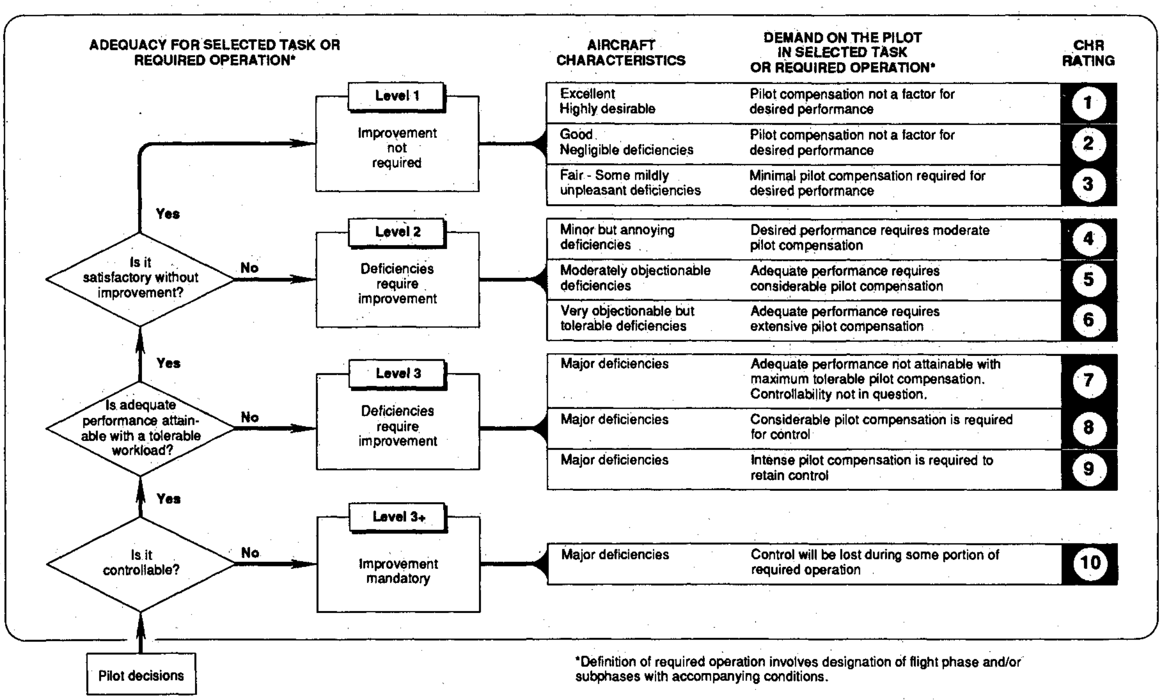

Fig. 7 Pilot rating scale (from Cooper-Harper).

when the simulation began operating and required considerable pilot compensation to remove the resulting airspeed error.

Outside visual cues (provided by the computer-generated imagery system and a set of two mirror-beam-splitter displays) and a head-down electronic attitude display were used (Fig.5) by the pilot to perform a series of approaches to landing. Altitude callouts and a preflare warning call were made by the copilot on all approaches. Each pilot was allowed five practice approaches for each L/D configuration and was then asked to perform five approaches during which time-history data and touchdown statistics were recorded. During each recorded approach, pilot hand controller activity was recorded. After each set of five recorded approaches, the pilot was asked to provide a numerical rating using the Cooper-Harper rating scale (Fig. 7) as well as any comments about the task or the given rating. For this test, the primary measure of landing performance was touchdown sink rate, with additional constraints on pitch attitude, touchdown location, and lateral touchdown velocity. Adequate performance was defined to be a touchdown sink rate less than 10 ft/s; desired performance was defined as a sink rate of less than 5 ft/s. Additional constraints required the pitch attitude to be less than 20 deg to avoid scraping the tail, and the touchdown point to be in the first 3000 ft of the runway. The lateral velocity at touchdown was limited by the landing gear model. If the resultant forces on the landing gear exceeded some preset value, the simulation model would signal a "crash" by entering hold mode, and the landing was deemed to be unsuccessful.

Test Subjects

Test subjects included three pilots with fixed-wing low L/D landing experience and one pilot with both rotary- and fixed-wing experience. Pilot "A" was a research pilot with experience as a former Shuttle training aircraft instructor pilot with several thousand low L/D approaches. Pilot "B" was a dual rated pilot with several thousand hours piloting experience, including several hundred practice (idle throttle) autorotations. The autorotation maneuver is similar in

Table 2 Results of landing approaches with maximum lift-to-drag of 2.7

Pilot	Run	Pitch stick, deg/rms	Sink rate, ft/s	Landing CHR
A	1	0.0592	− 12.2	
	2	0.0463	− 5.6	
	3	0.0476	− 8.5	
	4	0.0533	− 4.1	
	5	0.0481	− 5.4	
	Average	0.0509	− 7.2	4.0
B	1	0.0586	− 10.8	
	2	0.0501	− 5.2	
	3	0.0557	− 13.9	
	4	0.0555	− 7.1	
	5	0.0545	− 1.9	
	Average	0.0549	− 7.8	4.0
C	1	0.0484	− 7.1	
	2	0.0453	− 5.3	
	3	0.0472	− 5.3	
	4	0.0531	− 6.1	
	5	0.0428	− 1.5	
	Average	0.0474	− 5.1	5.0
D	1	0.0518	− 8.3	
	2	0.0532	− 4.8	
	3	0.0459	− 2.0	
	4	0.0474	− 3.7	
	5	0.0491	− 5.4	
	Average	0.0495	− 4.8	N/G[a]

[a]N/G: not given.

Table 3 Results of landing approaches with maximum lift-to-drag of 3.2

Pilot	Run	Pitch stick, deg/rms	Sink rate, ft/s	Landing CHR
A	1	0.0320	− 3.5	
	2	0.0314	− 5.8	
	3	0.0322	− 10.3	
	4	0.0320	− 5.1	
	5	0.0347	− 7.9	
	Average	0.0325	− 6.5	3.5
B	1	0.0344	− 5.5	
	2	0.0350	− 4.0	
	3	0.0350	− 6.7	
	4	0.0379	− 14.1	
	5	0.0345	− 6.6	
	Average	0.0354	− 7.4	4.0
C	1	0.0301	− 4.3	
	2	0.0319	− 2.6	
	3	0.0299	− 1.4	
	4	0.0306	− 1.5	
	5	0.0315	− 1.0	
	Average	0.0308	− 2.2	4.0
D	1	0.0312	− 2.7	
	2	0.0304	− 5.5	
	3	0.0320	− 7.9	
	4	0.0314	− 1.5	
	5	0.0310	− 5.9	
	Average	0.0312	− 4.7	6.0

Table 4 Results of landing approaches with maximum lift-to-drag of 4.2

Pilot	Run	Pitch stick, deg/rms	Sink rate, ft/s	Landing CHR
A	1	0.0329	− 9.9	
	2	0.0337	− 12.3	
	3	0.0310	− 2.1	
	4	0.0298	− 6.0	
	5	0.0314	− 5.1	
	Average	0.0317	− 7.1	3.0
B	1	0.0370	− 5.0	
	2	0.0375	− 2.7	
	3	0.0388	− 5.8	
	4	0.0371	− 8.3	
	5	0.0360	− 4.2	
	Average	0.0373	− 5.2	3.0
C	1	0.0330	− 1.6	
	2	0.0349	− 0.7	
	3	0.0342	− 0.7	
	4	0.0315	− 0.7	
	5	0.0315	− 5.7	
	Average	0.0330	− 1.9	2.0
D	1	0.0287	− 2.4	
	2	0.0335	− 3.7	
	3	0.0311	− 3.3	
	4	0.0312	− 6.8	
	5	0.0314	− 5.0	
	Average	0.0312	− 4.2	N/G[a]

[a]N/G: not given.

Table 5 Results of landing approaches with maximum lift-to-drag of 5.2

Pilot	Run	Pitch stick, deg/rms	Sink rate, ft/s	Landing CHR
A	1	0.0351	− 6.3	
	2	0.0372	− 3.0	
	3	0.0375	− 4.2	
	4	0.0363	− 1.9	
	5	0.0361	− 3.1	
	Average	0.0365	− 3.7	3.0
B	1	0.0485	− 5.3	
	2	0.0444	− 3.1	
	3	0.0466	− 2.4	
	4	0.0450	− 6.3	
	5	0.0450	− 6.0	
	Average	0.0459	− 4.6	2.0
C	1	0.0390	− 4.6	
	2	0.0390	− 1.1	
	3	0.0396	− 1.0	
	4	0.0360	− 3.7	
	5	0.0364	− 3.6	
	Average	0.0380	− 2.8	2.0
D	1	0.0367	− 2.9	
	2	0.0383	− 2.6	
	3	0.0392	− 3.6	
	4	0.0350	− 4.4	
	5	0.0335	− 5.4	
	Average	0.0366	− 3.8	N/G[a]

[a]N/G: not given.

trajectory to the approaches flown in this study, although the approach speed is considerably slower. Pilot "C" was a research pilot who had performed low L/D approach in the F-104 aircraft. Pilot "D" was a research pilot with extensive experience in many types of aircraft, and with experience in previous lifting-body and X-15 flight tests.

Study Results

Three principal results from this study are examined in this section. These results are based on pilot ratings, performance metrics, and pilot comments.

Following each set of five approaches, each pilot provided a numerical rating, using the standard Cooper-Harper rating (CHR) scale (Fig. 7), of the difficulty in performing three portions of landing: outer glideslope, preflare, and final flare. Tables 2–5 provide the numerical scores given by each pilot for the four different L/D configurations tested. Pilot D only provided a CHR score for the nominal [$(L/D)_{max}$ = 3.2] configuration.

Tables 2–5 also give the root-mean-square (rms) pitch-stick displacement and aircraft sink rate at touchdown for each run. The rms pitch-stick displacement from trim was obtained by recording the longitudinal position of the hand controller, by subtracting the trimmed controller position, and by summing the absolute value of the displacement during the period of time from initiation of preflare to main gear touchdown. This summed displacement value was then divided by the measurement duration. The result provides a measure of the amount of pitch-stick motion generated by the pilot during the preflare and landing. This data-reduction method was necessary since different L/D configurations had slightly different amounts of time between preflare and touchdown. The values for the five runs in each configuration are averaged in the data tables, and the statistical values (mean/rms) are plotted in Fig. 8 vs the $(L/D)_{max}$ of the configuration. The symbols at either end of the vertical bar indicate the maximum and minimum values of stick rms deflection, and the mean value is shown as a horizontal bar. Figure 9 shows the variation in average touchdown sink rate for each pilot and each L/D configuration. The same symbol convention is used in Fig. 8. Although no obvious correlation is apparent, the trend appears to be lower sink rates (softer landings) as lift-to-drag ratio increases. Figure 10 shows the relationship between L/D ratio and numerical pilot rating. This figure clearly shows a preference by the pilots for increased lift-to-drag ratio in the landing task.

Pilot Comments

Selected pilot comments for different $(L/D)_{max}$ configurations illustrate the nature of the task. The highest drag configuration, for which $(L/D)_{max}$ was 2.7, resulted in comments such as "Difficult to judge proper pitch rate. Could not see runway environment out the window during most of preflare. Easy to overcontrol preflare, resulting in being high at runway threshold," and "(Flight-path angle) for (this configuration) was too steep to keep the approach end of runway in sight. Severely restricted opportunity to make corrections (to preflare). High (approach) speed required." This same pilot said of the remaining configurations that, in general, "Quite easy to stay in the loop and modify sink rate all the way to touchdown." The next configuration, with an $(L/D)_{max}$ of 3.2, yielded "Energy bleed rate on inner glide slope acceptable. Longitudinal transients apparent when landing gear lowered" and "Very similar in performance to the M2-F2, which was the most uncomfortable to land of the three lifting bodies." The next configuration evaluated [$(L/D)_{max} = 4.2$] caused one pilot to comment, "Much easier preflare task than previous configurations." The last configuration, with the highest $(L/D)_{max}$(= 5.2), caused one pilot to comment, "Very similar

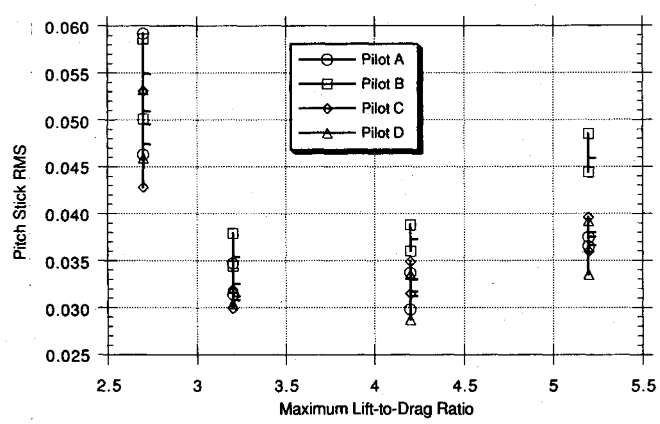

Fig. 8 Pitch-stick displacement vs maximum L/D ratio.

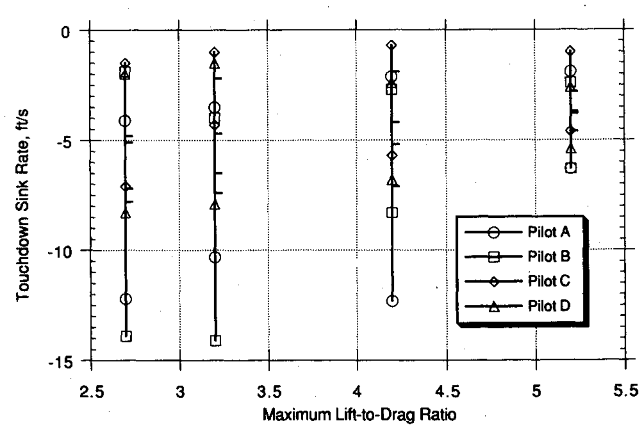

Fig. 9 Touchdown sink rate vs maximum L/D ratio.

to $(L/D)_{max}$ 4.2 configuration. Biggest problem is still in determining flight-path angle in final flare. Milder preflare maneuver reduced tendency to overcontrol pitch inputs." Regarding all of the configurations, one pilot commented, "Depended on g (meter to judge) flare and transitioned outside at 200 ft or when sink rate was under control. This task is too much (of an) open loop (task). Hard landings are possible, especially if not concentrating," while another pilot noted, "No problems with control in preflare. Very difficult to judge rate-of-sink in visual simulator. Had lots of trouble keeping sink rates low. An $(L/D)_{max}$ of 3.5–4.0 would provide a more acceptable landing capability. Low L/D provides short 'float time'."

Discussion of Results

A significant effect between maximum lift-to-drag ratio and pilot rating was found for the HL-20 type of lifting body. Although the two secondary objective measurements (stick activity and sink rates) do not demonstrate as clear an indication, they do not contradict the pilot ratings. With lower L/D configurations, less opportunity for final flare corrections was available to the pilot due to the rapid deceleration of the vehicle. Higher L/D configurations provided a larger touchdown "window" or landing opportunity. Note that for the steepest approach $[(L/D)_{max} = 2.7]$, the upper limit of the simulator out-the-window display caused the runway environment to disappear just prior to preflare initiation. Two pilots commented that this made judging the preflare pitch rate difficult and this limitation is probably a factor in the poorer (higher) pilot ratings.

The stick activity measurement shown in Fig. 8 appears to describe a saddle point between two competing effects. The decrease in stick activity between the configuration which one pilot described as a "controlled crash" $[(L/D)_{max} = 2.7]$ and the next higher L/D configuration $[(L/D)_{max} = 3.2]$ is clearly the result of lower pilot workload. For configurations with $(L/D)_{max}$ higher than 3.2, stick activity shows a small positive gradient with respect to L/D. This increase in stick activity can be attributed to greater time spent in the final flare "float" condition for the higher L/D conditions. The higher L/D configurations required the stick to be held back for a longer period of time and, thus, showed more stick displacement. A better measure of stick activity might, therefore, be an integral of absolute stick rate, but these data were not measured in this experiment. Measurements of sink rate show a slightly positive trend toward lower sink rates as L/D is increased, although in two segments the gradient for individual pilots is negative. This amount of scatter is not felt to contradict the pilot rating data, when the relatively small sample size is considered.

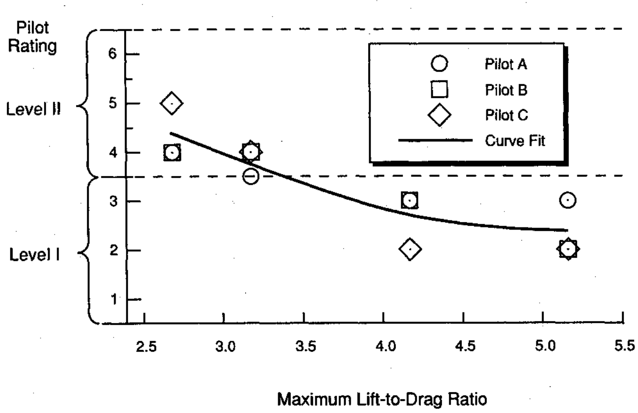

Fig. 10 Pilot rating for landing task vs maximum L/D ratio.

Conclusions

A study was conducted to identify and substantiate opportunities for improving handling and landing performance qualities of the HL-20 personnel launch system. The results of this study are given as follows: unpowered landings are possible in the baseline HL-20 configuration; pilot ratings were consistently better for the higher L/D configurations; upper limits to pilots' field of view can be a hindrance in performing the preflare maneuver for lower $(L/D)_{max}$ configurations; rms stick activity indicates higher levels of pilot effort were required for lower $(L/D)_{max}$ configurations, despite decreased duration of measurement; touchdown sink rates tend to improve (decrease) as $(L/D)_{max}$ is decreased; and Level 1 flying qualities appear to be possible for configurations with a maximum L/D ratio of 3.8 or higher.

Supported by these conclusions, the value of $(L/D)_{max}$ should apparently be increased to at least 3.8 to provide reduced pilot workload and improved performance while landing the HL-20. This evidence, in part, motivated a successful effort to improve the subsonic aerodynamic efficiency of the HL-20.[11] As a result of that effort, the subsonic trimmed $(L/D)_{max}$ of the modified HL-20 is approximately 4.3.

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