AN ANALYSIS AND SIMULATION OF LANDINGS UTILIZING STORED-ENERGY LIFT

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SUMMARY

The various phases of a landing, in which energy stored on board the aircraft is used to support its weight during deceleration from flare to hover, are considered. The deceleration is assumed to be done at constant altitude and pitch attitude, lift due to stored energy being commanded as required by a separate control at the lefthand of the pilot.

Simulation of the deceleration phase of the landing was provided in a simple analogue computer, oscilloscope display, stick and lift control, arrangement. Variation of velocity and various aerodynamic parameters with time were programmed in accordance with theoretical calculations of constant attitude deceleration with reverse thrust. Simulated deceleration and touch down runs were made with various initial conditions and airplane parameters.

Simulation of the landing procedure indicates that when the stored-energy lift is brought on during final approach prior to the braking phase, the landing maneuver is easy and natural for the pilot. This technique, however, is very wasteful of stored-energy. It is much more efficient to use stored-energy lift only as needed during deceleration, to support the aircraft as aerodynamic lift decreases. The latter technique is more difficult for the pilot, but appears to be feasible, given that certain other conditions are favorable. Estimates of stored-energy requirements are made for the various techniques and ranges of parameters.

INTRODUCTION

All the various means to support a flying vehicle continuously at very low speeds are quite inefficient and require large or complicated power plants and lifting elements. The large installed power or complicated lifting systems for Vertical Take-off and Landing capability seem always to compromise the aircraft in one way or another.

If, however, short bursts of lift energy could be stored on board the aircraft, and used for lift during the momentary deceleration phase from "flight speed" to hovering, perhaps VTOL capability could be furnished without a large handicap in terms of installed power or complicated systems.

This idea raises questions about piloting problems during the transients involved in slowing down - near the ground - from a normal approach or flare speed to a hover. In this phase, of course, the stored-energy lift is required to support the aircraft. It is expected that the management of the stored-energy would have an important bearing on the stored-energy capacity requirements and the ease of performing the maneuver.

The study reported here was undertaken to explore the general feasibility of such landings, and to indicate the range of energy requirements for various piloting techniques and ranges of parameters.

SYMBOLS

C_D	drag coefficient $\frac{\text{Drag}}{qS}$
C_{D_O}	zero-lift drag coefficient
C_L	lift coefficient $\frac{\text{Lift}}{qS}$
D	drag
g	acceleration due to gravity
h	altitude
i	subscript denoting start of deceleration
I_y	moment of inertia about pitch axis
I_s	stored energy specific impulse $\frac{L_{\delta_T}}{g}\int \lvert\delta_T\rvert \, dt = \frac{1}{W}\int T_L dt$
k_i	induced drag parameter $\frac{n_i^2}{u_i^4}$
K	induced drag constant for parabolic drag polar $C_D = C_{D_O} + KC_L^2$
ℓ	tail length
L	lift
$\frac{L_\alpha}{V}$	stability derivative, $\frac{1}{mV}\frac{\partial L}{\partial \alpha}$
L_{δ_T}	stored-energy lift control derivative, $\frac{1}{m}\frac{\partial L}{\partial \delta_T}$
m	mass

M	pitching moment
M_α	longitudinal stability derivative $\frac{1}{I_y}\frac{\partial M}{\partial \alpha}$
$M_{\dot{\alpha}}$	longitudinal stability derivative $\frac{1}{I_y}\frac{\partial M}{\partial \dot{\alpha}}$
$M_{\dot{\theta}}$	longitudinal stability derivative, $\frac{1}{I_y}\frac{\partial M}{\partial \dot{\theta}}$
M_{δ_s}	longitudinal control derivative, $\frac{1}{I_y}\frac{\partial M}{\partial \delta_s}$
M_{δ_T}	pitching moment due to stored energy lift, $\frac{1}{I_y}\frac{\partial M}{\partial \delta_T}$
n	aerodynamic (wing) load factor, $\frac{L}{W}$
n_i	aerodynamic (wing) load factor at start of deceleration
q	dynamic pressure, $\frac{1}{2}\rho V^2$
S	wing area
t	time, seconds
t^*	deceleration time parameter, $\frac{tg}{V_R (L/D)_{max}}$
T	thrust
T_D	reverse thrust
T_L	stored energy lift
T_4	time required for deceleration phase
u	velocity ratio, $\frac{V}{V_R}$
V	velocity
V_R	velocity for minimum drag, $\sqrt{\frac{2W}{\rho S}\sqrt[4]{\frac{K}{C_{D_O}}}}$

w	vertical gust velocity
W	weight
x	distance along flight path
x^*	distance parameter, $\frac{xg}{V_R^2 (L/D)_{max}}$
Z_D	reverse thrust parameter, $\frac{T_D}{W} (L/D)_{max}$
α	angle of attack
γ	flight path angle
δ_s	moment control (center stick) deflection
δ_T	stored energy control (side lever) deflection
θ	pitch attitude angle
ρ	density
ω	longitudinal short period natural frequency
ζ	longitudinal short period damping ratio

ANALYSIS AND RESULTS

Two Types of Stored-Energy Landing

For the purposes of discussion and analysis in the following sections, one kind ($n_i = 0$) of stored-energy landing is broken down into five phases. They are illustrated in the sketch below.

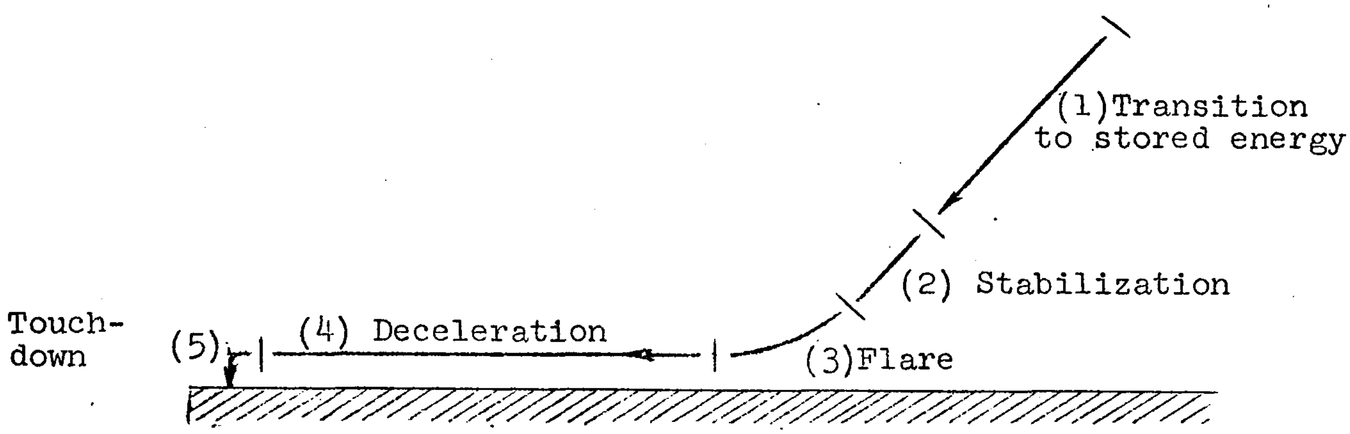

Fig. 1 The Phases of a Stored-Energy Landing ($n_i = 0$)

We shall not deal with preliminary phases which would not involve expenditure of stored energy, like navigation to the terminal area, maneuvering in the terminal area traffic patterns for position and sequence, then acquiring and stabilizing on the flight path for final approach. The landing begins, for our purposes, with the first use of stored-energy on final approach, in Phase 1, above. The stored-energy thrust, or lift, would be brought on from $T_L = 0$ to $T_L = W$ in this period. Speed and descent angle would be kept approximately constant, but angle-of-attack and attitude would undergo large changes. This phase would correspond roughly to lowering flaps, during final approach, from mid-position to landing position, in a conventional airplane.

Phase 2 is a short period of stabilization to eliminate transients arising in the transition, to acquire the correct position and speed for the flare to "get set", so to speak, for the exacting final phases of the landing. We assume, though it is not really crucial, that Phases 1 and 2 are done at $V = 100$ ft/sec and $\gamma = 6^{o}$. The rate of descent is therefore 10 ft/sec, or 600 ft/min.

Phase 3 is the flare from the 6 deg. descent path to level flight just off the ground. At the end of flare the aircraft is assumed to be in level flight at about 10 ft altitude, $V = 100$ ft/sec, ready for deceleration to hover.

During deceleration, Phase 4, the pilot applies reverse (braking) thrust, and while slowing down, controls height by modulating the stored-energy lift, controls attitude with conventional stick (or wheel), and monitors speed, V , in order to cut off reverse thrust when hovering is reached.

Finally, Phase 5 consists of a set-down, at zero forward speed, to the ground. It would be done by simply decreasing the stored-energy lift.

The procedure described above is a rather obvious extension of an ordinary landing technique. It is obviously feasible, given favorable values for certain parameters which will be discussed later. It is, however, obviously wasteful of stored energy, which is brought on in final approach long before it is really needed to sustain the weight of the aircraft. This has led to consideration of a second kind of stored-energy landing, in which the final approach and flare are to be done on ordinary aerodynamic wing lift, and the stored energy lift is saved for Phase 4 where it is brought on as needed for control of altitude during the deceleration. But in this method, precision height control during deceleration might be more difficult, possibly even impractical.

From the point of view of the piloting task, the significant differences between the two methods lie in Phase 4. To explore them experimentally, a simple piloted simulator for deceleration and touch-down was devised. The two principal parameters which were varied were the deceleration time, T_4 , representing different levels of reverse thrust; and the level of stored-energy lift at the beginning of Phase 4, proportional to $(1 - n_i)$. Where $n_i = 0$, the landing is of the first kind, where the transition to stored-energy lift is on final approach, as in Fig. . Where $n_i = 1$, the landing is of the other kind, in which the stored-energy lift is brought on as needed, during deceleration.

An intermediate value of n_i would correspond to a partial transition to stored-energy lift on final approach with the remainder brought on as needed during Phase 4. A few runs of that kind were made, with $n_i = .5$, representing stored-energy lift equal to one-half weight in Phases 1, 2 and 3, and at the beginning of Phase 4.

Besides variations of the two principal parameters T_4 and n_i , two other features of the system were varied also. They were the pitch dynamics of the aircraft, consisting of the set of stability derivatives; and a control coupling term, pitching moment due to stored-energy lift, M_{δ_T} . The variations in these parameters and their effects on the piloting task will be discussed in detail in the presentation of results.

The Deceleration Maneuver

The particular deceleration maneuver representing Phase 4 involves constant altitude and constant pitch attitude, in which the aircraft is borne partly upon aerodynamic lift and partly upon direct lift from a stored-energy source. It is assumed that reverse thrust independent of velocity is available.

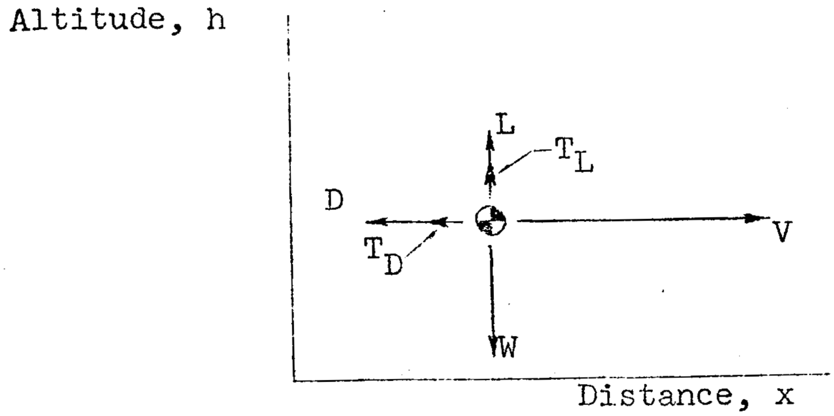

Fig. 2 Orientation of Force and Velocity Vectors for Deceleration

The flight path may be described by the following set of equations:

$$\dot{h} = 0 \tag{1a}$$

$$\dot{x} = V \tag{1b}$$

$$L + T_L - W = 0 \tag{1c}$$

$$T_D + D + \frac{W}{g}\dot{V} = 0 \tag{1d}$$

T_L and T_D are the stored-energy direct lift and the reverse thrust, respectively.

Equations (1c) and (1d) may be rewritten as

$$n - 1 + \frac{T_L}{W} = 0 \tag{2a}$$

$$\dot{V} + g\left(\frac{T_D}{W} + \frac{D}{W}\right) = 0 \tag{2b}$$

where

$$n = \frac{L}{W}$$

the ratio of aerodynamic (wing) lift to weight.

Constant C_L Constraint

Since flight-path angle, γ, pitch attitude, θ, and angle-of-attack, α, are related according to

$$\gamma = \theta - \alpha \tag{3}$$

limiting the maneuver to constant altitude and constant attitude also implies constant angle-of-attack. This in turn implies that the aerodynamic (wing) lift coefficient is constant.

If conditions existing at the beginning of the deceleration maneuver are denoted by a subscript "i", we have

$$C_L = \frac{nW}{1/2\rho SV^2} = \frac{n_i W}{1/2\rho SV_i^{\,2}} \tag{4}$$

We thus obtain the load factor variation during the maneuver:

$$n = n_i\left(\frac{V}{V_i}\right)^2 \tag{5}$$

Stored-Energy Lift - Function of Velocity

The amount of stored-energy lift which must be supplied to maintain level flight as the airspeed decreases is found by inserting equation (5) into the lift equation (2a) . The result is:

$$\frac{T_L}{W} = 1 - n_i\left(\frac{V}{V_i}\right)^2 \tag{6}$$

Differential Equations of Deceleration

The central problem of the analysis is to determine the distance and the time required to decelerate from some initial velocity to a final velocity, taking into account the initial aerodynamic (wing) load factor, the level of reverse thrust available, and the drag aerodynamics of the vehicle.

The governing equations are obtained by rearranging the "drag equation", (2b), with velocity as the independent variable, which gives

$$\frac{dx}{dV} = - \frac{V}{g\left(\frac{T_D}{W} + \frac{D}{W}\right)} \tag{7a}$$

$$\frac{dt}{dV} = - \frac{1}{g\left(\frac{T_D}{W} + \frac{D}{W}\right)} \tag{7b}$$

It is reasonable to assume that the drag aerodynamics of the machine may be represented by a parabolic polar,

$$C_D = C_{D_O} + KC_L^{\ 2} \tag{8}$$

so that the required variation of drag with speed is

$$\frac{D}{W} = \frac{(C_{D_O} + KC_L^{\ 2})}{2W} \rho V^2 S \tag{9}$$

Subsequent operations are simplified if we introduce at this point a non-dimensional velocity, u , defined as follows:

$$u = \frac{V}{V_R} \tag{10}$$

where V_R = velocity for maximum L/D (or minimum drag in level flight with L = W)

$$= \sqrt{\frac{2W}{\rho S}} \sqrt[4]{\frac{K}{C_{D_0}}}$$

In terms of u , equation (9) becomes

$$\frac{D}{W} = \frac{1}{2(L/D)_{max}} \left(u^2 + \frac{n^2}{u^2}\right) \tag{11}$$

Substituting the above expressions for u and $\frac{D}{W}$ into the time and distance equations, (7a) and (7b), yields

$$\frac{dx^*}{du} = - \frac{2u^3}{u^4 + 2Z_D u^2 + n^2} \tag{12a}$$

and

$$\frac{dt^*}{du} = - \frac{2u^2}{u^4 + 2Z_D u^2 + n^2} \tag{12b}$$

where

$$x^* = \frac{xg}{V_R{}^2 (L/D)_{max}}$$

$$t^* = \frac{tg}{V_R (L/D)_{max}}$$

$$Z_D = \frac{T_D}{W} (L/D)_{max}$$

= reverse thrust parameter

It may be noted that the reverse thrust parameter, Z_D , is the ratio of reverse thrust to minimum thrust required in level flight, with lift equal to weight.

Equations (12a) and (12b) represent, in parametric form, equations for decelerating flight paths with

$$L = nW$$

$$\gamma = 0$$

$$T_D = \text{constant}$$

which may now be integrated to yield the required distance and time for the maneuver.

Integrated Distance and Time

If the load factor appropriate to the constant - α condition - equation (5) - is inserted in the differential equations for distance and time, we have

$$dx^* = -\frac{2u^3du}{u^4 + 2Z_Du^2 + n^2}$$

$$= -\frac{2u^3du}{u^4 + 2Z_Du^2 + \left(n_i\frac{u^2}{u_i^2}\right)^2}$$

$$= -\left(\frac{u_i^4}{u_i^4 + n_i^2}\right)\left[\frac{2udu}{u^2 + \left(\frac{2u_i^4Z_D}{u_i^4 + n_i^2}\right)}\right]$$

$$= -\left(\frac{1}{1 + k_i}\right)\left[\frac{2udu}{u^2 + \left(\frac{2Z_D}{1 + k_i}\right)}\right] \qquad (13a)$$

and similarly,

$$dt^* = - \frac{2u^2 du}{u^4 + 2Z_D u^2 + n^2}$$

$$= - \left(\frac{2}{1 + k_i}\right)\left[\frac{du}{u^2 + \left(\frac{2Z_D}{1 + k_i}\right)}\right] \qquad (13b)$$

where $k_i = \frac{{n_i}^2}{{u_i}^4}$

Integrating, the general parametric distance and time solutions are

$$x^* = - \left(\frac{1}{1 + k_i}\right) \ln \left[u^2 + \frac{2Z_D}{1 + k_i}\right] + \text{Constant} \qquad (14a)$$

and

$$t^* = - \frac{1}{Z_D} \sqrt{\frac{2Z_D}{1 + k_i}} \, \text{Tan}^{-1} \frac{u}{\sqrt{\frac{2Z_D}{1 + k_i}}} + \text{Constant} \qquad (14b)$$

Using subscripts to denote initial, $(\ )_i$, and final, $(\ )_f$, conditions, the distance and time required to decelerate are given by

$$x = \frac{{V_R}^2 (L/D)_{max}}{g(1 + k_i)} \left[\ln\left({u_i}^2 + \frac{2Z_D}{1 + k_i}\right) - \ln\left({u_f}^2 + \frac{2Z_D}{1 + k_i}\right)\right] \qquad (15a)$$

and

$$t = \frac{V_R (L/D)_{max}}{g Z_D} \sqrt{\frac{2Z_D}{1 + k_i}} \left[Tan^{-1} \frac{u_i}{\sqrt{\frac{2Z_D}{1 + k_i}}} - Tan^{-1} \frac{u_f}{\sqrt{\frac{2Z_D}{1 + k_i}}} \right] \quad (15b)$$

for $Z_D \neq 0$ and

$$t = \frac{2V_R (L/D)_{max}}{g(1 + k_i)} \left[\frac{1}{u_f} - \frac{1}{u_i} \right] \quad (15c)$$

for the case $Z_D = 0$

Note that neither solution allows both the reverse thrust and the final velocity to be simultaneously zero; this is physically correct since the only retarding force present in that situation is the aerodynamic drag, proportional to V^2.

Figures 3 and 4, which present the logarithmic and inverse tangent portions of equations (15a) and (15b), are useful for estimating distance and time requirements.

Reverse Thrust Required to Decelerate in a Given Time

The time-required solution, Equation (15b), may be rearranged to yield the reverse thrust required to decelerate from the initial velocity to some final velocity in a given time. For this study, the most interesting case was that of zero final velocity, and Figures 5 and 6 present examples of this calculation. Figure 5 is for an initial aerodynamic load factor of unity (aircraft entirely wing-borne at start of deceleration) while Figure 6 is for $n_i = 0$ (aircraft supported entirely on stored-energy lift).

A comparison of the two sets of curves shows that at reasonably high initial velocities ($u_i > .8$), there is little difference between the two cases with respect to the amount of reverse thrust required to obtain a given t^*. In other words, the influence of induced drag (k_i) is small.

By contrast, at low initial velocities the differences are large, especially for short decelerations. However, these very low initial velocities are, in general, unobtainable for $n_i = 1$ flight as the following section indicates.

Limits on u_i and k_i

In order not to exceed the maximum lift coefficient of the aircraft

$$C_{L_i} = \frac{2W}{\rho S} \frac{n_i}{V_i^2} = \sqrt{k_i}\, C_{L_{(L/D)max}} < C_{L\ max} \tag{16}$$

Thus

$$k_i < \left(\frac{C_{Lmax}}{C_{L_{(L/D)max}}} \right)^2 \tag{17}$$

and since

$$k_i = \frac{n_i^2}{u_i^4}$$

this implies that the initial velocity must satisfy the inequality

$$u_i > \sqrt{n_i} \sqrt{\frac{C_{L_{(L/D)max}}}{C_{L_{max}}}} \tag{18}$$

Equation (18) indicates that any initial velocity is permissible for the $n_i = 0$ case, and this is so, since the machine is not dependent upon aerodynamic lift and $C_{L_i} = 0$. For the $n_i = 1$ case, however, u_i will be given approximately by

$$u_i > \frac{1}{\sqrt{C_{L_{max}}}} \tag{19}$$

since typically, $C_{L_{(L/D)max}}$ is about unity.

Thus, unless very large lift coefficients are obtainable, the lower values of u_i on Figure 5 are not permissible, and induced drag does not greatly lessen the reverse thrust requirements. (It should be also noted that, subject to the same conditions, the time history of velocity will be relatively independent of n_i.)

A sample calculation is carried out in the Appendix.

The Simulation

The pilot was seated before a simple instrument and visual display, and operated the aircraft through two control levers: a center stick for pitching moment control, and a left-hand side lever for controlling stored-energy lift, with a finger switch for shutting off reverse (decelerating) thrust. The visual presentation consisted of two horizontal lines displayed on a dual-beam oscilloscope. A broad line, by its distance above an index on the tube face, displayed height or altitude. A fine line, by its displacement from the broad line, indicated pitch attitude. In the "mind's eye" of the pilot, the broad line represented a horizontal line fixed to the aircraft near the CG - say the landing gear wheel axle - while the fine line represented a horizontal bar fixed to the nose of the aircraft. The altitude, h , signal in the analogue computer commanded vertical displacement equally of both horizontal lines; whereas the pitch attitude signal, $\Delta\theta$, affected only the fine line. This compromise display was considered to be fairly natural by the pilot. After some practice, the pilot could interpret the display without confusion, and even described the simulation as "quite realistic". Immediately above the oscilloscope, a voltmeter indicated velocity, derived from a signal in the analogue computer. Its scale, from zero to 100, read directly in feet per second.

The pilot "flew" the display by manipulating the two control levers connected electrically to the computer analogue representation of the pitch attitude and vertical displacement degrees of freedom of the aircraft. To represent atmospheric turbulence, random appearing signals were also applied to the two degrees of freedom, causing a random component of vehicle motion which had to be overcome by the pilot. The turbulence signals represented w (vertical) gusts of about three feet per second (rms). They were judged by the pilot to represent a rough, gusty day, but not a highly improbable or unrealistic condition.

The pilot did not have continuous, closed-loop control over velocity. It was considered that in a real landing, reverse thrust control would be ON-OFF. It would be turned ON at the end of flare and turned OFF on reaching a hover. The actual deceleration would thus be open-loop. In the simulation, velocity was programmed in accordance with the analytical results previously given, using the aircraft parameters computed in the Appendix. The velocity programs are shown in Figure 7 . The pilot was, however, required to monitor airspeed in order to shut off reverse thrust. This was done by releasing a spring-loaded switch on the left-hand stored-energy lever.

From the point of view of the pilot, runs were conducted in the following way:

a) Initially, the display was stationary, indicating an altitude of ten feet; a nominal or desired pitch attitude; and V = 100 ft/sec. The pilot would begin the run by pressing an OPERATE button on the center stick. In the next few seconds he would overcome the starting transient and attempt to hold height and attitude in the presence of the turbulence. Velocity would then start decreasing, as though in response to reverse thrust.

A few trial runs were made in which the pilot applied reverse thrust himself. Unconstrained with respect to landing point, and lacking any display of ground features, he tended to wait for a lull in disturbances to put on the reverse thrust. In an actual landing, however, the pilot would have ground references and he would be shooting for a particular flare point and touch-down point - so he would have to accept whatever disturbance existed at the point where reverse thrust had to be applied. A better representation of this real situation was achieved by having the computer operator start the reverse thrust and deceleration at random a few seconds after OPERATE.

b) During decleration, with velocity decreasing, the pilot would attempt to control height with the side lever, and attitude with the center stick. Disturbances due to turbulence had to be suppressed, and he would attempt to "let-down" to about 5 ft. He was required to shut-off reverse thrust accurately at $V = 0$; and then, finally, to slack off on stored-energy lift for the actual touch-down a few seconds later.

c) The pattern of runs for a given set of conditions was two or three for practice, not counted in scoring; then five to ten data runs; and finally, a rest and discussion of piloting difficulty and performance, including assignment of a Cooper rating.

The equations of the analogue computer for lift and pitching moment are given below.

$$-\left(\frac{L_\alpha}{V} + s\right) s\Delta h + L_\alpha \Delta\theta = -L_{\delta_T} \Delta\delta_T + \frac{L_\alpha}{V} W_g + g\left(1 - n_i\frac{V^2}{V_i^2}\right)$$

$$\left(\frac{M_{\dot\alpha}}{V} s + \frac{M_\alpha}{V}\right)s\Delta h + \left[s^2 - (M_{\dot\alpha} + M_\theta)s - M_\alpha\right]\Delta\theta = M_{\delta_s}\Delta\delta_s - \frac{\omega^2}{V} w_g$$

The responses can be given as

$$\frac{dh}{dt} = \frac{\begin{vmatrix} -L_{\delta_T}\Delta\delta_T + \frac{L_\alpha}{V} wg + g\left(1 - n_i\frac{V^2}{V_i^2}\right) & L_\alpha \\ M_{\delta_s}\Delta\delta_s - \frac{\omega^2}{V} w_g & \left[s^2 - (M_{\dot\alpha} + M_\theta)s - M_\alpha\right] \end{vmatrix}}{s\,(s^2 + 2\zeta\omega s + \omega^2)}$$

$$\Delta\theta = \frac{\begin{vmatrix} -\frac{L_\alpha}{V} - s & -L_{\delta_T}\Delta\delta_T + \frac{L_\alpha}{V} w_g + g\left(1 - n_i\frac{V^2}{V_i^2}\right) \\ \frac{M_{\dot\alpha}}{V} s + \frac{M_\alpha}{V} & M_{\delta_s}\Delta\delta_s - \frac{\omega^2}{V} w_g \end{vmatrix}}{s\,(s^2 + 2\zeta\omega s + \omega^2)}$$

These are the conventional, linear, small perturbation equations - novel only in their provision for turbulence and for the time variation of derivatives to correspond to variation of airspeed. The latter was accomplished by the computer operator who manipulated a set of ganged potentiometers to properly track the prescribed velocity function of time. In this way, the derivatives were made functionally dependent on V as follows:

$$M_\alpha \sim V^2$$

$$L_{\alpha/V} \sim V$$

$$M_{\dot\theta} \quad \text{constant}$$

$$M_{\delta_s} \quad \text{constant}$$

$$L_{\delta_T} \quad \text{constant}$$

$$M_{\delta_T} \quad \text{constant}$$

The pitch damping, $M_{\dot\theta}$, and the stick (elevator) effectiveness, M_{δ_s} , perhaps require some explanation. The natural, aerodynamic value of the former would, of course, vary as V , and the latter as V^2 . But in a real aircraft, control effectiveness would be needed at all speeds. There are many ways it could be achieved, the details of which are quite outside the objectives of this investigation. A logical and acceptable compromise for the simulation was simply to make M_{δ_s} constant. It was quickly found in preliminary trials that without pitch damping the simulator could not be flown adequately at low speed. It was therefore decided to make $M_{\dot\theta}$ constant also, to represent an artificial pitch damper, familiar in almost all VTOL aircraft, including many helicopters.

It can be shown that in the transfer functions of $\Delta\theta$ and Δh to lift and moment for forward flight, there are only five independent parameters. They are prescribed by values of $\dot{L}_{\delta/V}$, $L_{\alpha/V}$, M_δ, ζ, ω - independent of $M_{\dot{\alpha}}$, which may be put equal to zero without introducing any peculiarity or unnatural response characteristic. The angle-of-attack damping, $M_{\dot{\alpha}}$, occurs separately only in the numerator of the pitch-to-lift transfer function, as $\frac{M_{\dot{\alpha}}}{V}$ (or $M_{\dot{w}}$) . According to ordinary aerodynamic theory the latter would be independent of speed, but this is rather obviously wrong at $V = 0$, where it should be equal to zero. In hovering, a non-zero $M_{\dot{w}}$ would produce an undesirable anomalous pitch response to lift. The derivative was therefore put equal to zero in order to avoid the anomaly in the simplest possible way.

The disturbances due to turbulence were introduced in the compromise way indicated in the equations. Technically, only the w gust components were represented, and only approximately. The many details of the forces and moments due to turbulence are peripheral to the problem here. The features presented in the simulation were:

a) disturbances in both lift and pitching moment were correlated and approximately of proper relative magnitude

b) both lift and moment disturbances varied linearly with velocity

c) disturbances in magnitude were rationally related to the stability derivatives which determine the dynamic stability and response. The "good" configuration with large derivatives is disturbed more than the "bad" one, which has smaller derivatives.

d) the root-mean-square value of the w_g signal was about three feet per second. The resulting disturbances were considered by the pilot to be realistic and representative of a gusty, windy day. The w_g

signal was obtained from a rotating cam and follower device having a repetition period of two minutes. For practical purposes, its spectrum could be considered continuous, flat to about $\frac{1}{20}$ cps, then dropping off at 12 db/oct.

The "good" and "bad" dynamics configurations are fully described by only three parameters. Their values at the initial speed of 100 ft/sec, were

	"Good"	"Bad"
L_α/V	1.00	.25
ω	3.6 rad/sec	1.3 rad/sec
ζ	.7	.15

The individual stability derivatives could be found, if needed, from

$$M_{\dot{\alpha}} = 0$$

$$\omega^2 = M_\alpha + \frac{L_\alpha}{V} M_{\dot{\theta}}$$

$$2\zeta\omega = \frac{L_\alpha}{V} - M_{\dot{\alpha}} - M_{\dot{\theta}}$$

The control lever sensitivities were set at favorable values, in order to guarantee that their particular values did not influence the results. The side lever for stored-energy lift had a travel of about four inches from zero to lift = weight. Hence the derivative was

$$L_{\delta_T} = \frac{1}{m} \frac{\partial L}{\partial \delta_T} = \frac{g}{4} \doteq 8 \text{ ft/sec}^2\text{/in}$$

The sensitivity of the moment control, the center stick, was selected by the pilot to be optimum for the task. No consideration was given to other flight conditions or design compromises. The derivative had the value

$$M_{\delta_s} = \frac{1}{I_y} \frac{\partial M}{\partial \delta_s} = -\ .8 \text{ rad/sec}^2/\text{in}$$

The coupling parameter, pitching moment due to stored-energy lift, was tried at two different levels, besides zero. The most meaningful measure of their magnitudes would be in terms of stick motion required to produce cancelling moments. In those terms

$$\frac{g}{L_{\delta_T}} \frac{\partial \delta_s}{\partial \delta_T} \Big|_M = .5 \text{ and } 1.0$$

These values correspond respectively to one-half and one inch of stick motion to cancel the moment due to an increment of stored-energy lift equal to weight. The meaning of this, in terms of offset between the CG and the center of stored-energy lift, depends on many parameters of the aircraft. For the M_{δ_s} used in this simulation, the larger value is roughly an offset of

$$\chi \doteq \frac{I_y (\text{slug} - \text{ft}^2)}{W \text{ (pounds)}}$$

For a small aircraft of, say, 10,000 pounds, the equivalent offset would likely be a foot or two.

Results of the Experimental Simulation Program

The data taken in the deceleration and touch-down runs were of three kinds: pilot opinion ratings and commentary; time at which reverse thrust was shut off; and time histories of the following quantities

control deflections,	δ_T	and	δ_s
flight variables,	$\Delta\theta$	and	h
energy used,	$\int\|\delta_T\|dt$	and	$\int\|\delta_s\|dt$

We shall present these data first, and then try to draw general conclusions about the feasibility of the different techniques and the trade-off between energy requirements and quality of the piloting task.

It was quickly found in trial runs that the deceleration time, T_4, and the initial wing lift load factor, n_i, were parameters of outstanding importance. The whole task of two-dimensional control and of monitoring V, was very much easier for $n_i = 0$ than for $n_i = 1$, and of course it became more difficult as T_4 was decreased. The pilot opinion rating function of T_4 and n_i is presented in Fig. 8 for the "good" dynamics, and in Fig. 9 for the "bad" configuration. In both of those configurations the control coupling term M_{δ_T} was zero. In these figures, the small numerals indicate actual POR assigned by the pilot. The contours and identifying circled numerals represent fairing of the data. They are dotted where they are considered to be extrapolations. The well-known Cooper scale was used with the standard descriptions given in Table 1 .

Configuration With "Good" Dynamics

Consider first the "good" configuration, Fig. 8 . The best rating was 3.2 at $n_i = 0$, $T_4 = 10$. The pilot reported, "Nothing really wrong. Easy to control both pitch and height. No danger of premature ground contact. Completely confident of good landing. Plenty of time to monitor V . Would rate better except that turbulence is quite strong. Would not improve appreciably to increase T_4 ."

The recorded histories of δ_T , δ_s , $\Delta\theta$ and h are shown in Fig. 10 . They show excellent control over attitude and height, and a moderate level of activity of the two controls - largest at the beginning, and diminishing as the disturbances decrease along with speed. Note that δ_T varies due to turbulence about the trim position, which for $n_i = 0$ is steady at stored-energy lift equals weight. The average error in shutting off reverse thrust was only .2 seconds - hardly any worse than could be done with no tracking task at all, full attention on V (.1 seconds).

Next consider the small degradation to a rating of 3.5 due to shortening the time, T_4 to 5 seconds, keeping $n_i = 0$. Control was essentially the same as for longer T_4 , touch-down was easy and consistent, pilot felt slightly rushed in judging reverse thrust cut-off time, although the average error was again only .2 seconds.

Now consider the right-hand side of the figure, for $n_i = 1$ - starting again with $T_4 = 10$ seconds, and a pilot rating of 4. The pilot reported,

"Almost contacted ground prematurely on one run, but mostly good performance. Confident about landing. Necessity to pull on δ_T , to counter tendency to sink, requires more attention, and makes it harder to shut-off reverse thrust on time."

Time histories for one run are shown in Fig. 11 . The fluctuations in δ_T seem larger, and they now vary about a trim position which itself varies quite rapidly as speed decreases. Height and attitude control performance are not as good. The near ground hit is noted in the figure. The average error in reverse thrust shut-off was .4 seconds. It is clear that although the task can still be done with confidence, it is noticeably harder than for $n_i = 0$, and accuracy and performance are definitely degraded.

This situation improved slightly to a rating of 3.5 by lengthening the deceleration time to 15 seconds. The improvement was due to easier timing of reverse thrust shut-off. Pilot could devote more attention to height and attitude, and achieved better performance. Average timing error was only .2 seconds.

With a reduction, however, of T_4 to 5 seconds, the pilot rating deteriorated rapidly to 5.4. Commentary included,

"Really feel rushed. Have to work hard to get into position for landing, and at same time pay attention to shutting-off reverse thrust. Necessity to bring on δ_T very fast is effectively a disturbance and requires close attention to h, neglecting $\Delta\theta$ at times. Landable but not under precision control."

Time histories of one run are shown in Fig. 12 . Very large excursions in δ_T are evident, and there are large variations in $\Delta\theta$ and h . It looks as though this run was pretty frantic, almost out of control. In spite of this, the shut-off timing was quite good - average error of .3 seconds.

A few intermediate runs were made at $n_i = .5$, with generally intermediate results, as indicated by the ratings noted in the figure. The expectation that $n_i = 0$ should be optimum, suggests that the iso-opinion contours should have zero slope at that point, and the general shape with which they are drawn. It is clear that under these conditions with $n_i = 0$, deceleration time is not of much importance down to as little as 5 seconds, with the landing being easy and precise. With $n_i = 1$, however, the task is harder and less precise, and deceleration time becomes an important factor. Deceleration times of 15 seconds are satisfactory and acceptable with good performance and pilot confidence; but times as short as 5 seconds are only marginally acceptable, with unsatisfactory performance. From this isolated point of view, the $n_i = 0$ deceleration is clearly preferable. There are, however, other implications which remain to be developed.

Configuration With "Bad" Dynamics

With the "bad" configuration of dynamics, the difficulty of the task is greater, the performance worse, and the pilot ratings correspondingly higher. The iso-opinion contours are faired and presented in Fig. 9 . They are similar to the other, "good" case, but generally higher. The best rating obtainable is now about 4. Lest one be tempted to draw invalid comparisons with other data like Refs. 1 or 2 , it should be noted that they are not comparable because of differences of task and conditions; and above all, because the ω , ζ tabulated apply only at the beginning of the runs, where V = 100 fps. Here, in the course of deceleration, they change radically.

In any case, the 4 rating, obtainable for $n_i = 0$, corresponds to,

"Damping undesirably low, obviously light, but not too much problem. Partly compensated by smaller disturbances. h and $\Delta\theta$ not too hard to control. Good confidence in flying and landing, even with precision. Only disadvantage is low damping."

The time histories of these runs indeed show performance roughly comparable to their counterparts of the "good" dynamics. This pilot, however, is obviously somewhat apprehensive about the low damping, even though he successfully copes with it. The errors of reverse thrust cut-off time average only .2 seconds.

For $n_i = 1.0$, the situation is again quite different. For the rapid deceleration, $T_4 = 5$ seconds, the pilot comments,

"Rather bad. Completely inconsistent in performance. Aircraft tends to sink, hard to get h back. Low damping in pitch, yet because of primary h task, $\Delta\theta$ control must suffer. Cannot spare any attention for speed - consistently late in turning off reverse thrust. Cannot guarantee successful landing."

The time histories amply confirm these remarks. Many of them, like Fig. 13 , show the aircraft essentially out of control, with large changes in pitch attitude and height, and frantic manipulation of the controls. Although several technically successful landings were made, on two runs out of fourteen, control was lost and they have to be labeled "crashes". In the successful runs, the average reverse thrust timing error was .5 seconds.

Increasing the deceleration time of course alleviates the difficulties. Of the 5 rating at $T_4 = 15$ seconds, the pilot says,

"Quite a bit harder than $n_i = 0$, which does not require tight h control like this one. Different technique. This one bounces more (in h), which feeds pitch, which is too lightly damped. Hard task - keeps you busy - too many things to do. Doubt if you could ever do as well as with $n_i = 0$."

Again the time history records confirm the commentary. Although all runs could be completed, some were near-crashes, like Fig. 14 where the aircraft grazed the ground while still in forward motion. Some runs involved very active control motions with noticeable over-controlling and "chasing" the display. The average reverse thrust timing error was .3 seconds.

The effects and interplay of the T_4 and n_i parameters are clearly similar here to the case of the "good" dynamics with only a general degradation. The $n_i = 0$ decelerations, though not easy or pleasant, are nevertheless consistently flyable. With $n_i = 1$, however, the task varies between marginally acceptable at $T_4 = 15$ seconds to occasional disaster at $T_4 = 5$ seconds.

Configurations With Control Coupling, M_{δ_T}

A few runs were made to investigate the effect of the pitching moment due to stored-energy lift, M_{δ_T} . This effect, of either sign, appeared to be undesirable. It was worst, however, for the direction of nose-down moment for increasing lift, and was exaggerated in the case of "bad" dynamics. For M_{δ_T} of that sign, negative, the angle of attack change induced by it tends to counteract, or defeat, the lift change commanded by δ_T in the first place. It is possible to combat this by careful control coordination, but the whole effect changes with speed, and is difficult to learn. The inputs into pitch from the lift lever are like additional disturbances, and they force the pilot to devote more attention to $\Delta\theta$, which he can ill afford to do. Fig. 15 shows how pilot ratings are affected by M_{δ_T} , for various kinds of runs and conditions. For the not-too-unfavorable case of "bad" dynamics, $T_4 = 5$ seconds, $n_i = 0$ [a 4 in Fig. 15], the gradient in the nose-down direction of M_{δ_T} is very steep, with the rating quickly climbing to 7. The pilot reported,

"Inconsistent performance. Cannot guarantee successful landing. Cannot really cope with it. Pitching gets out of hand. Cannot keep control over both h and $\Delta\theta$."

Of the nose-up M_{δ_T} , the pilot also reported difficulty with pitching, but he says he is more tolerant of moment correlated this way to lift, where nose-up pitch enforces the "up" lift change. The degradations of rating are nearly equal, however.

With the better dynamics and $n_i = 0$, the unfavorable effect of either sign of M_{δ_T} is again appreciable. The flaw is that the $\Delta\theta$ response to δ_T demands attention to the pitch loop, with consequent degradation in h control and V monitoring. The pilot would "rather not fight the pitch response". He comments (although his ratings do not show it here) that nose-up M_{δ_T} requires the easier, more natural, control coordination.

In the more critical task of $n_i = 1$, the larger activity of the δ_T control is felt more strongly in the $\Delta\theta$ loop. In this case, the pilot downrates the nose-up M_{δ_T} the more severely because he feels that the change of trim δ_T , as speed reduces, produces a tendency to over-rotate. He "hates to push hard forward while slowing down, for fear of landing on the nose".

In any case, it is clear that M_{δ_T} of the magnitudes tested, of either sign, is a severe disadvantage in the deceleration and touch-down task as simulated here. It might well degrade an otherwise acceptable and satisfactory situation to a distinctly marginal one; or it might move a more difficult, otherwise marginal case into the completely unacceptable, uncontrollable category. In an actual design, this derivative would have to be contained within rather narrow limits. Although the data are somewhat limited and not entirely consistent, it appears that values corresponding to $\frac{g}{L_{\delta_T}} \frac{\partial \delta_s}{\partial \delta_T} \Big|_M$ greater than $\pm$ .25 inch might be considered undesirable, and values greater than $\pm$ .5 inch would be definitely objectionable.

Limited Correlation With Flight Tests

An abbreviated series of landings with a real, variable stability airplane, in a small separate program, has tended to confirm the general feasibility of decelerations of the kind discussed above. In those real landings, the approach and flare (phases 1, 2 and 3) were made at a high speed (about 100 mph) with deceleration near the ground to about 65 mph, where touchdown occurred.

The deceleration rates were governed by the natural aerodynamic drag of the airplane, averaging about 5 seconds in duration. Throughout the deceleration phase, the pilot controlled altitude, h , through a separate thumb-wheel which commanded lift by flap deflection. For most of the landings pitch attitude was automatically controlled by an attitude-hold autopilot working the elevator. As speed decreased during deceleration, the pilot brought on lift through flap deflection to stay airborne as long as possible. The task, therefore, was height control, with changes of both lift trim and stability derivatives, roughly similar to the simulator runs of "good" dynamics and $n_i = 1$, described above.

The principal result was that the height control by direct lift during deceleration was easy and natural. It was certainly feasible from the piloting point of view, and possibly even had some advantages over the conventional control of lift through angle of attack. There were, however, important differences between those exploratory flight tests and the fixed-base simulator runs representing stored-energy landings. Because of those differences, entirely valid correlation between the two is not possible. It is expected that the flight tests will be reported separately (Ref. 3).

Discussion of Stored-Energy Requirements for Complete Landings

We shall attempt, in this section, to interpret the results of the simulation of deceleration and touch-down in terms of stored-energy requirements for complete landings under different conditions. The largest demand upon stored-energy is, of course, for stored-energy lift, ordered by δ_T , to support the weight of the aircraft. A convenient measure of this is specific impulse defined in the following way

$$I_s = \frac{L\delta_T}{g} \int |\delta_T| dt = \frac{1}{W} \int T_L dt$$

The units of it are simply seconds, indicating numerically the necessary capacity in terms of duration in seconds of stored-energy lift equal to weight.

Deceleration - Phase 4

We shall start with the deceleration phase, Part 4, Fig. 1, where we have a direct recording of the δ_T control requirement available in the time histories. The data are presented in Fig. 16, showing how the specific impulse needed for δ_T varies with n_i and deceleration time. The small numerals represent average readings from time histories of runs. The lines and circled numbers are the faired contours. It may be noted that at $n_i = 0$, the required specific impulse is just T_4 itself, which is reasonable, since in that case the average stored-energy lift requirement is the weight itself and the duration is T_4 seconds. As n_i is increased, the necessary specific impulse is decreased, as more lift is carried by the wing, until at $n_i = 1$ it is only about sixty percent of T_4. Although some intermediate values are shown in Fig. 16, we shall consider in the following only the extremes, $n_i = 0$ and 1. The impulse requirement for δ_T, Phase 4, may be read directly from Fig. 16.

There are two other requirements for stored-energy during deceleration, which should be considered. They are for artificial damping and for control, both probably required for all three axes. Although we do not have data for these requirements, fortunately they are small, and their orders of magnitude can be estimated in the following way. Consider first the pitch channel alone. The recorded $\int |\delta_s| dt$ is, in the worst cases, on the order of 2.5 inch-seconds. If we arbitrarily interpret this for

$$M_{\delta_s} = -1 \text{ rad/sec}^2/\text{in}$$

$$I_y = 20{,}000 \text{ slug-ft}^2$$

$$W = 10{,}000 \text{ pounds}$$

$$\ell = 20 \text{ ft}$$

it will correspond to a specific impulse of .25 seconds. Now not all of this should be charged, since while slowing down, the aerodynamic controls would remain partially effective. On the other hand, some energy is needed for artificial damping. We assume that these compensating factors just cancel, but we multiply by three to allow for roll and yaw. Rounding off, we estimate an increment of specific impulse for damping and control (all axes) of an even

1 second

Touch-down - Phase 5

Simulated touch-downs were made in the experimental runs described earlier. They required an average of about 2 to 3 seconds, after shutting off reverse thrust, to let down slowly, under control. We therefore allow a specific impulse for this phase of

3 seconds.

Total Impulse Requirements, $n_i = 1$ Landings

For the $n_i = 1$ landings the minimum stored-energy specific impulse is therefore simply the requirement for Phase 4 (Fig. 16) plus 4 seconds. This is displayed as a function of Cooper rating with deceleration time as a parameter in Fig. 17 .

We call the reader's attention to the fact that no allowance has been made for any emergency or abnormal situation, none for a balked landing, and none for a wave-off. It is not possible within the scope of this report to draw any valid conclusions about those matters.

Some pilots feel that up to the point of initiating reverse thrust, a wave-off might be made without using stored-energy; and that after starting deceleration with reverse thrust, the pilot would really be committed to land, and thereafter wave-off capability would not be required.

We believe that this and the reserve required for an abnormality or emergency (such as a bad gust upset or an obstacle on the field), are in the realm of conjecture at this time. Those questions cannot be decided without a much more realistic and complete simulation and even, perhaps, some experience with actual test vehicles.

$n_i = 0$ Landings

The $n_i = 0$ landing technique is a much more conservative one in which the pilot gets all "set" with the airplane configured for landing, back on final approach. This involves stored-energy lift being on, equal to weight, with the basic wing at near zero lift. Stored-energy lift would thus be needed during phases 1, 2 and 3 of Fig. 1 . We shall estimate roughly those impulse requirements.

Flare - Phase 3

The flare is a crucial maneuver. It must be initiated at exactly the right time and be completed in exactly the right position. The pilot must "close the loop" all the way and devote full attention to it. He cannot be expected to attend to any other adjustments at the same time, and hence throughout flare, stored-energy lift must be on, lift = weight, for this type of landing.

We assume for present purposes that the flare is a constant acceleration change in flight path from six degree descent on final approach to horizontal. If we use a load factor of 1.15 for the maneuver and

$$V = 100 \text{ ft/sec}$$

$$\Delta\gamma = .1 \text{ rad}$$

we find

$$\Delta t = \frac{V}{g} \frac{\Delta\gamma}{(n - 1)} \doteq 2 \text{ seconds}$$

We allow, in addition, one second at the beginning and end of flare for the transient adjustments in angle of attack, making a total time for Phase 3 of four seconds, and a specific impulse requirement of

$$4 \text{ seconds.}$$

Stabilization - Phase 2

The change in the airplane's flight condition associated with turning on the stored-energy lift will be a big one. Specifically, large changes in angle-of-attack, attitude, and drag will be involved. Even after the stored-energy is fully on, some residual transients may remain, and speed and position may be off desired values. The stabilization period is needed to damp the transients, to adjust power - to force the airplane "into the groove", preceding flare. We allow five seconds, which is little enough, considering that it corresponds to only 50 ft of altitude! The specific impulse requirement is therefore

$$5 \text{ seconds.}$$

Transition and Configuration Change - Phase 1

The trim change associated with putting on stored-energy lift, at essentially constant speed, involves the large changes in α, θ, and drag mentioned above. Although there are differences, it is in some ways comparable to the deceleration maneuver, $n_i = 1$. The latter involves a very tight h control at almost constant $\Delta\theta$ (except for disturbances) and a velocity loop involving only monitoring, hence essentially open. Now the Phase 1 transition maneuver involves a much looser h loop (but not open), a very large $\Delta\theta$ change, and a closed velocity loop requiring throttle control. These are reasons to suspect that the Phase 1 task may be similar to the one of Phase 4 for $n_i = 1$, and that it may require about the same time.

The time requirement viewed in this way, would be different for the two configurations tested in the simulator. In order to account for this factor in some rational way, we take the time for a Cooper rating of 5, from Figs. 8 and 9, and then the specific impulse from Fig. 16 . This leads to specific impulse estimates of

"good" configuration: 4 seconds
"bad" configuration: 8 seconds

Total Impulse Requirements, $n_i = 0$ Landings

The sum of all these impulse requirements is displayed in Fig. 17 as a function of Cooper rating, with deceleration time as a parameter.

The energy requirements are quite considerably greater than those for $n_i = 1$. This is of course to be expected, since the $n_i = 0$ is a far more conservative procedure. It gives the pilot, just for example, a chance to see if the stored-energy lift really comes on - before he is committed to landing - and a chance to escape if it does not. As we have noted before, however, a valid final judgment about the relative merits of the different landing techniques will have to await better simulation and possibly flight tests.

IFR Landings

Landings under Instrument Flight Rules would certainly be of interest for stored-energy vehicles. There seems to be no reason why they could not be done. It seems unlikely, however, that manual deceleration and touch-down could be done except with visual ground reference.

For $n_i = 1$, there is no reason why a conventional ILS approach should not be appropriate. In a runway landing, an over (or under) flare may simply result in a hard touch-down. In the stored-energy landing, however, the flare is more crucial and it must be complete since no premature touch-down can be permitted. The result is that the minimum ceiling could be expected to be a bit higher than for conventional runway landings. With that qualification, the energy requirements should not be appreciably different, and if the $n_i = 1$ technique is practical at all, then it should work well enough under IFR conditions.

With $n_i = 0$, the configuration (or trim) change of turning on stored-energy lift would not be permissible in the latter stages of an ILS approach. The glide slope and localizer tracking tasks are so demanding in themselves as to permit no competition for the pilot's attention. They would be even more critical in the stored-energy landing, where position and velocity at break-out and entry into flare are more crucial. The ceiling would either have to be high enough to turn on stored-energy lift after break-out (perhaps 700 ft), or the transition would have to be complete by, say, the middle marker. This latter condition would very likely be impractical, since it would require another 30 to 60 secs. of specific impulse to last over the extended stabilization phase.

Conclusions

Generalized equations and charts are derived and presented for the level-flight deceleration of a stored-energy vehicle under various levels of reverse thrust and support by stored-energy lift. These are used in an exploratory simulation of the deceleration and touch-down phases of stored-energy landings.

The vehicle was described by the parameters

$$\frac{V_R (L/D)_{max}}{g} = 30 \text{ sec}$$

$$V_R = \sqrt{\frac{2W}{\rho S}} \sqrt{\frac{K}{C_{D_o}}} = 120 \text{ fps}$$

$$(L/D)_{max} = 8$$

In $n_i = 0$ landings, where the transition to stored-energy lift is made on final approach, the deceleration and touch-down are easy and natural, even with rather unfavorable conditions of turbulence, airplane dynamics, and with abrupt decelerations as short as 5 seconds. The minimum requirement for stored-energy specific impulse under these conditions, not allowing for emergencies or wave-off, and in VFR, would be the order of 25 seconds.

In $n_i = 1$ landings, where the transition to stored-energy lift is made only as required during the deceleration prior to touch-down, the piloting task is harder and deceleration time is much more of a factor. Again ignoring emergency or wave-off requirements, it appears that VFR landings of this type could be performed under favorable conditions with specific impulse capacity as low as ten to twelve seconds.

The control coupling parameter, pitching moment due to stored-energy lift, of either sign, is a disadvantage, and must be restricted to small values.

Under Instrument Flight Rules, the advantage of $n_i = 1$ landings for smaller energy requirements, would be more outstanding. In fact, if $n_i = 1$ landings are feasible at all, then they should be suitable for IFR with little if any additional penalty in energy storage requirement. On the other hand, the $n_i = 0$ landing under IFR would be so heavily penalized for energy-storage specific impulse requirement as probably to be impractical.

This study has to be regarded as exploratory, and the conclusions qualitative. In order to validate them more fully, experience with an actual flight test vehicle would be desirable. A more realistic simulation would also be helpful.

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APPENDIX

Example Deceleration Calculation

In this section an example calculation is carried out using the airplane characteristics selected for the fixed-base simulation.

The two quantities which specify the drag aerodynamics of the airplane are the speed for minimum drag in level flight and the maximum lift-drag ratio. These were assigned values

$$V_R = \sqrt{\frac{2W}{\rho S}}\sqrt[4]{\frac{K}{C_{D_O}}} = 120 \text{ ft/sec}$$

$$(L/D)_{max} = \frac{1}{2\sqrt{KC_{D_O}}} = 8$$

which are typical of light transport aircraft in landing configuration.

The velocity at the start of the deceleration was chosen to be

$$V_i = 100 \text{ fps}$$

so that

$$u_i = \frac{V_i}{V_R} = \frac{100}{120} = .833$$

Considering two initial aerodynamic load factor cases, $n_i = 0$ and $n_i = 1$,

$$k_i = \frac{n_i^2}{u_i^4} = \begin{cases} 2.08 , & n_i = 1 \\ 0 & n_i = 0 \end{cases}$$

For a 15-second deceleration from 100 ft/sec to a hover ($u_f = 0$),

$$t^* = \frac{tg}{V_R (L/D)_{max}} = \frac{(15)(32.2)}{(120)(8)} = .503$$

From Figures 5 and 6

$$Z_D = \begin{cases} 1.36 \ , & n_i = 1 \\ 1.55 \ , & n_i = 0 \end{cases}$$

Inserting these numbers into equation (15a) yields distance,

$$x = \frac{V_R^{\,2} (L/D)_{max}}{g(1+k_i)} \left[\ln \left(u_i^{\,2} + \frac{2Z_D}{1+k_i} \right) - \ln \left(u_f^{\,2} + \frac{2Z_D}{1+k_i} \right) \right]$$

$$= \begin{cases} 655 \text{ ft} \ , & n_i = 1 \\ 823 \text{ ft} \ , & n_i = 0 \end{cases} \qquad u_f = 0$$

Rearranging equation (15b) with $u_f = 0$, gives the velocity as a function of time:

$$V = V_R \sqrt{\frac{2Z_D}{1+k_i}} \ \text{Tan} \ \frac{t}{\dfrac{V_R (L/D)_{max}}{gZ_D} \sqrt{\dfrac{2Z_D}{1+k_i}}}$$

$$= \begin{cases} 114 \ \text{Tan} \ \dfrac{t}{20.3} \ , & n_i = 1 \\ 211 \ \text{Tan} \ \dfrac{t}{33.8} \ , & n_i = 0 \end{cases}$$

(here t is the time remaining in the deceleration).

A similar calculation for a 5-second deceleration gives

$$Z_D = \begin{cases} 4.8 \ , & n_i = 1 \\ 5.0 & n_i = 0 \end{cases} \qquad \text{from Figs. 5 and 6}$$

$$x = \begin{cases} 232 \text{ ft}, & n_i = 1 \\ 250 \text{ ft}, & n_i = 0 \end{cases}$$

$$V = \begin{cases} 212 \text{ Tan } \frac{t}{11.0} \ , & n_i = 1 \\ 379 \text{ Tan } \frac{t}{18.85} \ , & n_i = 0 \end{cases}$$

Velocity as a function of time is plotted in Figure 7. The differences in the curves for a given deceleration time are relatively small and are due to the presence of induced drag for the $n_i = 1$ case. This emphasizes the fact that induced drag is not a large factor if the initial velocity is high. It should also be noted that the reverse thrust required for a short deceleration is very large $\left(\frac{T_D}{W} \cong .6 \right)$.

CONTROLLABLE CAPABLE OF BEING CONTROLLED OR MANAGED IN CONTEXT OF MISSION, WITH AVAILABLE PILOT ATTENTION	**ACCEPTABLE** MAY HAVE DEFICIENCIES WHICH WARRANT IMPROVEMENT, BUT ADEQUATE FOR MISSION. PILOT COMPENSATION, IF REQUIRED TO ACHIEVE ACCEPTABLE PERFORMANCE, IS FEASIBLE.	**SATISFACTORY** MEETS ALL REQUIREMENTS AND EXPECTATIONS, GOOD ENOUGH WITHOUT IMPROVEMENT CLEARLY ADEQUATE FOR MISSION.	EXCELLENT, HIGHLY DESIRABLE	A1
			GOOD, PLEASANT, WELL BEHAVED	A2
			FAIR. SOME MILDLY UNPLEASANT CHARACTERISTICS. GOOD ENOUGH FOR MISSION WITHOUT IMPROVEMENT.	A3
		UNSATISFACTORY RELUCTANTLY ACCEPTABLE. DEFICIENCIES WHICH WARRANT IMPROVEMENT. PERFORMANCE ADEQUATE FOR MISSION WITH FEASIBLE PILOT COMPENSATION.	SOME MINOR BUT ANNOYING DEFICIENCIES. IMPROVEMENT IS REQUESTED. EFFECT ON PERFORMANCE IS EASILY COMPENSATED FOR BY PILOT.	A4
			MODERATELY OBJECTIONABLE DEFICIENCIES. IMPROVEMENT IS NEEDED. REASONABLE PERFORMANCE REQUIRES CONSIDERABLE PILOT COMPENSATION.	A5
			VERY OBJECTIONABLE DEFICIENCIES. MAJOR IMPROVEMENTS ARE NEEDED. REQUIRES BEST AVAILABLE PILOT COMPENSATION TO ACHIEVE ACCEPTABLE PERFORMANCE.	A6
	UNACCEPTABLE DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT. INADEQUATE PERFORMANCE FOR MISSION EVEN WITH MAXIMUM FEASIBLE PILOT COMPENSATION.		MAJOR DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT FOR ACCEPTANCE. CONTROLLABLE. PERFORMANCE INADEQUATE FOR MISSION, OR PILOT COMPENSATION REQUIRED FOR MINIMUM ACCEPTABLE PERFORMANCE IN MISSION IS TOO HIGH.	U7
			CONTROLLABLE WITH DIFFICULTY. REQUIRES SUBSTANTIAL PILOT SKILL AND ATTENTION TO RETAIN CONTROL AND CONTINUE MISSION.	U8
			MARGINALLY CONTROLLABLE IN MISSION. REQUIRES MAXIMUM AVAILABLE PILOT SKILL AND ATTENTION TO RETAIN CONTROL.	U9
UNCONTROLLABLE CONTROL WILL BE LOST DURING SOME PORTION OF MISSION.			UNCONTROLLABLE IN MISSION.	10

Table 1. Pilot Rating Scale (Reference 4)

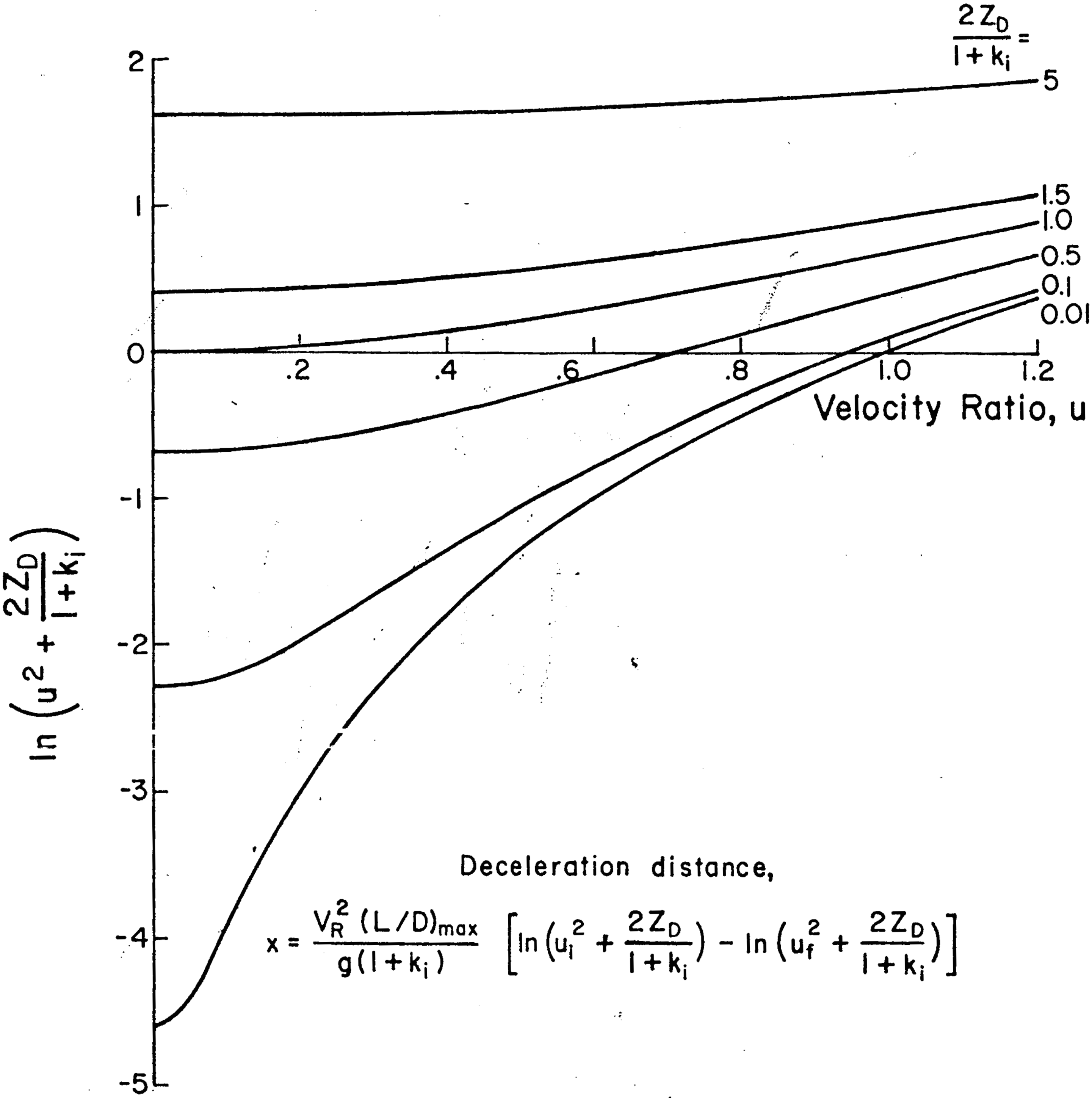
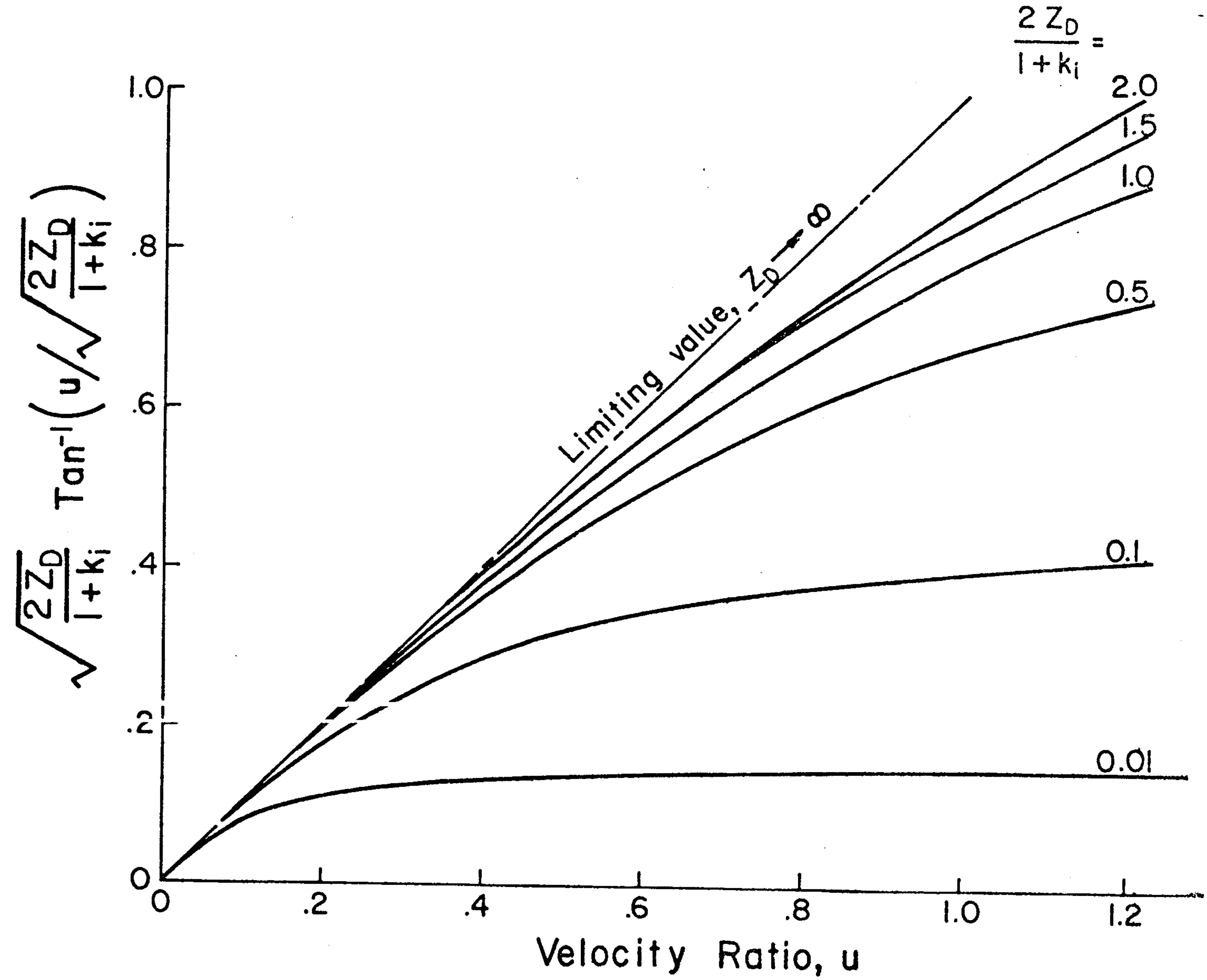


Figure 3. Logarithmic factor in deceleration distance equation



Time to decelerate,

$$t = \frac{V_R (L/D)_{max}}{g Z_D}\left[\sqrt{\frac{2Z_D}{1+k_i}}\ \mathrm{Tan}^{-1}\left(u_i\Big/\sqrt{\frac{2Z_D}{1+k_i}}\right) - \sqrt{\frac{2Z_D}{1+k_i}}\ \mathrm{Tan}^{-1}\left(u_f\Big/\sqrt{\frac{2Z_D}{1+k_i}}\right)\right]$$

Figure 4. Inverse tangent parameter in deceleration time equation

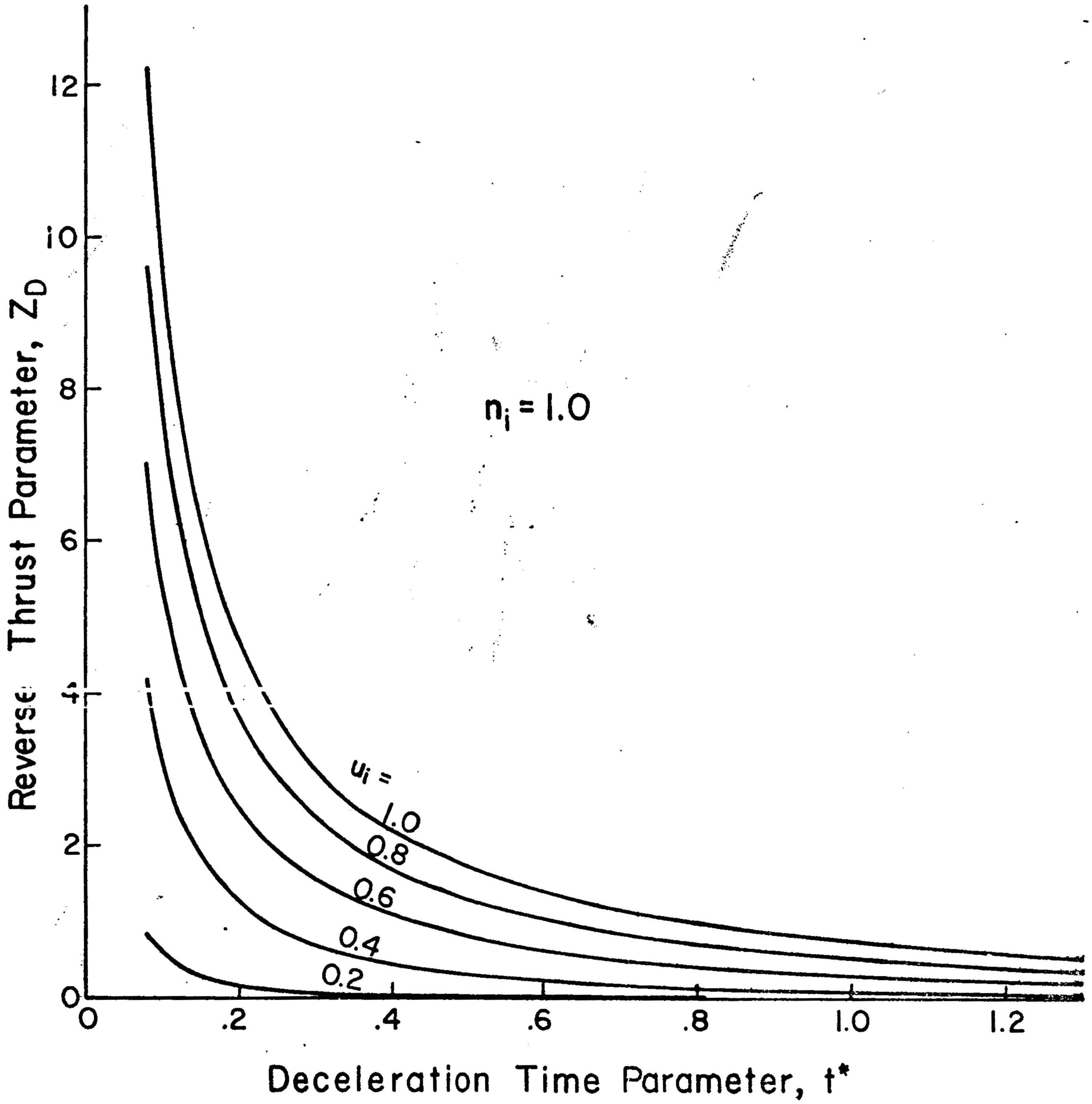


Figure 5. Reverse thrust parameter versus deceleration time parameter for deceleration to $u_f = 0$, $n_i = 1.0$

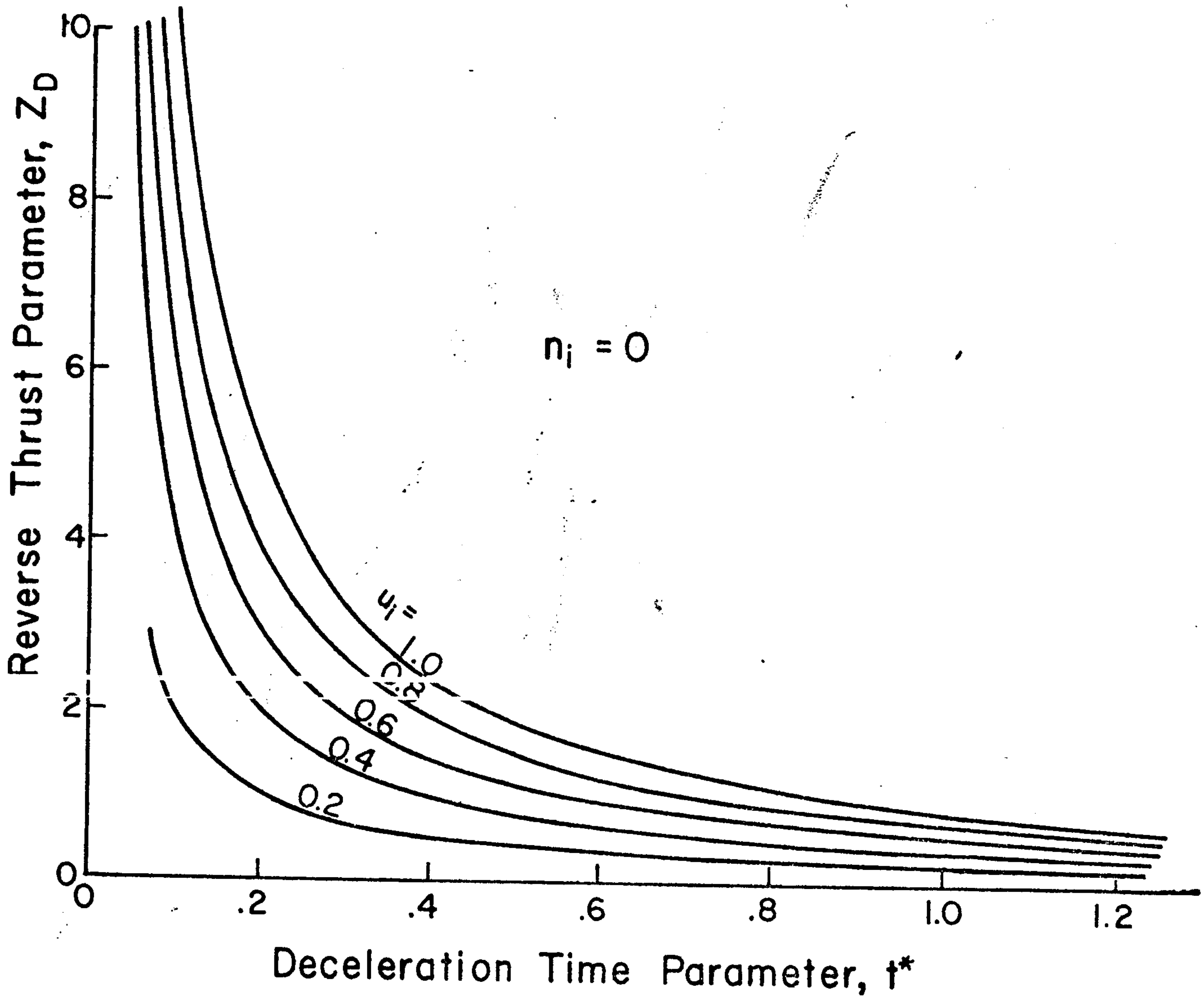


Figure 6. Reverse thrust parameter versus deceleration time parameter for deceleration to $u_f = 0$; $n_i = 0$

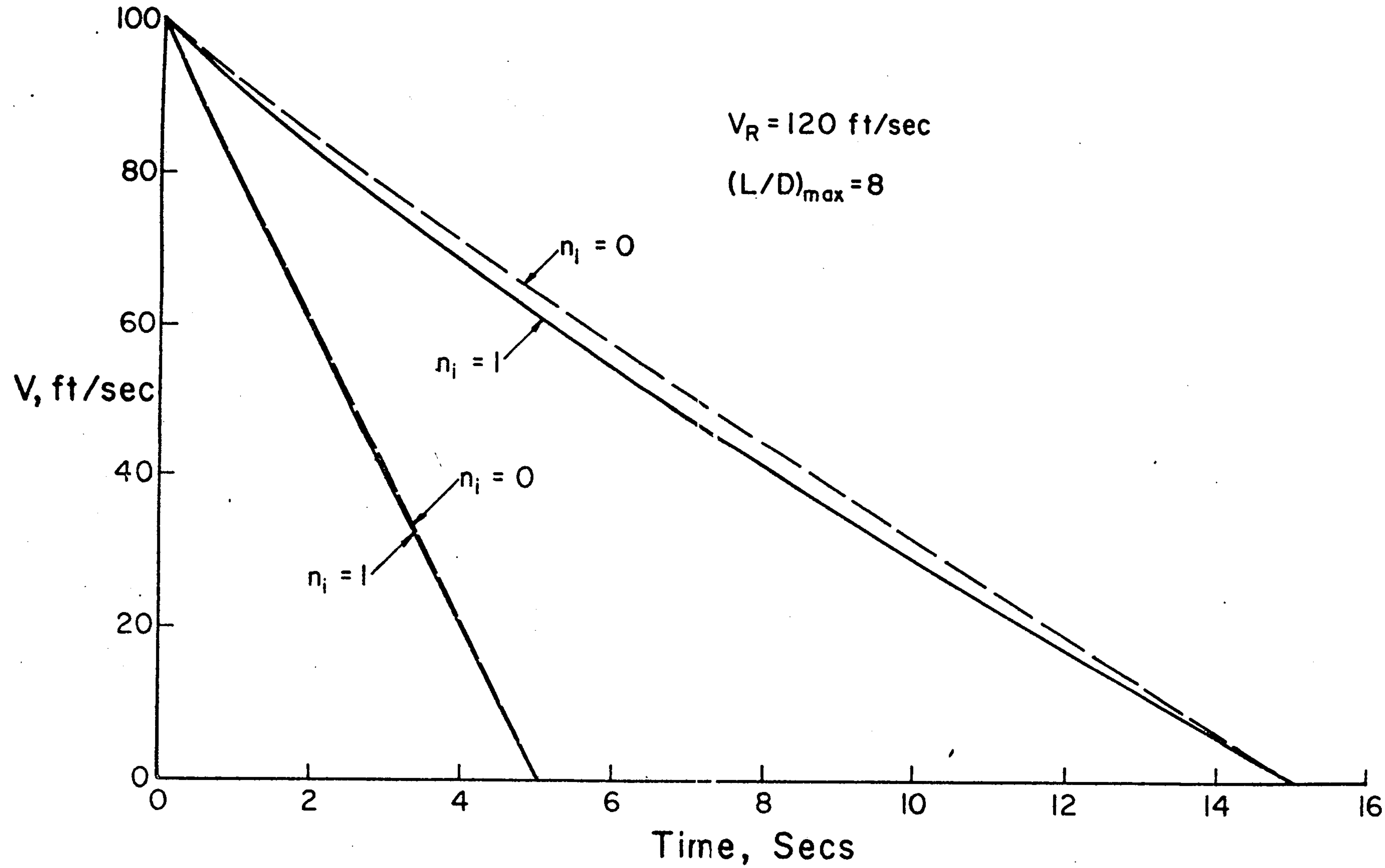


Figure 7. Velocity programs $n_i = 1$ and $n_i = 0$

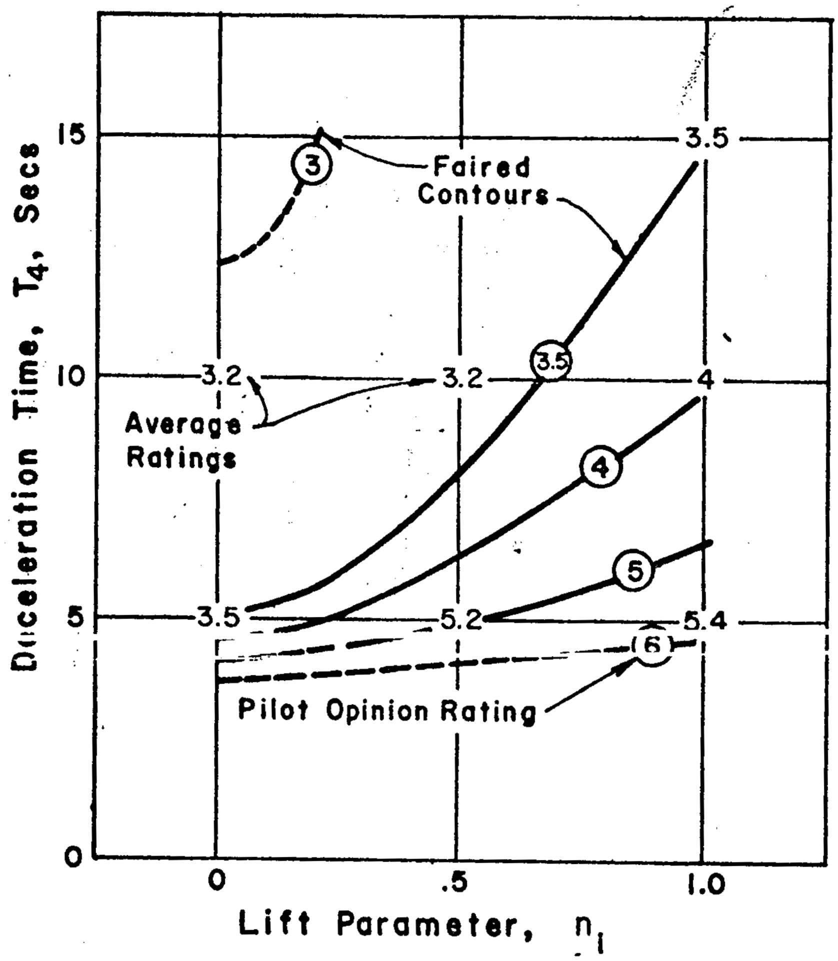


Figure 8. The pilot opinion rating function of T_4 and n_i — "good" dynamics, $M_{\delta_T} = 0$

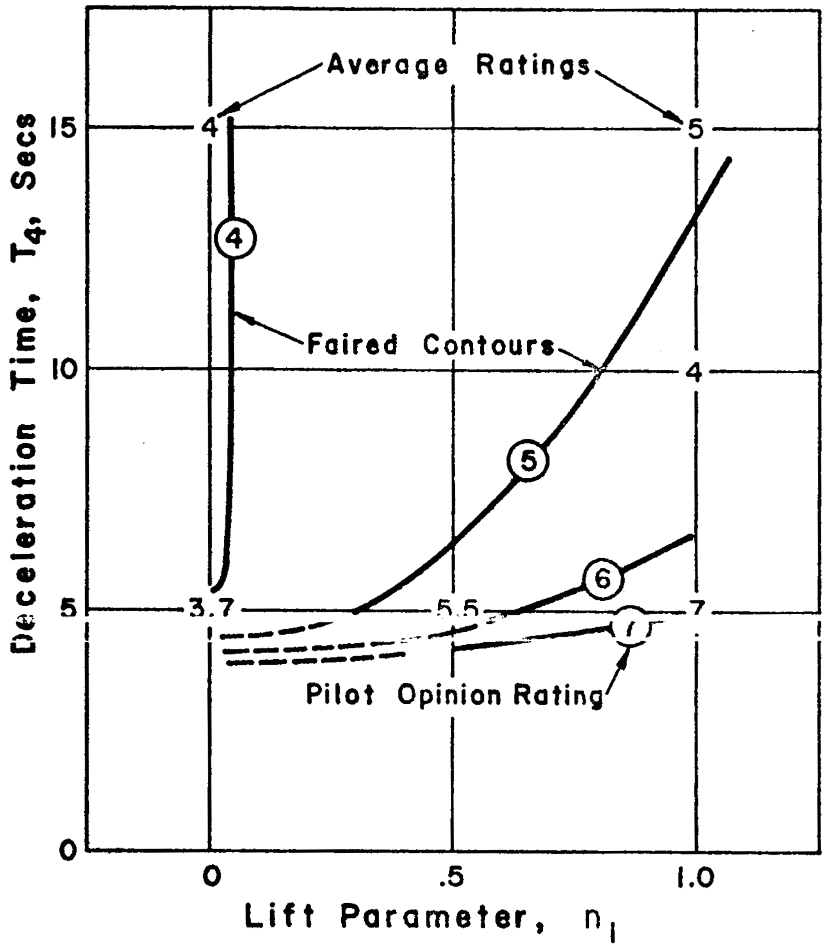


Figure 9. The pilot opinion rating function of T_4 and n_i — "bad" dynamics, $M_{\delta_T} = 0$

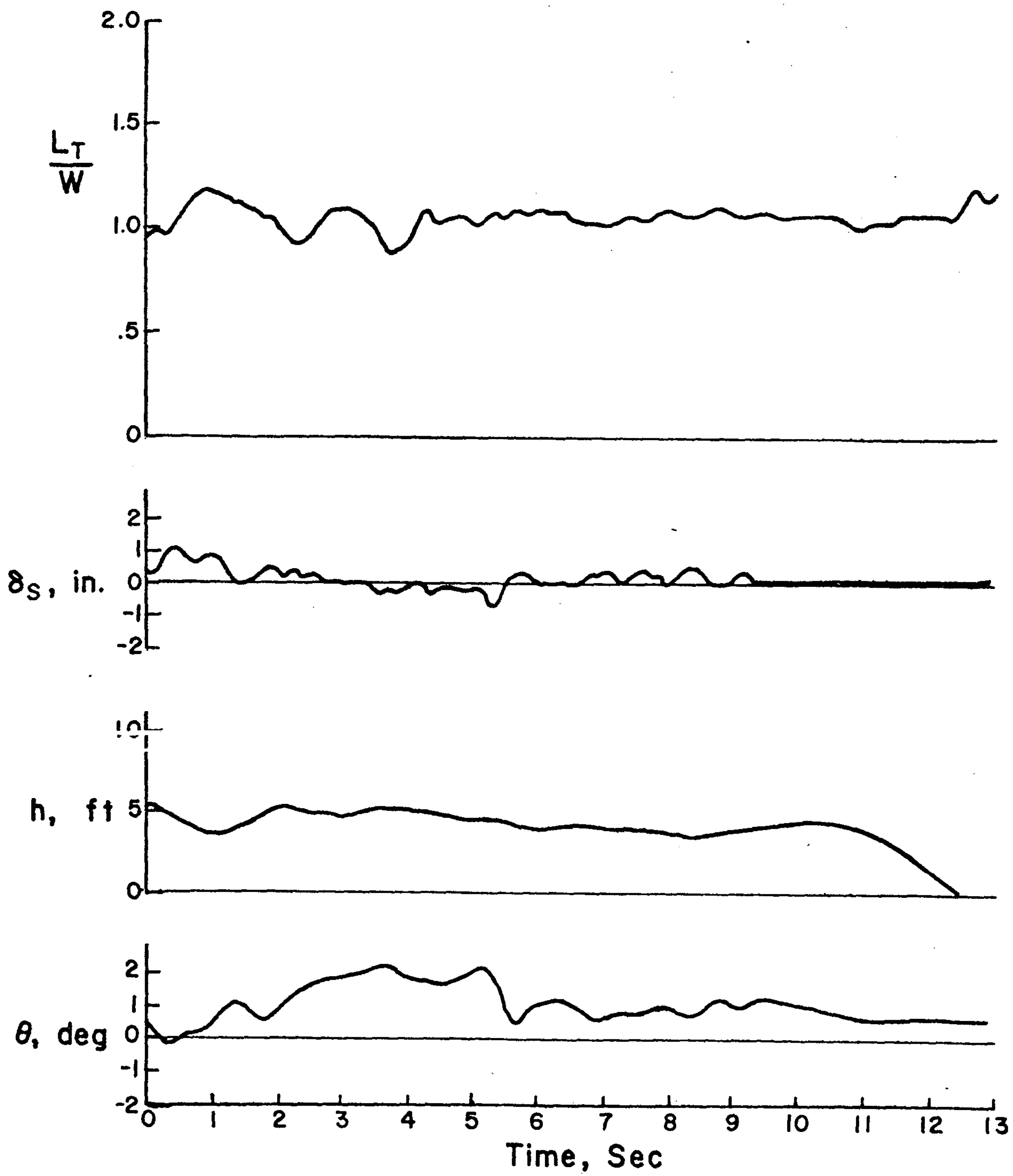


Figure 10. Altitude and pitch attitude performance, "good" dynamics, $M_{\delta_T}=0$, $n_1=1$, $T_4=10$ secs

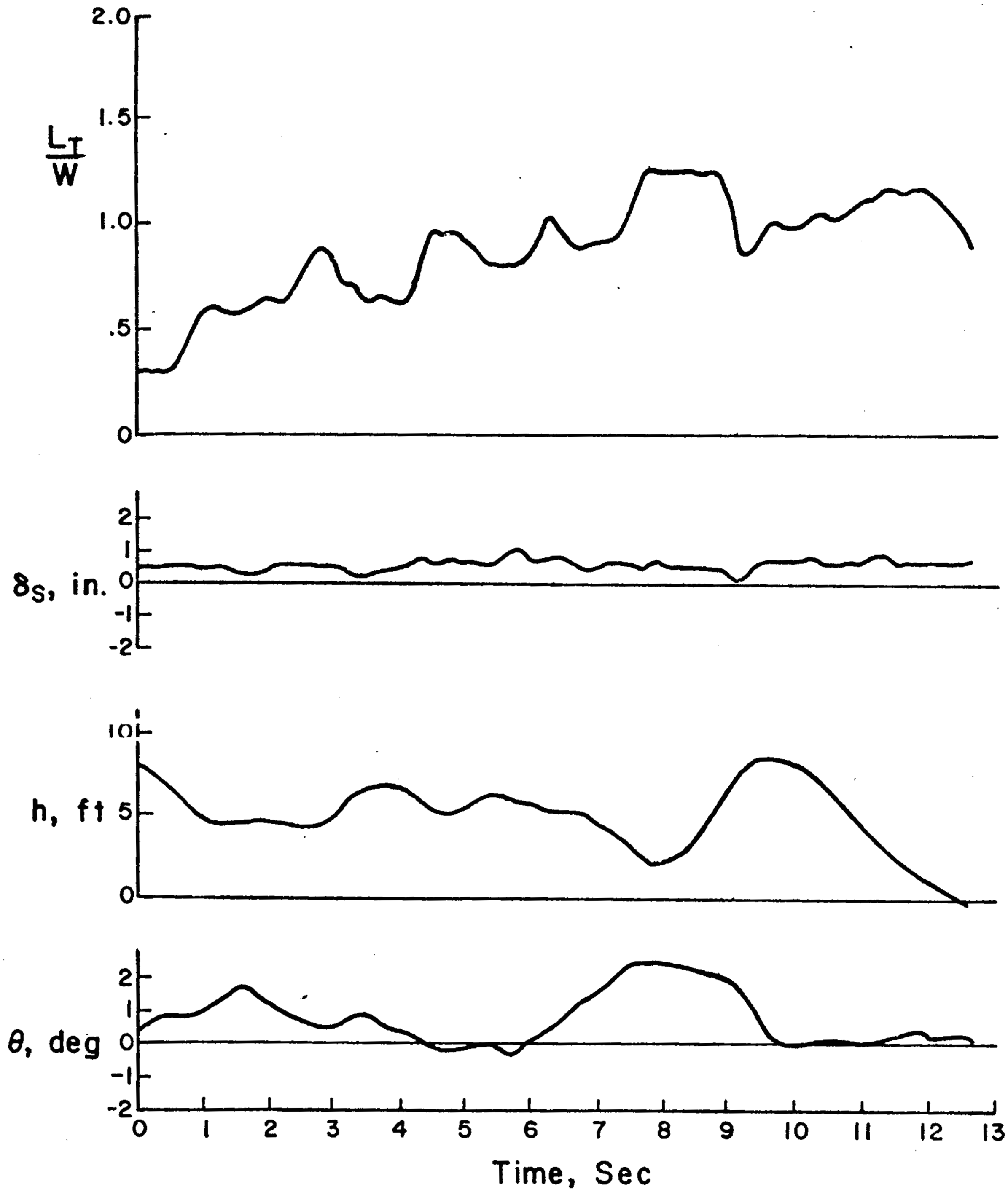


Figure 11. Altitude and pitch attitude performance, "good" dynamics, $M_{\delta_T}=0$, $n_1=1$, $T_4=10$ secs

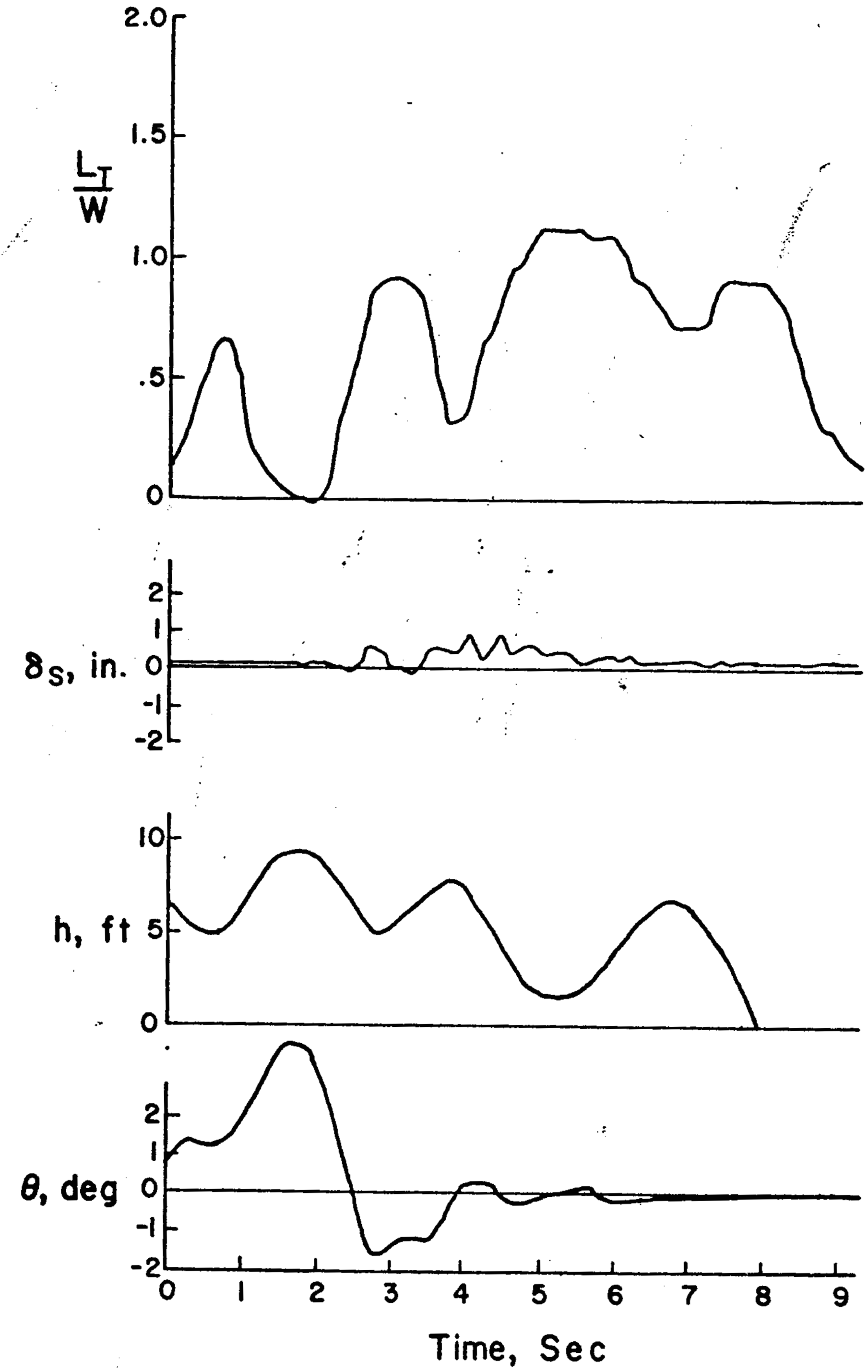


Figure 12. Altitude and pitch attitude performance, "good" dynamics, $M_{\delta_T}=0$, $n_l=1$, $T_4=5$ secs

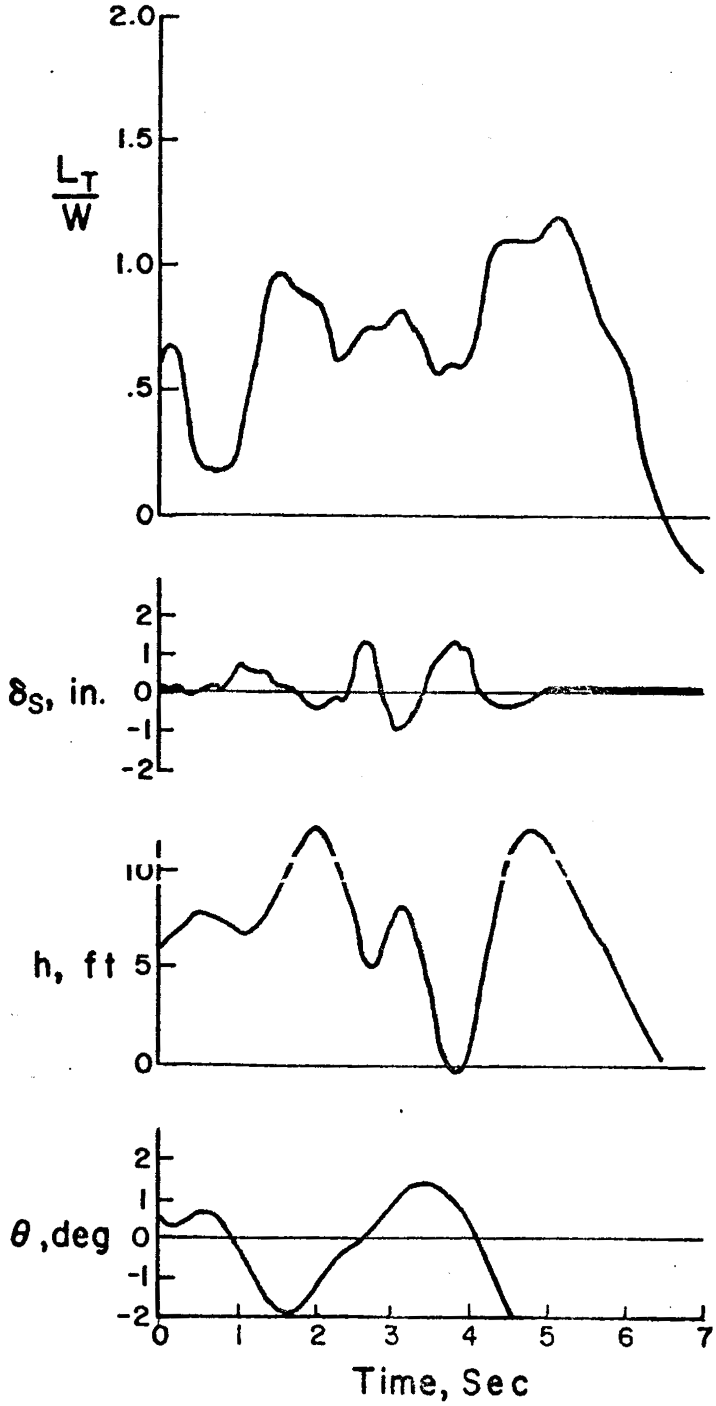


Figure 13. Altitude and pitch attitude performance, "bad" dynamics, $M_{\delta_T}=0$, $n_i=1$, $T_4=5$ secs

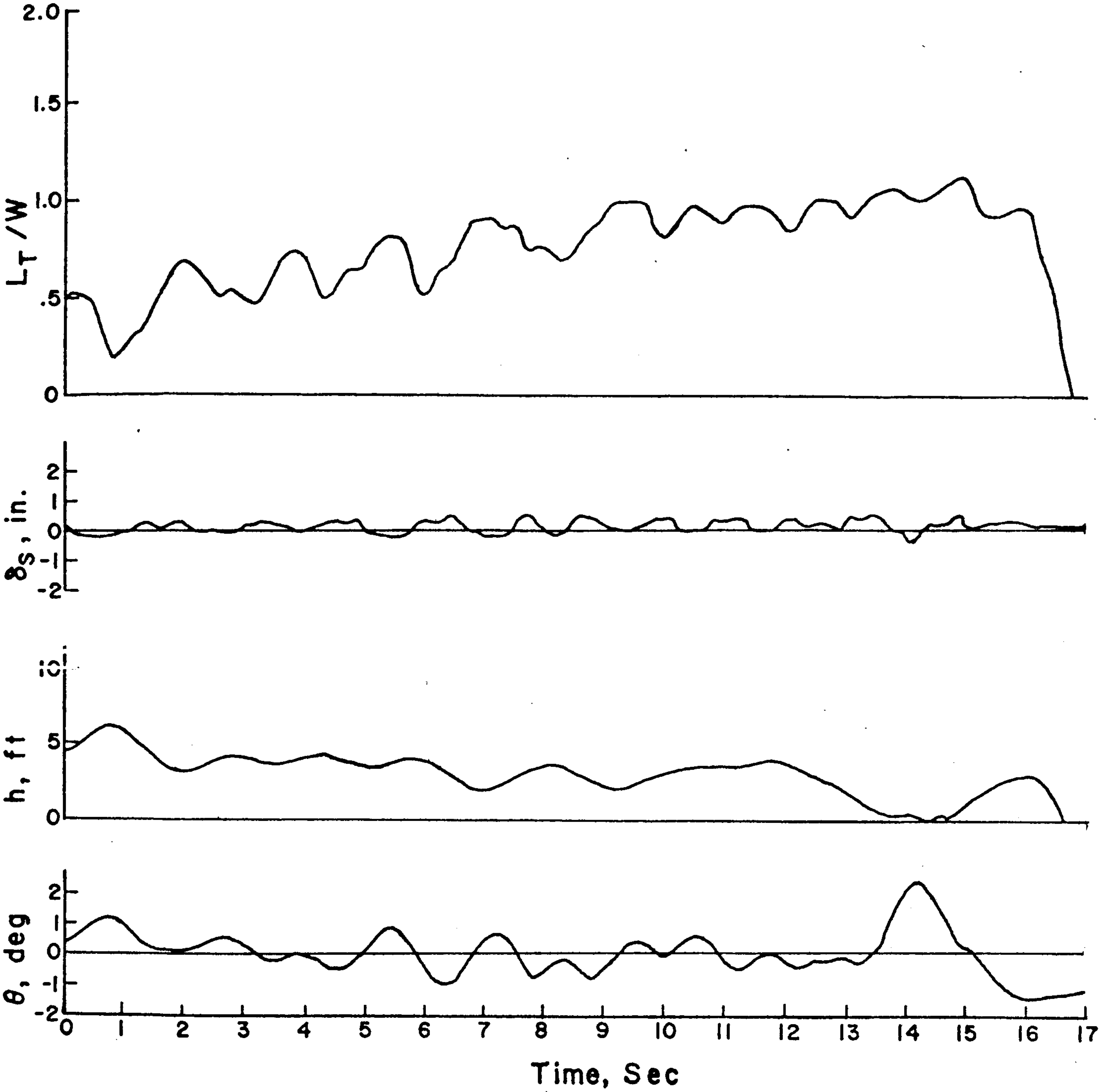


Figure 14. Altitude and pitch attitude performance, "bad" dynamics, $M_{\delta_T} = 0$, $n_1 = 1$, $T_4 = 15$ sec

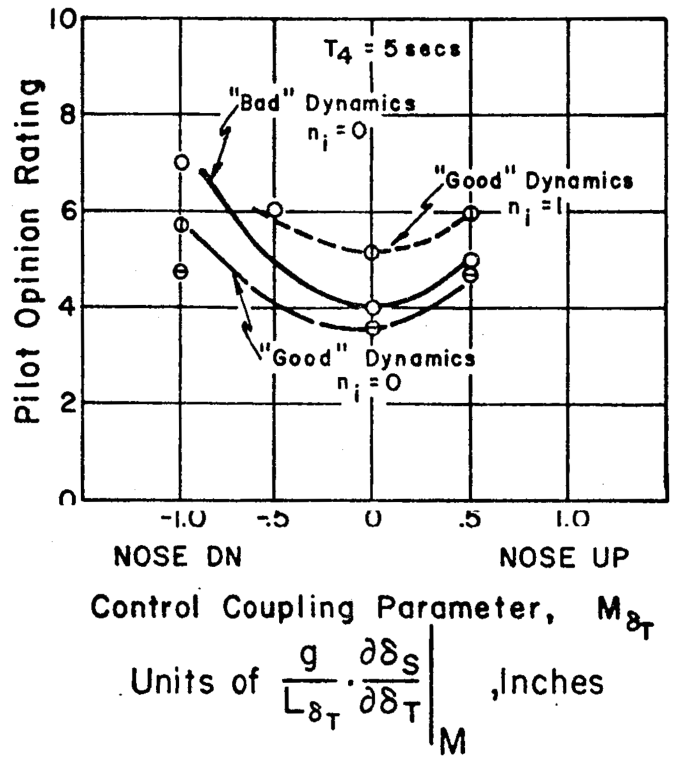


Figure 15. Effect of control coupling parameter, M_{δ_T}, on pilot opinion rating of the deceleration task, phase 4

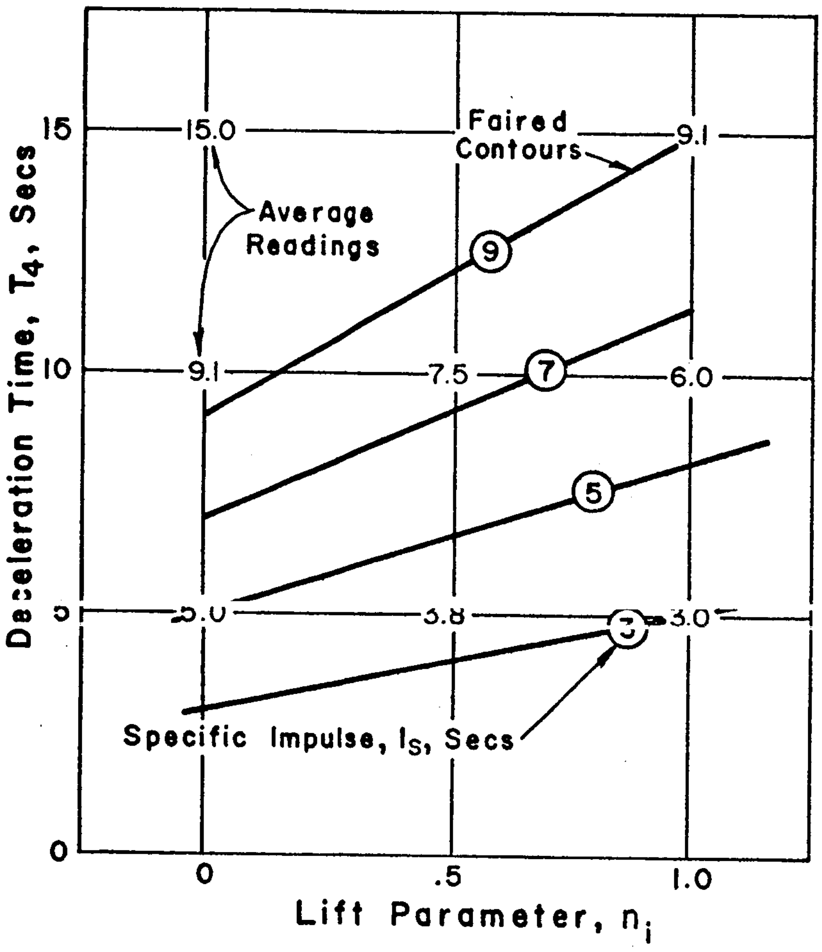


Figure 16. Contours of the specific impulse, I_S, function of T_4 and n_i — all dynamics, $M_{8_T} = 0$

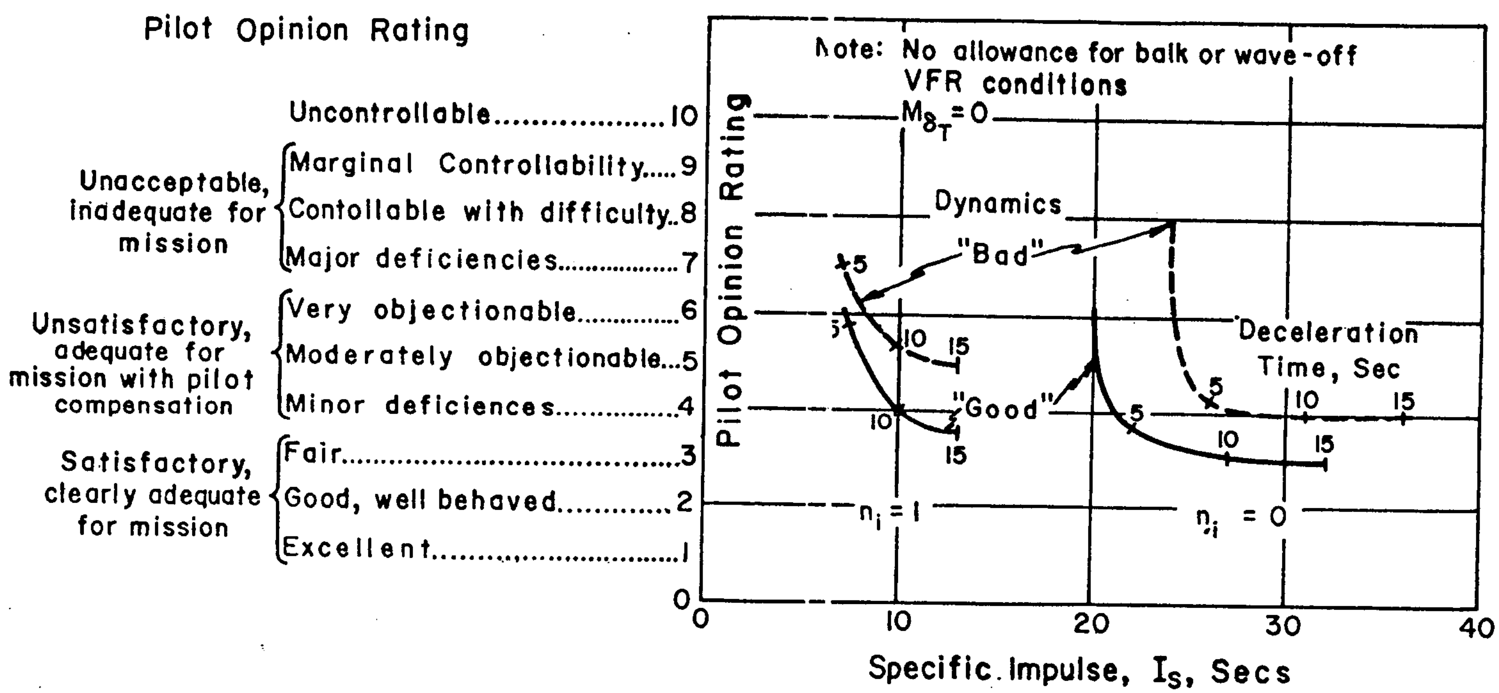


Figure 17. Total impulse requirements, $n_i = 1$ and $n_i = 0$ landings