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INVESTIGATION OF THE CONTROLLABILITY OF THE M2-F2 LIFTING-BODY LAUNCH FROM THE B-52 CARRIER AIRPLANE

by Berwin M. Kock and Weneth D. Painter

Flight Research Center
Edwards, Calif.

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INVESTIGATION OF THE CONTROLLABILITY OF THE M2-F2 LIFTING-BODY LAUNCH FROM THE B-52 CARRIER AIRPLANE*

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SUMMARY

The launch characteristics of the M2-F2 lifting body after release from the B-52 carrier airplane were studied by using analytical methods and simulators to predict launch safety and to determine the piloting requirements during launch. The predicted launch characteristics and the flight results are compared.

Studies were conducted by using a digital-computer program to solve the six-degree-of-freedom equations of motion and aerodynamic data obtained in a wind tunnel with the M2-F2 model mounted in proximity to the B-52 model to determine if the M2-F2 and B-52 pylon/adapter would collide. Digital and analog computing equipment was then used to simulate the launch and to assess the vehicle controllability during the launch. The results of these studies indicated that launches could be made at the planned conditions of a Mach number of 0.6 at an altitude of 45,000 feet (13,700 meters) without a collision problem and with acceptable controllability. However, B-52 angle of attack, launch dynamic pressures, and M2-F2 trim settings and damper failures had a significant effect on M2-F2 launch transients. The M2-F2 roll and yaw SAS authorities of ±5° and ±4°, respectively, were determined to give acceptable damping and hardover failure characteristics from simulator studies of launch.

Flight launches at 45,000 feet (13,700 meters) altitude, a Mach number of approximately 0.6, and a B-52 angle of attack of approximately 2° presented no severe control problems. The predicted and actual launch transients correlated reasonably well.

INTRODUCTION

The M2-F2 lifting body is a research vehicle designed to investigate the stability, control, and performance characteristics of a representative lifting-body vehicle during the terminal phase of a reentry maneuver (Mach numbers less than 2). To achieve as great a performance potential as possible the vehicle is carried to the launch altitude under the right wing of a B-52 aircraft between the fuselage and inboard engine nacelle. In this location, the M2-F2 is immersed in the B-52 flow field during captive flight and for a brief period after launch. Prior to its initial flight, the possible reactions of the M2-F2 to the B-52 flow field during launch were of concern, both in relation to the possibility of collision between the two aircraft and the controllability of the M2-F2 after release.

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To evaluate these problem areas a combined wind-tunnel, analytical, and flight-test program, comparable to that performed for the X-15 research airplane (refs. 1 to 3), was undertaken jointly by the NASA Langley Research Center, the NASA Flight Research Center, and the U. S. Air Force Flight Test Center. The primary objectives of the program were to: (1) determine the conditions where the M2-F2 would clear the B-52 pylon/adapter during launch; (2) determine the character of the transient motions during launch and the necessary pilot techniques for recovery; and (3) confirm the prediction techniques used by comparing them with flight results. Launch transients predicted on the basis of the analytical studies and model tests conducted at the Langley Research Center are presented in references 4 and 5.

This paper discusses the results from ground-based simulator studies that were used to predict the vehicle transient motions and to determine the pilot techniques required to minimize the M2-F2 motions and insure a safe launch. In addition, flight results are summarized and compared with predictions.

SYMBOLS

a	speed of sound, ft/sec (m/sec)
b	body reference span, ft (m)
C_D	drag coefficient, $\frac{\text{Drag}}{\bar{q}S}$
C_L	lift coefficient, $\frac{\text{Lift}}{\bar{q}S}$
C_{L_o}	lift coefficient for $\alpha = 0°$
C_l	rolling-moment coefficient, $\frac{L}{\bar{q}Sb}$
C_{l_o}	rolling-moment coefficient for $\delta_a = \delta_r = \beta = 0°$
C_{l_β}	effective dihedral derivative, $\frac{\partial C_l}{\partial \beta}$, deg^{-1}
$C_{l_{\delta_a}}$	aileron-effectiveness derivative, $\frac{\partial C_l}{\partial \delta_a}$, deg^{-1}
C_m	pitching-moment coefficient, $\frac{M}{\bar{q}S\bar{c}}$
C_{m_o}	pitching-moment coefficient for $\alpha = 0°$
C_{m_α}	longitudinal-stability derivative, $\frac{\partial C_m}{\partial \alpha}$, deg^{-1}

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$C_{m_{\delta_l}}$ lower-flap-effectiveness derivative, $\frac{\partial C_m}{\partial \delta_l}$, deg^{-1}

$C_{m_{\delta_u}}$ upper-flap-effectiveness derivative, $\frac{\partial C_m}{\partial \delta_u}$, deg^{-1}

C_n yawing-moment coefficient, $\frac{N}{\bar{q}Sb}$

C_{n_o} yawing-moment coefficient for $\delta_a = \delta_r = \beta = 0°$

C_{n_β} directional-stability derivative, $\frac{\partial C_n}{\partial \beta}$, deg^{-1}

C_y side-force coefficient, $\frac{\text{Side force}}{\bar{q}S}$

C_{y_o} side-force coefficient for $\delta_a = \delta_r = \beta = 0°$

C_{y_β} side-force derivative, $\frac{\partial C_y}{\partial \beta}$, deg^{-1}

$\bar{c}$ body reference longitudinal length, ft (m)

g acceleration due to gravity, 32.2 ft/sec^2 (9.80 m/sec^2)

h altitude, ft (m)

I_X rolling moment of inertia (body axis), slug-ft^2 (kg-m^2)

I_Y pitching moment of inertia (body axis), slug-ft^2 (kg-m^2)

I_Z yawing moment of inertia (body axis), slug-ft^2 (kg-m^2)

I_{XZ} product of inertia referred to body X- and Z-axes, slug-ft^2 (kg-m^2)

K_I rudder-to-aileron interconnect ratio, $\frac{\delta_r}{\delta_a}$, deg/deg

K_p roll-damper gain, $-\frac{\delta_a}{p}$, deg/deg/sec

K_q pitch-damper gain, $\frac{\delta_l}{q}$, deg/deg/sec

K_r yaw-damper gain, $\frac{\delta_r}{r}$, deg/deg/sec

L rolling moment, $\bar{q}SbC_l$, ft-lb (m-N)

M pitching moment, $\bar{q}S\bar{c}C_m$, ft-lb (m-N)

m mass, slugs (kg)

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N	yawing moment, $\bar{q}SbC_n$, ft-lb (m-N)
N_{Ma}	Mach number
n_z	normal acceleration, g units
p	roll rate, deg/sec
q	pitch rate, deg/sec
$\bar{q}$	dynamic pressure, lb/ft^2 (N/m^2)
r	yaw rate, deg/sec
S	body planform reference area, ft^2 (m^2)
T	thrust, lb (N)
t	time, sec
V	true airspeed, ft/sec (m/sec)
V_E	range east component of total-velocity vector, ft/sec (m/sec)
V_i	indicated airspeed, knots (m/sec)
V_N	range north component of total-velocity vector, ft/sec (m/sec)
W	weight, lb (kg)
$\dot{X}$	ground speed, ft/sec (m/sec)
y, z	lateral and vertical distance, respectively, of M2-F2 center of gravity from captive position under B-52 (see fig. 5)
α	angle of attack, deg
β	angle of sideslip, deg
γ	flight-path angle, deg
Δ	incremental value of flight-path azimuth angle, deg
δ_a	differential aileron deflection, deg
δ_l	lower-flap deflection, deg
δ_r	total rudder deflection, deg
δ_u	average upper-flap deflection, deg

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Θ pitch attitude, deg

ρ mass density of air, slugs/ft^3 (kg/m^3)

φ roll attitude, deg

ψ heading angle, deg

Subscript:

max maximum

A dot over a quantity represents the derivative of that quantity with respect to time.

VEHICLE DESCRIPTIONS

M2-F2

The M2-F2 lifting body (fig. 1) is basically a 13° half-cone with vertical end-plate-type fins attached to the boattailed aft end of the vehicle. It was designed for flight to Mach 2 and a maximum dynamic pressure of 400 lb/ft^2 (1915 N/m^2). An aluminum structure was used.

The flight control system is an irreversible electromechanical hydraulic system with conventional artificial-feel bungees. Pitch control is accomplished by use of the lower flap (fig. 1). The upper flaps (fig. 1) are used for pitch trim. Roll control is provided by differential operation of the upper flaps in conjunction with an interconnect between the rudder and upper flaps (ref. 6). The interconnect ratio is adjustable by the pilot. Directional control is provided by the rudders alone. For the tests discussed in this report, each rudder was flared 5° (for a total of 10°) from the closed, or streamline, position.

Cockpit controls are conventional in that a center stick provides both pitch control and roll control by operating the lower and upper flaps, respectively. Conventional rudder pedals are connected to the rudders. Upper-flap pitch-trim position is controlled by a wheel on the left side of the cockpit. The rudder-to-aileron interconnect ratio is also controlled by a wheel in the cockpit.

During flight the upper flaps ordinarily were trimmed to a predetermined value, where they remained throughout the flight. All pitch control was accomplished by using the center stick, which had a force trim system to enable the pilot to remove large stick forces.

Stability augmentation is provided about all three axes by a pilot-adjustable fixed-gain rate damper system. The system consists of rate gyros to sense the angular rates about each vehicle body axis, an electronics assembly, and servoactuators to drive the control surfaces. The damper inputs are summed with the pilot's inputs and operate the same control surface as the pilot's control.

Pertinent dimensions of the M2-F2 vehicle, including control-system authorities, are presented in table I.

For the first 14 M2-F2 flights the primary flight instruments were an airspeed indicator, altimeter, angle-of-attack and angle-of-sideslip meters, and surface-position indicators used primarily for prelaunch settings and system checks. No heading indicator was included. The next two flights had, in addition, an attitude direction indicator to display pitch and roll attitude and heading.

B-52 and Adapter

The carrier airplane for the M2-F2 is a B-52 that had been previously modified to carry and launch the X-15 research airplanes (ref. 3). The principal modifications for the X-15 program consisted of the addition of an underwing pylon-supporting structure midway between the fuselage and the inboard engine nacelle on the right wing and a cutout in the wing trailing edge to allow clearance for the X-15 vertical tail.

The X-15 pylon was not compatible with the M2-F2 mounting requirements, which necessitated the addition of an adapter between the X-15 pylon and the M2-F2. The adapter was designed to place the M2-F2 cockpit far enough forward to allow the pilot to eject with adequate clearance from the B-52 wing and to place the M2-F2 near free-stream zero-lift angle of attack in the captive position in order to reduce pylon loads. The M2-F2 was mounted so that it was 5° lower in angle of attack than the B-52. Photographs of the B-52, adapter, and M2-F2 are shown in figures 2(a) and 2(b), and pertinent dimensions are given in figure 3.

The M2-F2 receives electrical power from the B-52 for only the cabin air and pilot's pressure-suit heaters and canopy defog blowers until a few minutes before launch when power for these functions is transferred to M2-F2 batteries. Breathing oxygen and cabin-pressurization air are obtained from storage bottles contained in the adapter for use during captive flight. A liquid-oxygen system was installed in the adapter to insure that the M2-F2 liquid-oxygen tank would be full at launch when the XLR-11 rocket engine was to be used.

The M2-F2 is attached to the B-52 pylon adapter by two hooks, one aft of the canopy and one near the aft end of the vehicle, to absorb the M2-F2 vertical forces and pitching moments. Longitudinal and side forces and yawing and rolling moments of the test vehicle are absorbed by a sway brace that contacts the upper surface of the M2-F2 on each side of the centerline.

To launch the M2-F2, compressed air is supplied to a piston-cylinder arrangement which releases the two hooks, thus allowing the vehicle to fall away from the B-52. Ordinarily, the M2-F2 pilot controls the launch release system by a switch in the cockpit; however, if required, the B-52 pilot can also launch the M2-F2.

VEHICLE INSTRUMENTATION

The instrumentation system of the M2-F2 consists of 77 channels of data transmitted from the vehicle to a ground station via a PCM telemetry system. The transmitted data are recorded on magnetic tape at the ground station for later analysis.

Some quantities are displayed also in real time in the ground control station at the Flight Research Center for in-flight monitoring.

The data recorded from the M2-F2 included altitude, airspeed, and angle of attack and angle of sideslip, obtained from sensors on a nose boom; linear accelerations along the three body axes; pitch, roll, and yaw angular rates; pitch and roll attitudes; control-surface positions; pilot's control positions; SAS actuator positions and SAS gain-selection switch positions. The accuracy of these recorded quantities is believed to be within 2 percent of the full-scale recording range for the data-recording system. (For more details regarding the data system, see reference 6.) In addition to the onboard data, movie cameras are provided on the B-52 so that the launch can be viewed from various angles.

PREDICTION TECHNIQUES

Wind-Tunnel Tests

A wind-tunnel investigation was conducted in the NASA Langley Research Center's high-speed 7- by 10-foot tunnel through a Mach number range from 0.6 to 0.85 to determine the M2-F2 aerodynamic forces and moments in the region of the B-52 (refs. 4 and 5). An 0.025-scale model of the M2-F2 was used. The tests were conducted through representative ranges of angle of attack and angle of sideslip of the M2-F2 in the vicinity of the B-52 and at various B-52 angles of attack. Complete results for the flight configuration are given in reference 5.

Digital-Computer Studies

An investigation was made by the NASA Langley Research Center utilizing a digital computer and the wind-tunnel aerodynamic coefficients for the M2-F2 in proximity to the B-52 to solve the six-degree-of-freedom equations for the M2-F2 motions during launch. From these results, the launch conditions that would result in contact between the M2-F2 and B-52 pylon were determined; collision between the adapter and the M2-F2 was not considered to be a problem. In addition, vehicle transients subsequent to launch, particularly the maximum roll angle encountered, were obtained.

Analog-Simulator Studies

Analog simulations were set up at the NASA Flight Research Center (FRC) and the Air Force Flight Test Center (AFFTC) to investigate the vehicle motions during launch and to develop piloting techniques to reduce the transients during launch. The pilot display in the FRC simulations consisted of a color-contact visual display, a three-axis ball-type attitude indicator, and airspeed, altitude, and angle-of-attack meters. The AFFTC display was similar but did not include the contact-analog unit.

Analog computers were used to solve the six-degree-of-freedom equations of motion in conjunction with the aerodynamic derivatives obtained from the Langley M2-F2 wind-tunnel tests. The aerodynamic coefficients in these calculations were expressed as free-stream values, with increments added to account for the interference effects in the vicinity of the B-52 as a function of vertical separation distance between the B-52 and the M2-F2. The derivative increments due to separation distance were stored in a digital computer and converted to analog signals that were fed directly into an analog computer (fig. 4). The equations of motion mechanized on the analog computer are presented in the appendix.

The number of data inputs to the analog computer from the digital computer was limited by the equipment available. As a result, the longitudinal and lateral-directional modes were mechanized separately and the cross-coupling derivatives ignored. In addition to ignoring these terms, the data had to be linearized, although some of the wind-tunnel data were quite nonlinear. As a result of these simplifications, the data table used in the simulator was not as complete as that used for the digital calculations.

The effects of altitude, Mach number, B-52 angle of attack, and M2-F2 upper- and lower-flap settings, interconnect ratio, and damper gains on vehicle motion during launch were investigated. Recordings of the various motion parameters (such as α, β, and φ) were made for comparison with the results of the digital-computer studies and flight tests.

RESULTS AND DISCUSSION

The results from the digital-computer and simulator studies are discussed first in order to illustrate the trends that had been established before the first M2-F2 flight. These trends are then compared with the results from the first 14 flight launches of the vehicle.

Digital-Computer Studies

The results from reference 5 predicted that safe M2-F2 launches from the B-52 could be accomplished. Figures 5(a) to 5(d) illustrate typical paths of the M2-F2 fins in the vicinity of the X-15 pylon during launch for specified conditions on the B-52 and given control configurations on the M2-F2. For the launch conditions shown, it appears that there would not be a collision. From other results of this study at various launch altitudes and Mach numbers, a range of conditions was established in which launches could be made without contact between the M2-F2 fins and the B-52 pylon. The contact boundaries shown in figures 6(a) and 6(b) indicate that launches without contact could be made at altitudes above 32,000 feet (9,800 meters) at a Mach number of 0.7 and above 43,000 feet (13,100 meters) at a Mach number of 0.8. At a Mach number of 0.6, launches without contact could be expected at altitudes of 25,000 feet (7,600 meters) and above; 25,000 feet (7,600 meters) was the lowest altitude investigated. The operation of the M2-F2 dampers had no significant effect on the safe launch clearance envelope.

Approximate values for maximum roll angle with and without augmentation are shown in figure 6. It can be seen that the M2-F2 bank angle becomes larger as the B-52 angle of attack is reduced. If the B-52 angle of attack is constant, the maximum roll angle is reduced with increasing Mach number and altitude. Operation of the M2-F2 dampers reduces the bank-angle excursions.

The study of reference 5 was completed before the M2-F2 configuration was finalized for flight. Consequently, the M2-F2 weight, inertias, damper gains, and interconnect ratio were different from those used in flight. The values of these quantities used for this study are shown in table II. Also, this study was limited to $\delta_a = \delta_r = 0°$ at launch, thus no conclusions could be drawn about the effect of preset controls on launch safety.

Simulator Studies

To assess the controllability of the M2-F2 during launch, simulator studies were made for Mach numbers from 0.6 to 0.8, B-52 angles of attack of 4° to -2°, and dynamic pressures of 80 lb/ft^2 to 120 lb/ft^2 (383 N/m^2 to 575 N/m^2).

The pilots experienced the most difficulty in attempting to control the roll attitude of the M2-F2 because of the rapid roll reversal, as shown in figure 7. If the pilot attempted to control the initial left roll, the following right roll was exaggerated, and vice versa. The pilots preferred to allow the vehicle to stabilize in the right roll and then take corrective action. Care had to be exercised to avoid negative M2-F2 angles of attack, where lateral-directional stability deteriorated (ref. 6).

It was found that the roll and yaw rates increased with increasing dynamic pressure for a constant B-52 angle of attack. The effect of B-52 angle of attack on bank angle and roll rates in terms of pilot ratings for launch only is illustrated in figure 8. The pilot ratings were based on the Cooper rating scale (ref. 7), modified as shown in table III. The maximum roll and yaw rates and the maximum roll angle were reduced as the B-52 angle of attack was increased. This trend is reflected in the more favorable pilot ratings. Figure 8 indicates that the dampers considerably improved the controllability. Thus it appears that the most easily controlled launch would be at low dynamic pressures and high B-52 angles of attack.

The upper- and lower-flap settings had a significant effect on the vehicle motions and piloting task as a result of the deterioration in the lateral-directional stability of the M2-F2 at low angles of attack. The vehicle had a tendency to pitch down after launch because of the ineffectiveness of the upper flaps when located immediately behind the adapter. The lateral-control problem was alleviated by the pre-launch positioning of the lower flap for a nose-high attitude to counteract the ineffective upper flaps; however, an objectionable pitch up occurred as the upper flaps regained effectiveness when the M2-F2 cleared the pylon. If, on the other hand, the lower flap were positioned for a low angle of attack, the vehicle would pitch down at launch and the resulting lateral-directional motions would become uncontrollable. The compromise in flap settings that resulted in acceptable launches is shown in figure 9.

In evaluating the effects of damper failures on M2-F2 launch transients, it was found that a damper failure was most critical in the pitch axis, since this allowed larger negative angle-of-attack excursions, thereby aggravating the lateral-control task, followed in importance by failures in the roll and yaw axes. However, successful launches could be made with all dampers off if the B-52 angle of attack were 0° or greater. A successful launch was defined as one in which the pilot could gain control of the vehicle and assume a normal flight attitude.

No special rudder-to-aileron-interconnect ratio or damper gains were required for launch, and it appeared that the settings used during the remainder of the flight (ref. 6) could also be used for launch.

The studies on the simulator included the definition of the required stability augmentation authority in roll and yaw, since no hardover failure protection was available in the M2-F2 control system. The authorities had to be large enough to provide adequate damping but not so large as to become catastrophic in a hardover failure. The results of varying rudder and aileron hardover authority are shown in figures 10(a) and 10(b) and 11(a) and 11(b). These results formed the basis for a final selection of rudder and aileron authorities of $\pm 4^\circ$ and $\pm 5^\circ$, respectively. The pitch axis had hardover protection, and conditions other than launch established the pitch-control authority requirements.

Flight Characteristics

On the basis of the pre-flight simulator and digital studies, the desired launch conditions for the M2-F2 were established as 45,000 feet (13,700 meters) altitude with the B-52 at as high an angle of attack and as slow an airspeed as possible. The operational limitations of the B-52 determined that the launch conditions would be at a B-52 gross weight of approximately 240,000 pounds (108,862 kilograms), an indicated airspeed of 170 knots (87.4 meters/second), and a Mach number between 0.6 and 0.65 which provided a B-52 angle of attack of approximately 2°. Table IV shows the conditions of the M2-F2 at launch for each flight. Control settings for flights 15 and 16 reflect a forward center-of-gravity shift and a difference in lower-flap contour from previous flights (see ref. 6).

A time history of a typical launch is shown in figure 12. For this maneuver the pilot commented, "The launch was very mild, as the chase reported. I came off [the B-52 pylon/adapter] and I am sure that it wasn't more than about 10 or 15° of bank angle at the most. It did excite a lateral-directional oscillation that probably damped-out in two cycles. Pitch control was very good . . . the launch [control surface] settings seemed to work out real well."

For the 16 flights discussed herein, the pilots, in general, commented that the launch presented no significant control problem, and in most cases the control task was considered to be mild. Typically, the maximum bank angle attained was on the order of 20°, and normal acceleration dropped to -0.2g at launch and then slowly built up to positive values.

Most of the launches were given a pilot rating of 2 (see table III); however, ratings for the remainder of the launches ranged from 2.5 to 4. The time histories of the launches do not provide an obvious explanation for the variation in pilot ratings.

The predicted and the flight range of launch motions are compared in figure 13. The predicted launches show larger bank angles, higher roll rates, and larger pitch rates than experienced in the actual launches. Although the correlation is not exact, it is reasonably good. There are several factors that could contribute to the differences between flight, simulator results, and digital calculations; among these are variation in (or absence of) pilot control inputs, differences in M2-F2 weights and inertias, differences in trim settings, differences in interpretation and use of the data, and, of course, possible differences between wind-tunnel and flight data. The digital calculations

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agree well with the flight results over the critical (from a collision standpoint) first second. The simulator presented a slightly more severe control problem than was encountered in flight and was conservative from that viewpoint.

SUMMARY OF RESULTS

Analytical, simulator, and flight studies of the launch characteristics of the M2-F2 lifting body from a B-52 carrier aircraft provided the following results:

The digital-computer study indicated that launches could be made without contact between the B-52 pylon/adapter and the M2-F2 vertical fins at altitudes of 25,000 feet (7,600 meters) and above at a Mach number of 0.6, 32,000 feet (9,800 meters) and above at a Mach number of 0.7, and 43,000 feet (13,100 meters) and above at a Mach number of 0.8.

The simulator studies indicated that the most severe piloting task during launch would be control of bank angle and that the mildest launch transients would occur at low dynamic pressures and high B-52 angles of attack. The simulator studies also showed that a compromise in trim settings was required to avoid post-launch pitch up or lateral-directional instability which could result from a pitch down to very low angles of attack. Damper failures aggravated the control task during launch, with pitch failure being the most critical, followed by roll and yaw, respectively. A roll stability augmentation system authority of $\pm 5^\circ$ and a yaw stability augmentation system authority of $\pm 4^\circ$ provided adequate damping and acceptable damper-failure characteristics in the simulations.

Flight launches at an altitude of 45,000 feet (13,700 meters), a Mach number of approximately 0.6, and a B-52 angle of attack of approximately 2° presented no serious control problems. Flight results also indicated that the launch transients were not as severe as predicted; however, the predicted and actual transients correlated reasonably well.

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APPENDIX

EQUATIONS FOR MECHANIZATION OF M2-F2 LAUNCH SIMULATION

The translational equations for the mechanization of the M2-F2 simulation were written in a wind-axis system. The equations used were as follows:

$$\dot{V} = \frac{T \cos \alpha}{m} - \frac{\bar{q}S\Sigma C_D}{m} - g \sin \gamma \tag{1}$$

$$\dot{\beta} = \frac{\bar{q}S\Sigma C_Y}{mV} - r \cos \alpha + p \sin \alpha + \frac{g}{V} \cos \alpha \sin \varphi \tag{2}$$

$$\dot{\alpha} = q - p\beta \cos \alpha - \frac{T \sin \alpha}{mV} - \frac{\bar{q}S\Sigma C_L}{mV} + \frac{g}{V} \cos \alpha \cos \varphi \tag{3}$$

where p, q, and r are angular rates as measured in the vehicle body axes.

The following rotational equations were written in a body-axis system:

$$\dot{p} = (\dot{r} + pq)\frac{I_{XZ}}{I_X} + qr\left(\frac{I_Y - I_Z}{I_X}\right) + \frac{\Sigma L}{I_X} \tag{4}$$

$$\dot{q} = (r^2 - p^2)\frac{I_{XZ}}{I_Y} + pr\left(\frac{I_Z - I_X}{I_Y}\right) + \frac{\Sigma M}{I_Y} \tag{5}$$

$$\dot{r} = (\dot{p} - rq)\frac{I_{XZ}}{I_Z} + pr\left(\frac{I_X - I_Y}{I_Z}\right) + \frac{\Sigma N}{I_Z} \tag{6}$$

$$\dot{\varphi} = p + \dot{\psi} \sin \Theta \tag{7}$$

$$\dot{\psi} = \frac{1}{\cos \Theta}(r \cos \varphi + q \sin \varphi) \tag{8}$$

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$$\Theta = q \cos \varphi - r \sin \varphi \tag{9}$$

$$\gamma = \Theta - \alpha \cos \varphi - \beta \sin \varphi \tag{10}$$

$$\dot{h} = V \sin \gamma \tag{11}$$

$$\dot{X} = V \cos \gamma \tag{12}$$

$$\Delta = \psi + \beta \cos \varphi - \alpha \sin \varphi \tag{13}$$

$$V_N = \dot{X} \cos \Delta \tag{14}$$

$$V_E = \dot{X} \sin \Delta \tag{15}$$

$$\bar{q} = \frac{1}{2}\rho V^2 \tag{16}$$

$$N_{Ma} = \frac{V}{a} \tag{17}$$

$$V_i = 17.17 \sqrt{\bar{q}} \text{ knots} \tag{18}$$

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TABLE I.– PHYSICAL CHARACTERISTICS OF THE M2-F2 VEHICLE

Body –	
Planform area, $feet^2$ ($meters^2$):	
Actual	160 (14.9)
Reference, S	139 (12.9)
Longitudinal length, feet (meters)	
Actual	22.2 (6.76)
Reference, $\bar{c}$	20.0 (6.11)
Span, without rudder flare, feet (meters):	
Actual	9.63 (2.94)
Reference, b	9.54 (2.91)
Aspect ratio, $\frac{b^2}{S}$, basic vehicle	0.655
Body leading-edge sweep, degrees	77
Lower flap –	
Area, $feet^2$ ($meters^2$)	15.23 (1.41)
Span, feet (meters)	5.42 (1.65)
Chord, feet (meters)	2.81 (0.86)
Deflection, degrees:	
Pilot's control authority, down	5 to 30
Pitch stability augmentation system authority	±5
Upper flaps, two –	
Area, each, $feet^2$ ($meters^2$)	9.57 (0.89)
Span, each, feet (meters)	4.28 (1.31)
Chord, feet (meters)	2.23 (0.68)
Deflection, degrees:	
Pitch trim (symmetric travel), up	0 to 35
Pilot's aileron authority (differential travel)	±10
Roll stability augmentation system authority (differential travel)	±5
Vertical stabilizers, two –	
Area, each, $feet^2$ ($meters^2$)	16.10 (1.50)
Height, trailing edge, feet (meters)	3.79 (1.16)
Chord, feet (meters):	
Root	7.36 (2.24)
Tip	2.58 (0.79)
Leading-edge sweep, degrees	62.3
Rudders, two –	
Area, each, $feet^2$ ($meters^2$)	5.27 (0.49)
Span, each, feet (meters)	4.20 (1.28)
Chord, feet (meters)	1.25 (0.38)
Deflection, degrees:	
Pilot's effective control authority	12
Yaw stability augmentation system authority	4.2
Weight, including pilot, pounds (kilograms)	6000 (2722)
Center of gravity:	
Percentage of actual length	49
Percentage of reference length	54
Planform-area loading, $\frac{W}{S}$, pounds/$foot^2$ (kilograms/$meter^2$)	43.2 (196)
Moments of inertia –	
I_X, slug-$foot^2$ (kilogram-$meter^2$)	956.3 (1269)
I_Y, slug-$foot^2$ (kilogram-$meter^2$)	5583 (7570)
I_Z, slug-$foot^2$ (kilogram-$meter^2$)	6005 (8142)
I_{XZ}, slug-$foot^2$ (kilogram-$meter^2$)	-417 (-565)

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TABLE II. – PARAMETERS USED IN THE DIGITAL-COMPUTER STUDIES

Weight of M2-F2, W_{M2-F2}, lb (kg)	5029 (2281)
Moment of inertia about principal X-axis, slug-ft^2 (kg-m^2)	1037.48 (1406.20)
Moment of inertia about principal Y-axis, slug-ft^2 (kg-m^2)	4388.5 (5940.0)
Moment of inertia about principal Z-axis, slug-ft^2 (kg-m^2)	4747.7 (645.03)
Inclination of principal axis, deg	-4.9
Pitch-damper gain, sec	0.5
Roll-damper gain, sec	0.25
Yaw-damper gain, sec	0.25
Rudder-to-aileron interconnect gain	-0.30
Damper authority limits, deg:	
δ_a	±20
δ_l	±5
δ_r	±5
Damper rate limits, deg/sec:	
$\dot{\delta}_a$	±30
$\dot{\delta}_l$	±25
$\dot{\delta}_r$	±30

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TABLE III. – MODIFIED COOPER PILOT RATING SCALE

General classification	Numerical rating	Adjective	Handling qualities	Ability to complete mission	Ability to land
Satisfactory	1	Excellent	Easy to control precisely - little corrective control required.	Yes	Yes
	2	Very good	Good response but necessitates attention for precise control.		
	3	Good	Acceptable controllability but more than desired attention generally needed.		
Unsatisfactory	4	Fair	Submarginal for normal use - requires excessive pilot attention.	Yes	Yes
	5	Poor	Controllability poor - demands constant pilot attention and continuous control inputs.	Probably	Yes
	6	Bad	Can be controlled but pilot must exercise considerable care.	Doubtful	Yes
Unacceptable	7	Very bad	Difficult to control and demands considerable pilot concentration.	No	Probably
	8	Dangerous	Controllable only with a high degree of pilot concentration and large control inputs.	No	Doubtful
	9	Very dangerous	Extremely dangerous - can be controlled only with exceptional piloting skill.	No	No
	10	Catastrophic	Uncontrollable.	No	No

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TABLE IV.– M2-F2 LAUNCH CONDITIONS

Flight number	h, [1]		V_i, [1]		N_{Ma}	W,		δ_u, deg	δ_l, deg	K_I	K_p	K_r	K_q
	ft	m	knots	m/sec		lb	kg						
1	44,438	13,545	165	84.9	0.592	5930	2690	-11.7	20.7	-0.6	0.6	0.6	0.6
2	44,421	13,539	165	84.9	.589	5930	2690	-11.6	20.4	-.5	.4	.6	.6
3	44,529	13,572	169	86.9	.632	5930	2690	-11.7	20.7	-.5	.4	.6	.6
4	44,404	13,534	175	90.0	.593	5952	2700	-12.0	20.7	-.5	.4	.6	.6
5	44,324	13,510	175	90.0	.625	5952	2700	-11.5	21.2	-.5	.4	.6	.6
6	44,374	13,525	170	87.4	.609	5944	2696	-11.2	21.0	-.5	.4	.6	.6
7	44,691	13,622	170	87.4	.614	5964	2705	-12.2	20.4	-.5	.4	.6	.6
8	44,108	13,444	170	87.4	.618	5886	2670	-11.6	20.5	-.5	.4	.6	.6
9	44,726	13,632	170	87.4	.625	5964	2705	-11.5	21.5	-.5	.4	.6	.6
10	44,558	13,581	171	87.9	.622	5964	2705	-11.3	21.0	-.5	.4	.6	.6
11	44,692	13,622	170	87.4	.621	5954	2700	-11.2	20.9	-.5	.4	.6	.6
12	44,338	13,514	170	87.4	.605	5954	2700	-11.7	21.5	-.5	.4	.6	.6
13	44,168	13,462	170	87.4	.624	5954	2700	-11.6	21.1	-.5	.4	.6	.6
14	44,646	13,608	170	87.4	.631	5954	2700	-11.6	21.2	-.5	.3	.5	.5
15	44,555	13,580	170	87.4	.613	6149	2790	-14.2	19.3	-.5	.4	.6	.6
16	44,555	13,580	170	87.4	.614	6117	2775	-14.8	18.9	-.5	.4	.6	.6

[1]Contains no position error.

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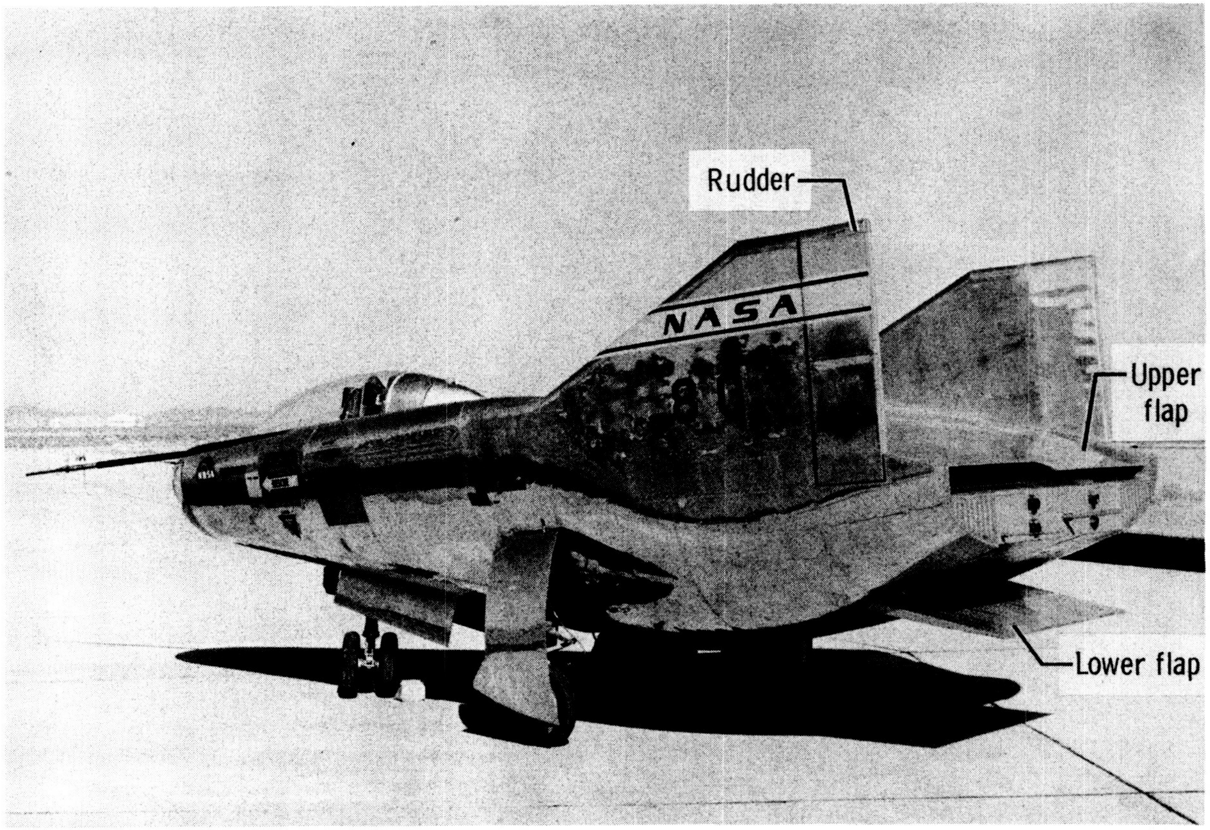

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Figure 1. – M2-F2 lifting-body flight vehicle.

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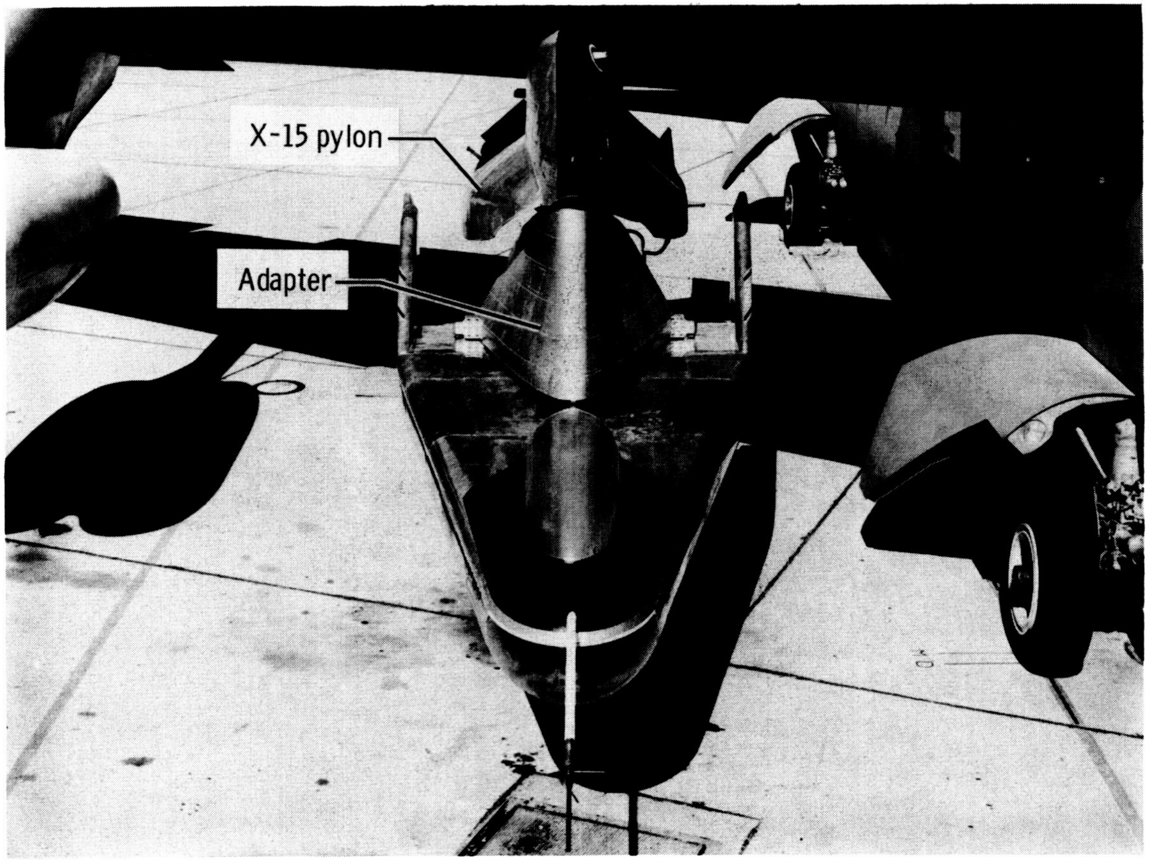

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(a) Overhead front view.

Figure 2. – Photographs of the M2-F2, adapter, and B-52 with X-15 pylon in mated configuration.

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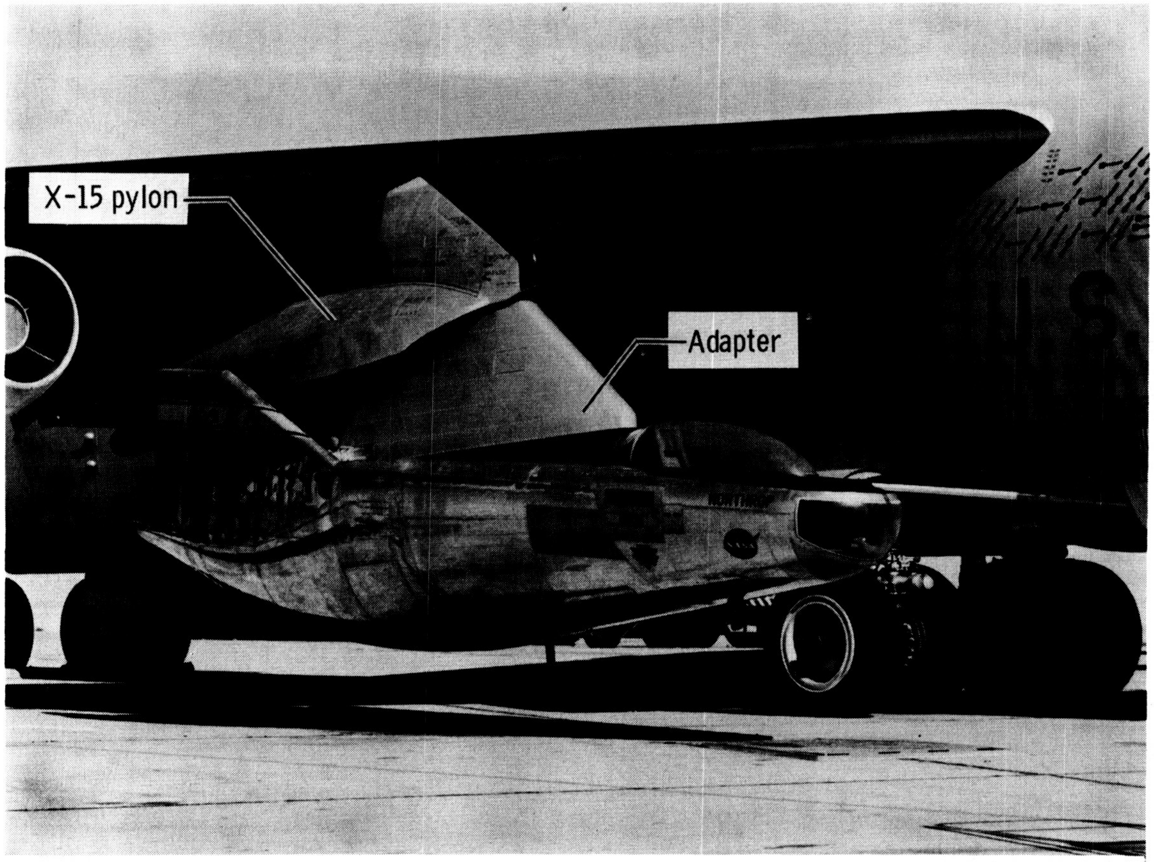

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(b) Three-quarter front view.

Figure 2. – Concluded.

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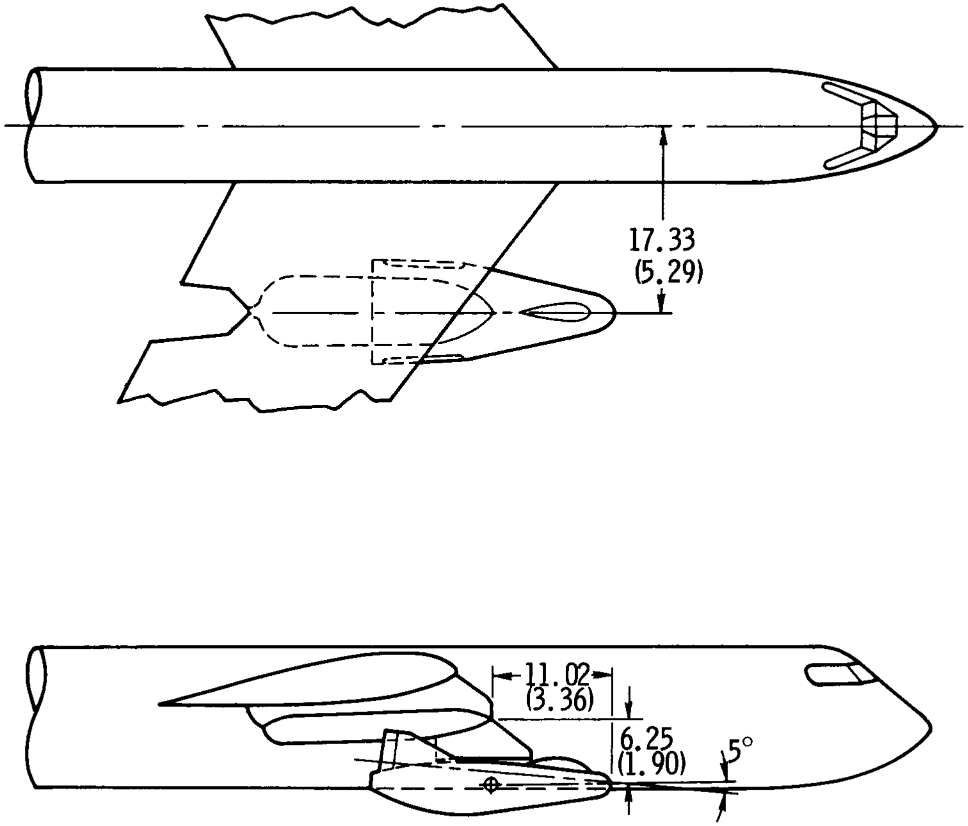

Figure 3.– Location of M2-F2 vehicle on B-52 airplane. Dimensions in feet (meters) unless otherwise noted.

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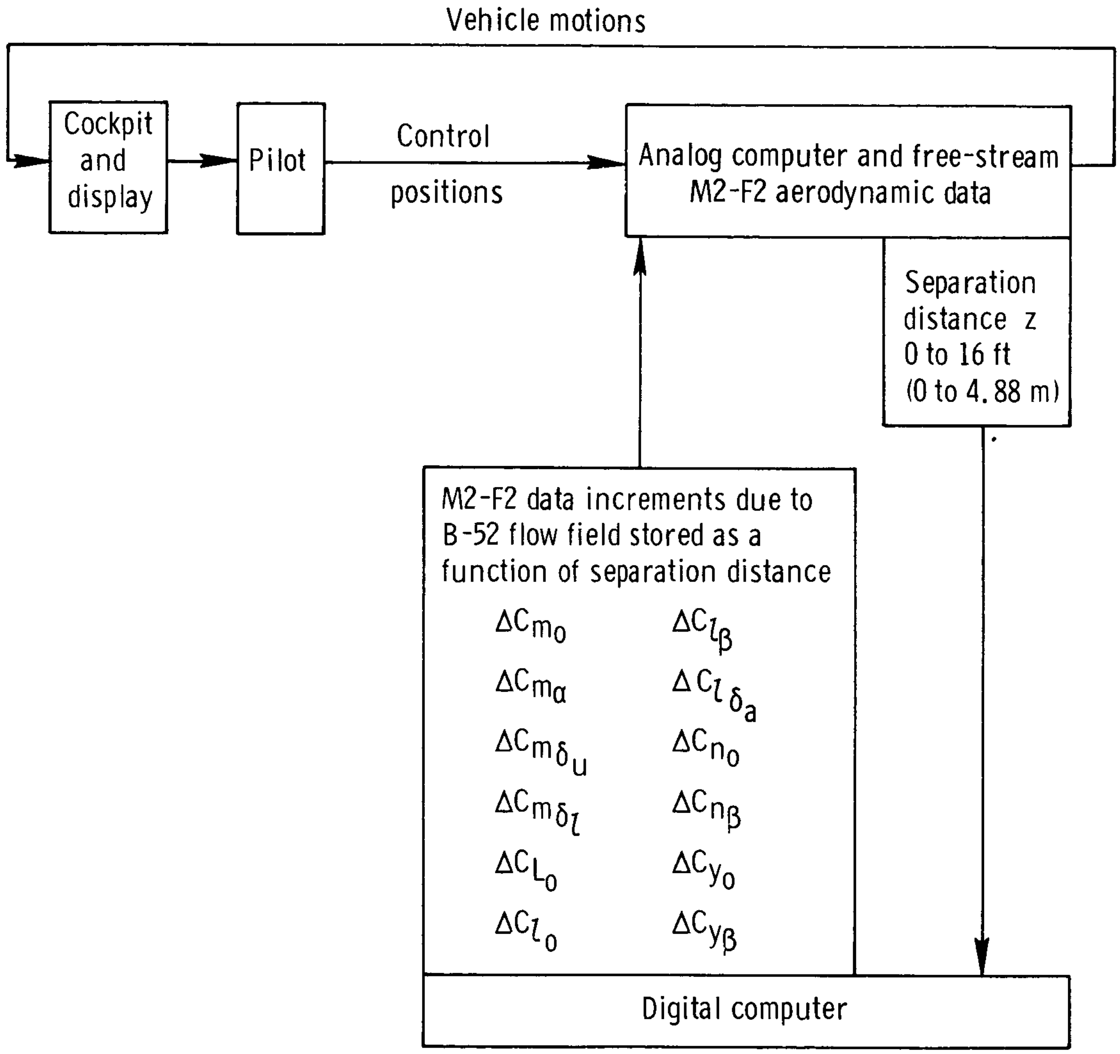

Figure 4. – Simulator setup for M2-F2/B-52 launch studies.

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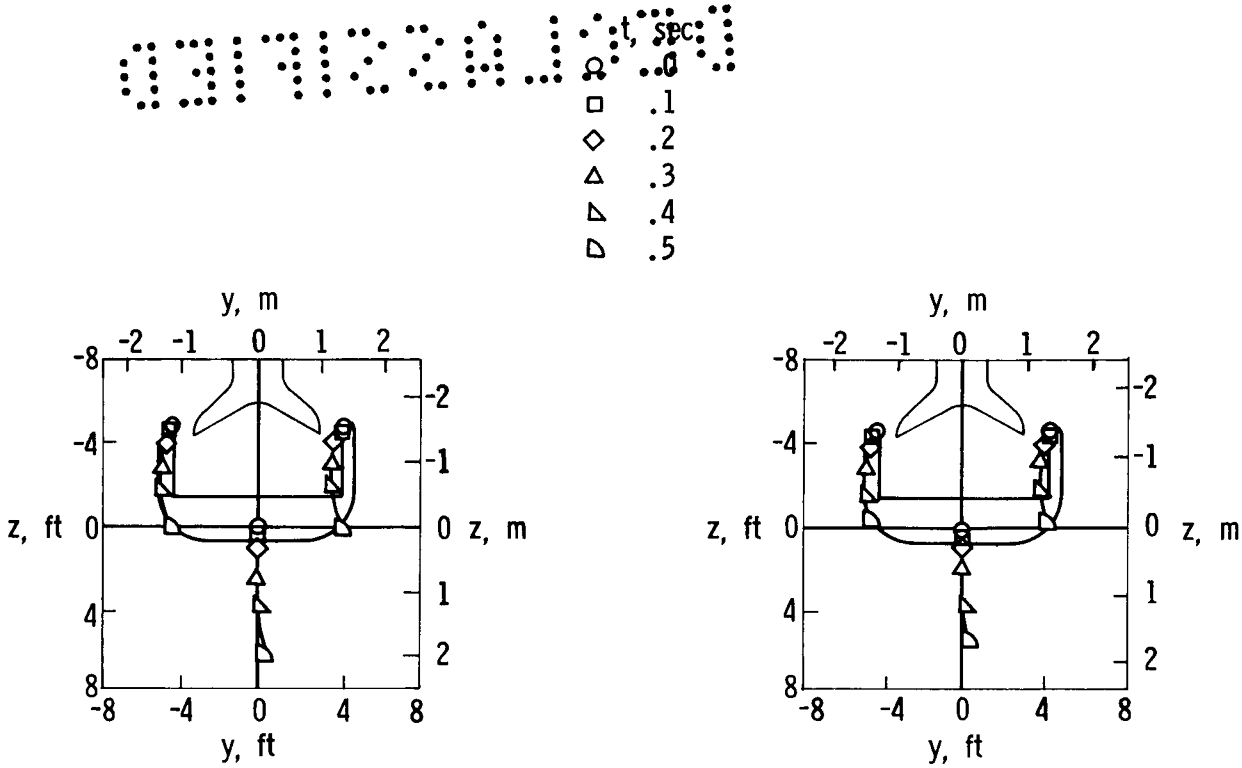
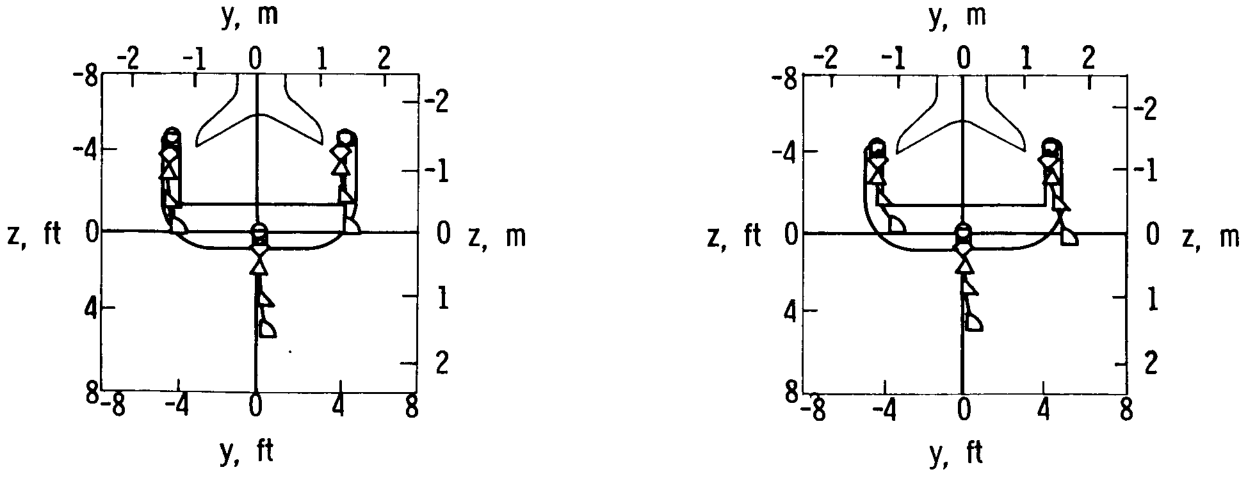


(a) α_{B-52} = -1°, h = 30,000 ft (9144 m).

(b) α_{B-52} = 0°, h = 34,000 ft (10,363 m).



(c) α_{B-52} = 2°, h = 40,000 ft (12,192 m).

(d) α_{B-52} = 4°, h = 45,000 ft (13,700 m).

Figure 5.— Effect of variations in B-52 angle of attack on paths of M2-F2 fin tips during M2-F2 launch determined by digital calculations (ref. 5). N_{Ma} = 0.6, dampers on; δ_u = -15°; δ_l = 25°; δ_a = 0°; rudder flare = 10°; W_{M2-F2} = 5029 lb (2281 kg).

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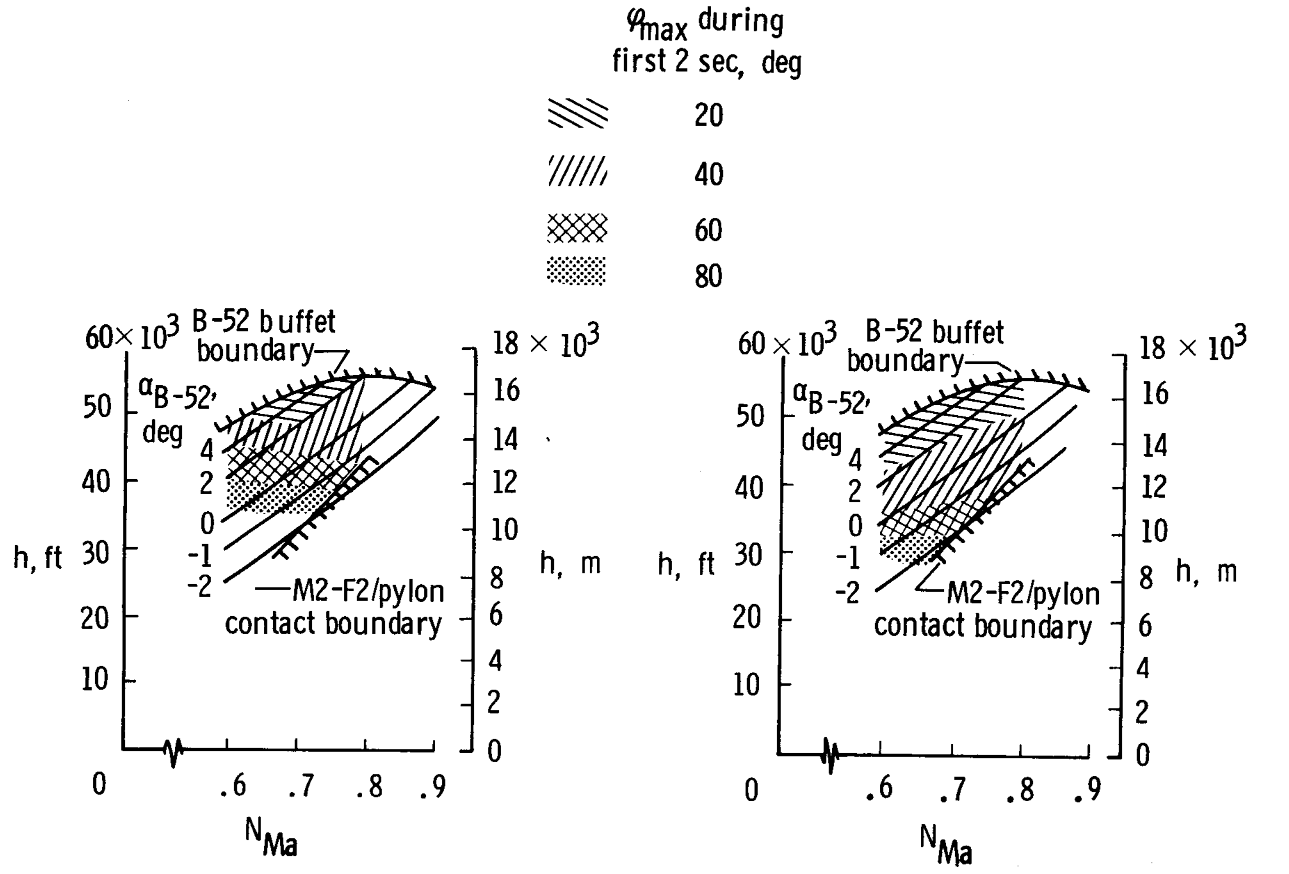

(a) Dampers off.

(b) Dampers on, $K_p = 0.25$, $K_r = 0.25$, $K_q = 0.5$, $K_I = -0.3$.

Figure 6. – **Satisfactory launch envelope determined by using digital calculations from reference 5.** $W_{M2\text{-}F2}$ = 5029 lb (2281 kg); $\delta_u = -15°$; $\delta_l = 25°$; $\delta_a = \delta_r = 0°$; rudder flare = 10°; $W_{B\text{-}52}$ = 250,000 lb (113,400 kg).

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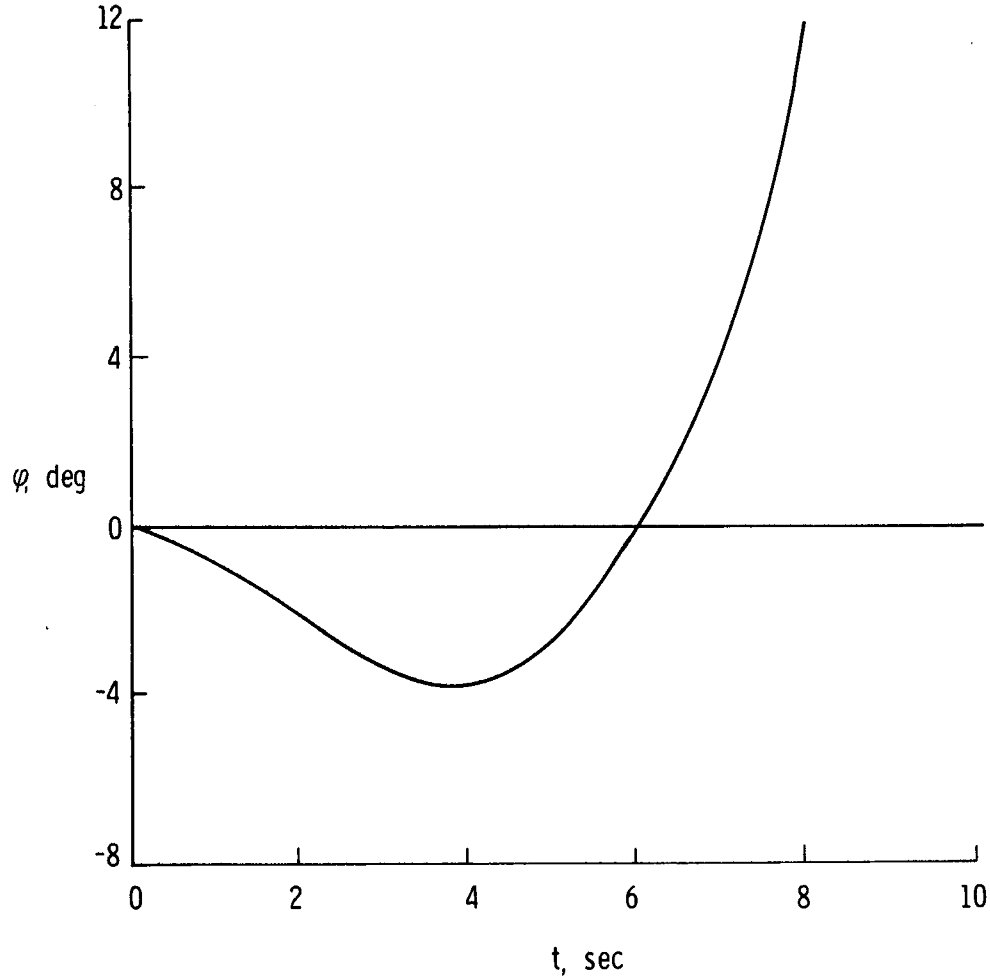

Figure 7. — Simulator time history of bank angle during M2-F2 launch, illustrating roll reversal. Dampers off; $N_{Ma} = 0.6$; h = 45,000 ft (13,700 m); $\delta_u = -15°$; $\delta_l = 25°$; $\delta_a = 0°$, $\delta_r = 0°$; rudder flare = 10°.

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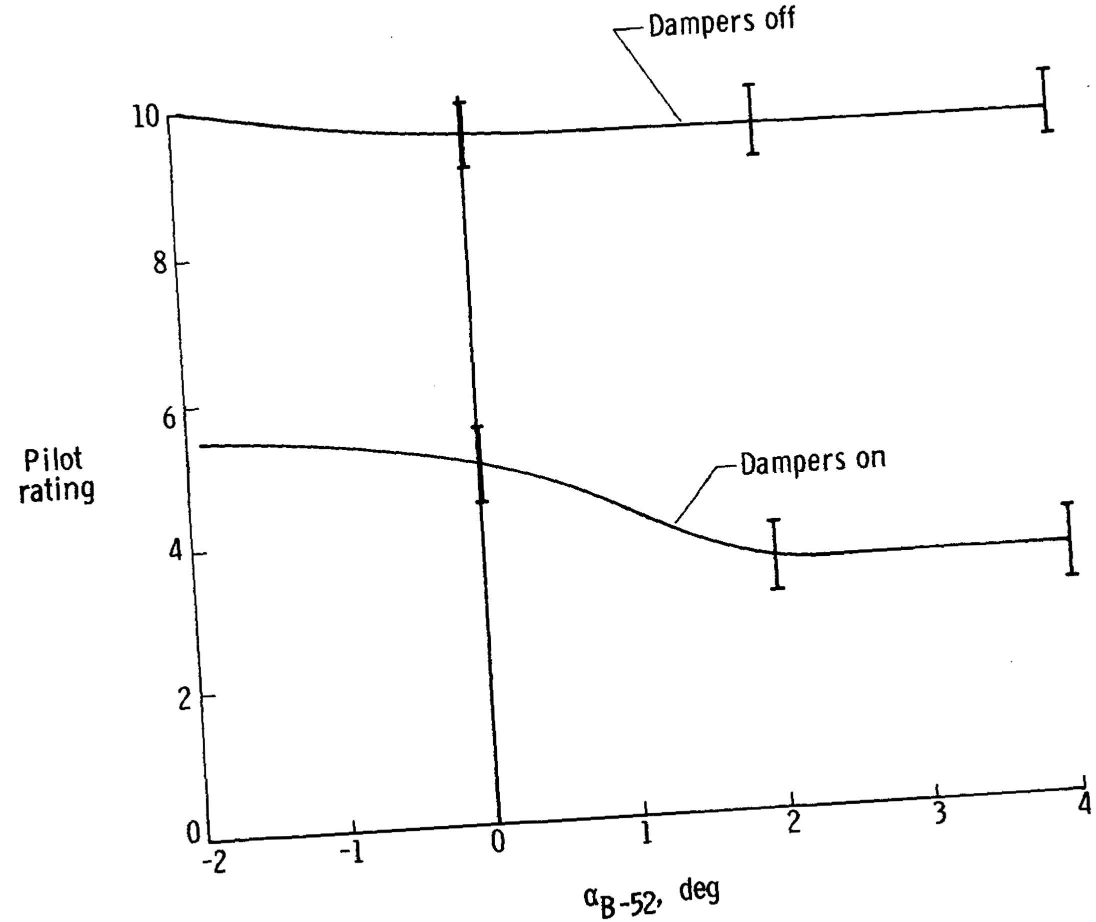

Figure 8. – Effect of B-52 angle of attack on pilot rating for launch maneuver as determined from simulator studies. $N_{M_a} = 0.6$; $h = 45,000$ ft (13,700 m); $K_q = 0.5$; $K_p = 0.25$; $K_r = 0.25$; $K_I = -0.5$.

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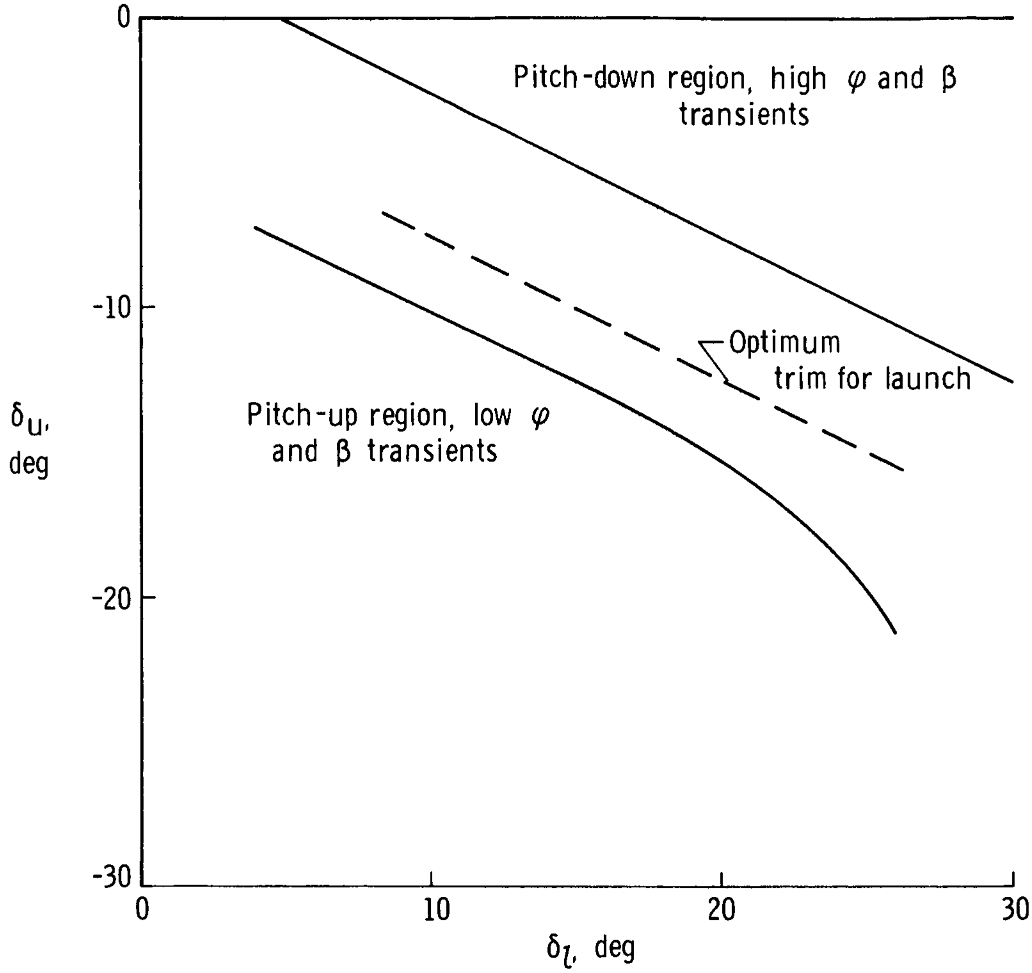

Figure 9.— Effect of upper- and lower-flap trim settings on M2-F2 launch transients as determined from simulator studies. $N_{Ma} = 0.6$; $\alpha_{B\text{-}52} = -1°$ to $2°$; B-52 $V_i < 170$ knots (87.4 m/sec); h = 45,000 ft (13,700 m); $K_I = -0.5$.

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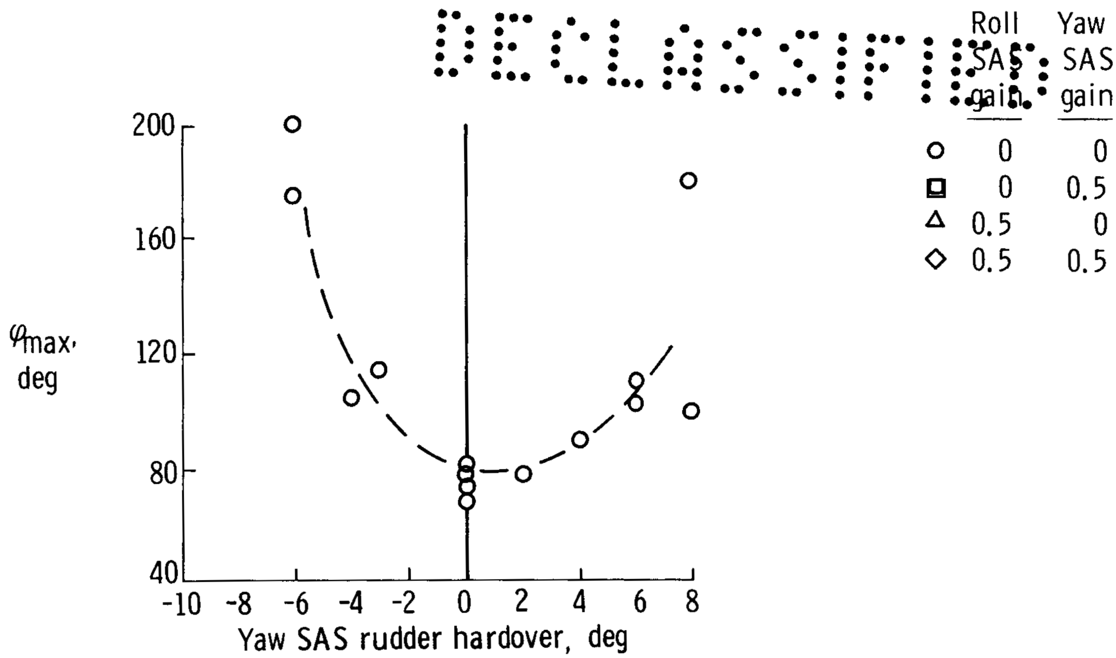
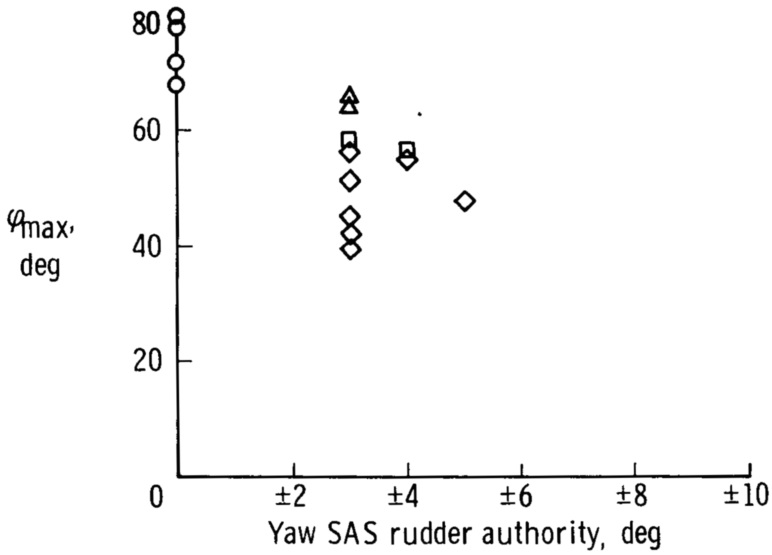


(a) Damper failed; hardover conditions in effect during entire launch.



(b) Damper operating.

Figure 10.— Simulator determination of the effects of yaw-damper authority on launch bank-angle transients. $\delta_u = -12.5°$; $\delta_l = 20°$; $K_I = -0.5$; $K_q = 0.5$; $N_{Ma} = 0.65$; h = 45,000 ft (13,700 m); $\alpha_{B-52} = 0°$; roll-damper authority = ±10°; no pilot inputs.

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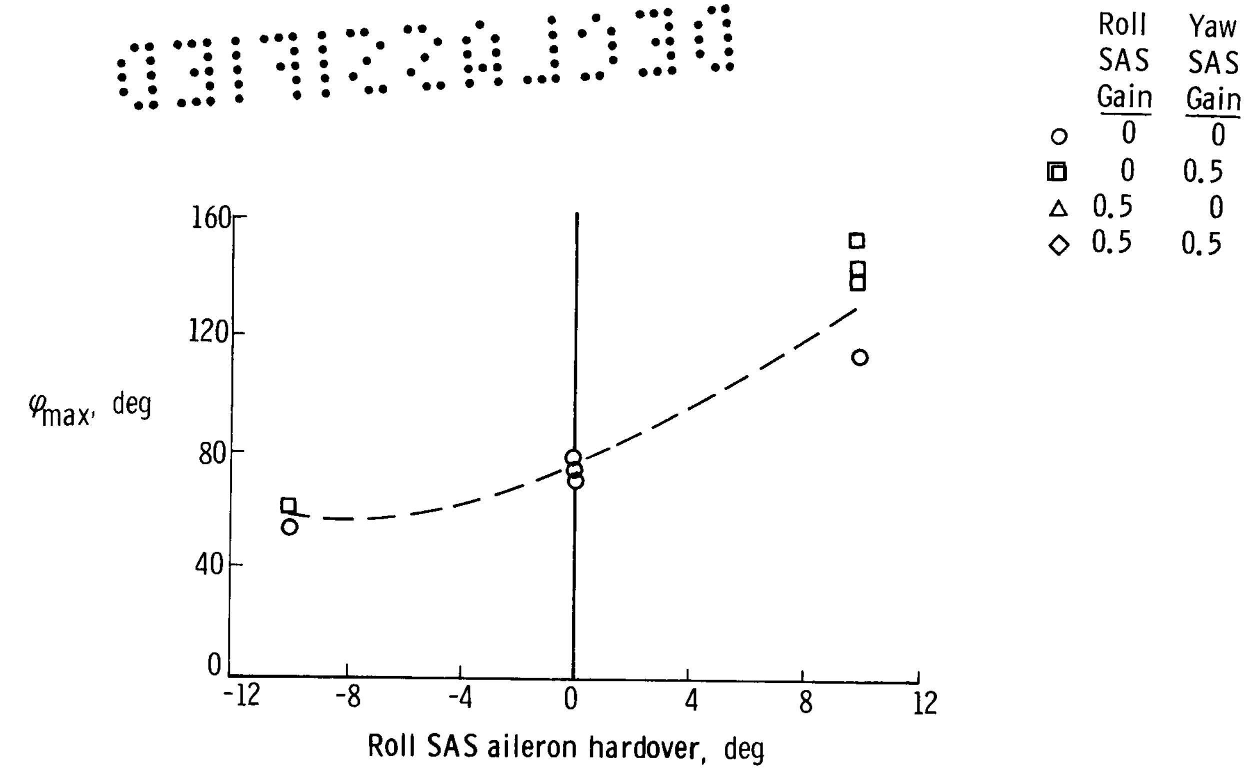
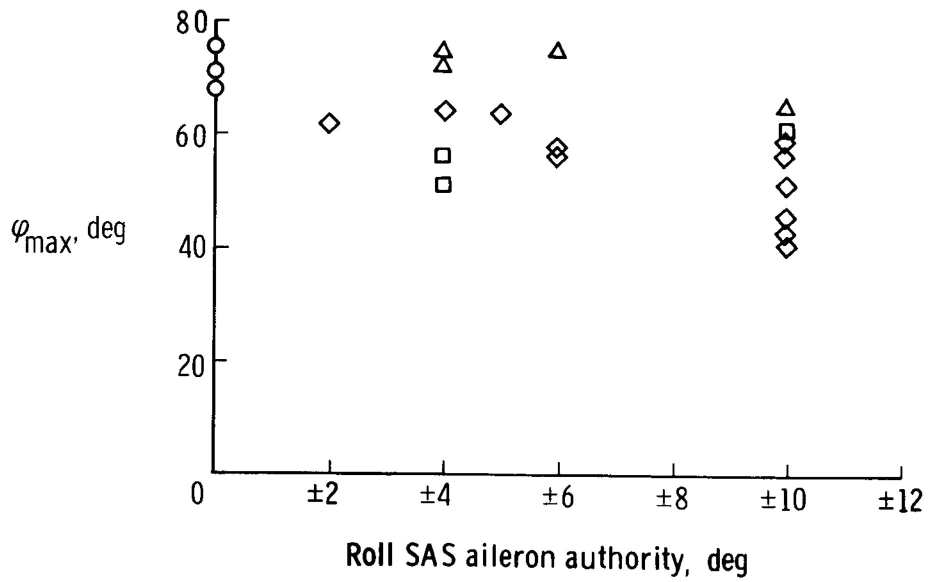


(a) Damper failed; hardover conditions in effect during entire launch.



(b) Damper operating.

Figure 11. – Simulator determination of the effects of roll-damper authority on launch bank-angle transients. $\delta_u = -12.5°$; $\delta_l = 20°$; $K_I = -0.5$; $K_q = 0.5$; $N_{Ma} = 0.65$; h = 45,000 ft (13,700 m); $\alpha_{B-52} = 0°$; yaw-damper authority = ±3°; no pilot inputs.

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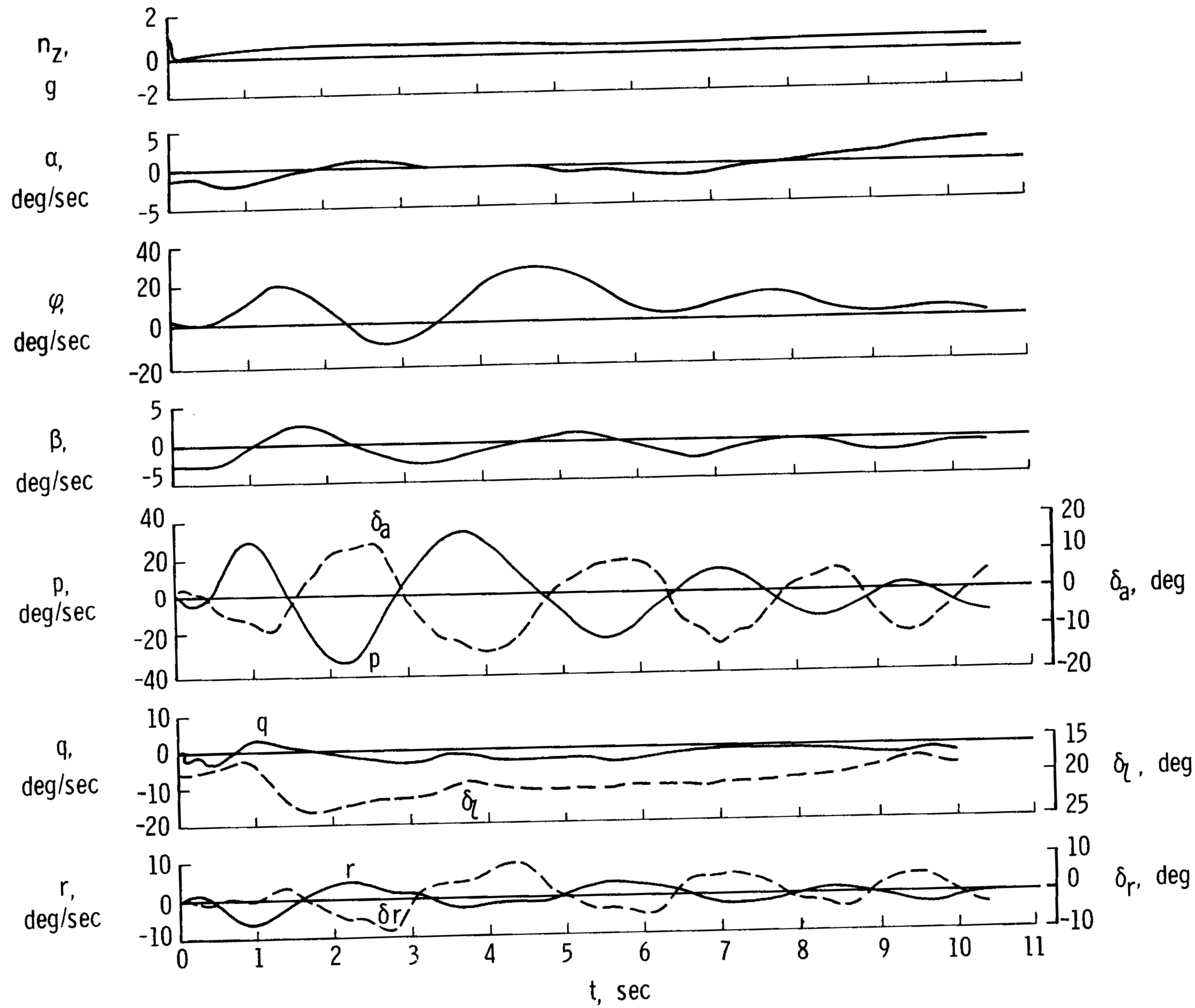

Figure 12. – A typical M2-F2 launch. $\delta_u = -11.7°$; $\delta_l = 20.7°$; $N_{Ma} = 0.592$; h = 44,438 ft (13,545 m); $W_{M2-F2} = 5930$ lb (2690 kg); $K_p = 0.6$; $K_r = 0.6$; $K_q = 0.6$; $K_I = -0.6$.

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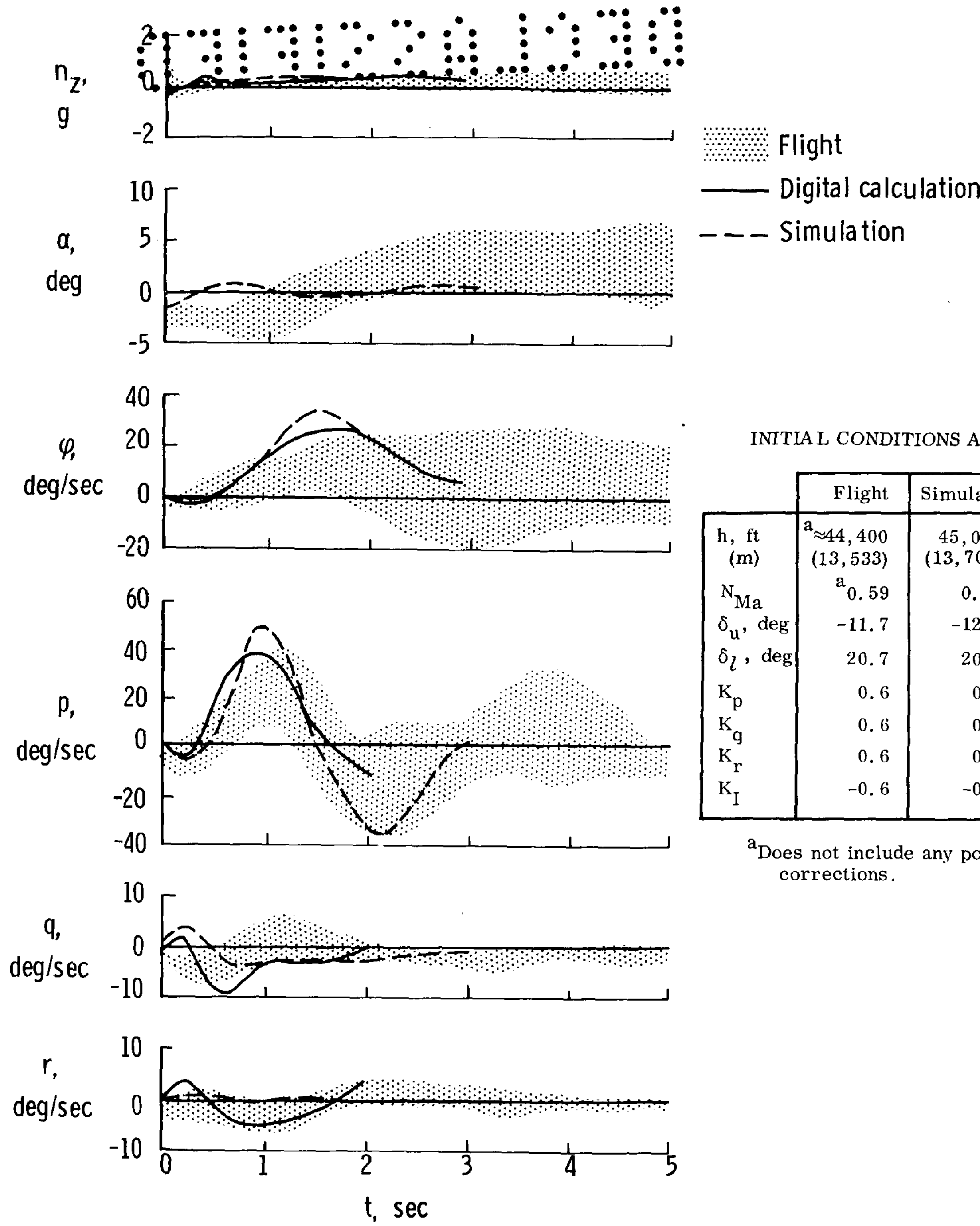

INITIAL CONDITIONS AT LAUNCH

	Flight	Simulator	Digital
h, ft (m)	[a]≈44,400 (13,533)	45,000 (13,700)	44,000 (13,411)
N_{Ma}	[a]0.59	0.65	0.64
δ_u, deg	-11.7	-12.5	-11.7
δ_l, deg	20.7	20.0	20.7
K_p	0.6	0.6	0.6
K_q	0.6	0.6	0.6
K_r	0.6	0.6	0.6
K_I	-0.6	-0.6	-0.6

[a]Does not include any position-error corrections.

Figure 13.– Comparison of flight, simulator, and digitally calculated launch transients for selected parameters.

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NASA-Langley, 1968 —— 31 H-517