Maneuvering Capabilities of Hypersonic Airframes

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The objective of this paper is to document weight dependent trends in the maneuverability and agility of extremely high-speed aircraft. At high true airspeeds, the maneuverability and agility may be impacted by fundamental structural, aerodynamic and propulsive limitations. This work reverse engineers the instantaneous and sustained maneuvering capabilities of the North American X-15 aircraft, the only general purpose powered hypersonic maneuvering aircraft flown. It shows the impact of flight weight and engine size on instantaneous and sustained maneuvering capabilities. Even at light weights when flown to high load factors, hypersonic aircraft have poor maneuvering capabilities compared to other combat or commercial aircraft.

I. Introduction

MANUEVERING HYPERSONIC airframes have beguiled engineers for more than half a century. An extremely high speed airframe can travel great distances in a brief amount of time. A Mach 5 average speed implies flight at more than 3,000 nautical miles per hour. In commercial service, a flight from New York to Los Angeles would take less than an hour. In a military application, a 500-nM downrange flight would take only 9 minutes from start to finish.

FIGURE 1 – North American X-15 [1]

FIGURE 2 – NASA/Rockwell Space Shuttle Orbiter [2]

To date U.S. developed hypersonic airframes include the North American X-15 from the 1960's [1], the NASA/Rockwell Space Shuttle Orbiter [2], the NASA X-43 [3] and the Boeing X-51 [4]. The X-15 was propelled by an ammonia / oxygen rocket motor and flew an extended test flight program of 199 missions over a period of 9 years. The Shuttle Orbiter flew independently as a unpowered hypersonic reentry glider on 133 successful missions. The X-43 and X-51 were powered by a mixed system incorporating a hydrocarbon-fueled scramjet as well as a solid rocket booster; these two technology demonstrators have flown on a much more limited basis (two successful flights of the X-43A and two successful flights of the X-51). At this point in time, we can consider the X-15 as the only truly successful general-purpose unitary airframe capable of powered hypersonic maneuvering flight. Both the shuttle and the X-15 are examples of successful general-purpose airframes capable of gliding hypersonic maneuvering flight.

This paper extends a discussion regarding the maneuvering capabilities of non-combat aircraft published at the 2022 AIAA Aviation Conference, [5] to aircraft capable of flight at extremely high speeds. For subsonic transport-category aircraft, subtle interrelations between wing size, thrust levels, stall characteristics and the "*V-n*" diagram greatly impact their instantaneous and sustained turn capabilities. These interactions become even more prominent as the flight speed

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range increases past the speed of sound to Mach 5 and above and the flight altitude extends to the outer reaches of the atmosphere.

II.Interaction of Aerodynamics and Structures

A. Structural Certification Basis

The basic idea to proof-test aircraft structures to some multiple of its maximum certified flight weight goes back to the earliest days of Federal Regulation, predating even the Code of Federal Regulations. [6] Modern civil and military aircraft a designed in terms of a *V-n* diagram, which provides an envelope of load factor and airspeed (both in terms of dynamic pressure and in terms of Mach number) that the aircraft structure must withstand.

Certification requires demonstration that structure withstands a strength test, that is a static test where the structure survives application of the limit load multiplied by the factor-of-safety. For hypersonic vehicles, the static test must also consider materials characteristic degradation imposed by the aero-thermal heating environment.

Beginning with the initial edition of the Code of Federal Regulations, published 1938, the Load Factor, n, is "the ratio of a load to the design weight. When the load in question represents the net external load acting on the airplane in a given direction, n represents the acceleration factor in that direction." [7] The Limit Load as the "load (or load factor, or pressure) which it is assumed or known may be safely experienced but will not be exceeded in operation" [8]. The Factor-of-Safety as "a factor by which the limit loads are multiplied for various design purposes." [9]

In an airframe lacking wing-borne fuel, the wing structural will be driven primarily by aerodynamically induced bending moments. Such a wing will exhibit the following trend:

$$nZmax = \frac{nZ_{cert} \cdot W}{MTOW} \tag{1}$$

A hypersonic "boost-glide" system, like the Space Shuttle Orbiter, will perform maneuvers over a moderate range of flight weights. In the case of the Orbiter, its empty weight was ~180,000-lbm and its maximum payload was ~55,000-lbm; thus its design maximum gliding weight was ~235,000-lbm. [2] Thus it is likely to maneuver when loaded from ~75% to 100% of its certification weight. If the Orbiter is stressed to, say, +2.5-gees at maximum gliding weight; it can safely maneuver at up to +3.3-gees when gliding at its empty weight.

A hypersonic "rocket-plane," like the X-15, will perform maneuvers over a broad range of flight weights. In the case of the X15-A2, its empty weight was ~14,600-lbm and its gross weight, fully fueled, was ~34,000-lbm. [1] Thus it is likely to maneuver when loaded from ~40% to 100% of its certification weight. If the X-15 is stressed to, say, +3-gees fully loaded; it can safely maneuver at up to +7.5-gees when gliding at its empty weight. This leads to a considerable flight weight variation in maneuverability limits based on flight weight.

B. Aerodynamic Limits due to Stability & Control Concerns

Both civilian and military aerodynamic certification limits must consider flight at a variety of weights, from the maximum weight selected by the applicant through a minimum weight. General purpose aircraft must be safely controllable and maneuverable during all expected flight phases – from low-speed/low-altitude flight through high-speed/high-altitude flight – heavily loaded as well as empty – at forward CG location through an aft CG location.

For extremely high-altitude aircraft, the low end of dynamic pressure limits should be chosen to reflect the realities of aerodynamic controllability. For "1-gee" flight, minimum scheduled flight indicated-airspeeds should be no slower than some multiplier of the "stall speed" and/or "minimum control speed." For quasi-ballistic or exo-atmospheric operations, where the dynamic pressure drops below the "1-gee stall speed" or "minimum control speed," supplemental reaction-control jets are required to augment aerodynamic control effectors otherwise used to pitch, roll and/or yaw the airframe.

For extremely high-speed aircraft, the upper bounds of the dynamic pressure limits should be chosen to reflect the realities of the interaction between aerodynamics and structures. As my colleague M. Christopher Cotting, Director of Research at the USAF/Test Pilot School says "linear-time-invariant systems interact as if they were toddlers playing with Lego's; you need to keep them well separated, otherwise the results could be disastrous." [10] In other published research, my students and I write about the need to keep the rigid body modes (i.e. the Short-Period and Dutch-Roll) apart from one-another in order to prevent inertial coupling; [11] [12] [13] also refer to Day. [14] But this concept applies more broadly than to the classic rigid-body modes; structural modes need to be kept above the rigid-body modes and/or the planned control-system synthesized characteristic frequencies otherwise unplanned aero/structural and/or GNC/structural induced coupling will occur. [14] Thus, the maximum scheduled flight indicated-airspeeds should held low enough so that the aero/control modes do not interact with the structural modes.

III. Turn Capability & Agility Metrics

This section recaps the mathematical foundations of metrics regarding airplane turning performance and agility characteristics. An airplane in flight has a velocity vector which defines both its speed and direction of flight. Maneuverability is the capability for an aircraft to change this vector. In order to quantify aircraft maneuverability, we must determine its linear acceleration, climb deceleration, and turning characteristics. Also remember that aircraft lack inherent pendulum stability. This is because the aerodynamic center of lift is nearly always longitudinally and laterally coincident with the aircraft's center of gravity. Any vertical displacement is at best small. In fact, since most aircraft have their wings mounted below their center of gravity, they actually have weak pendulum instability.

When maneuvering, pilots alter the forces of lift, weight, thrust, and drag a to generate linear or radial accelerations. As aircraft lack an inherent tendency to flight right-side up, they typically fly bank to turn flight profiles. Pilots command heading changes by rolling the aircraft to the left or right in order to tilt the direction of the lift vector. To finish the turn, the pilot rolls back to the wings-level position. The radial acceleration developed by the tilted lift vector causes a turn in the horizontal, vertical, or even in an oblique plane. Forces which cause a radial acceleration include: weight, side force, lift, and thrust. If the aircraft is to turn without a loss of altitude, the vertical component of the lift force must continue to equal the weight. Thus, the pilot must pull back on the stick to increase lift to an amount greater than the weight of the aircraft. The horizontal component is unbalanced; this force (balanced by centrifugal force) causes the aircraft to accelerate inward and execute the turn.

A. Instant Turn Radius and Rate

The Navy Test Pilot School Fixed Wing Performance Manual [15] suggests that the primary characteristics which describe an aircraft's instantaneous turn capability are its turn radius and heading-change turn rate. The instantaneous turn performance describes the capability of an airplane at a particular flight condition, at an instant in time. We do not consider the airplane's ability to sustain the performance for any length of time. In fact, the energy loss rate may be high – a turn at maximum instantaneous turn rate is often accompanied by rapid deceleration or altitude loss. But first, let us consider the maneuvering rotation of the airframe alone – as governed by its aerodynamics and structures.

The attainable load factor, *nZ*, represents the magnitude by which lift exceeds weight limited by structural concerns:

$$nZ = \min\left(\frac{W}{CLmax\ q\ Sref}, nZlimit\right) \qquad (2)$$

Where both the dynamic pressure, q, and the maximum lift coefficient, *CLmax*, are functions of speed and altitude. [16]

Geometry also implies a correlation between *NZ* and bank angle, Φ, for flight without loss of altitude (FIGURE 3):

$$nZ = 1/\cos(\Phi) \qquad (3)$$

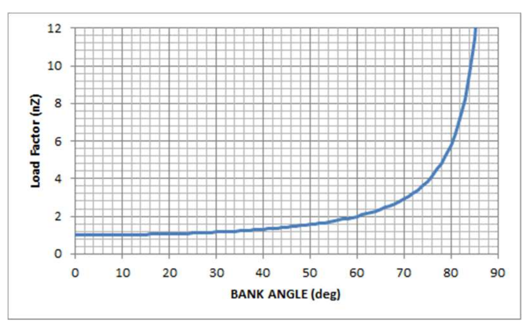

FIGURE 3 – Bank Angle / Load Factor Relationship for a steady level turn

Turning radius in nautical miles may be inferred from load factor, nZ, and flight speed in KTAS, where g = 32.2-ft/sec^2 (FIGURE 4)

$$TURNRADIUS = \frac{(V)^2}{g\sqrt{nZ^2-1}} = \frac{(VKTAS\cdot\frac{6076}{3600})^2}{32.2\cdot\sqrt{nZ^2-1}} \Big/ 6076 \qquad (4)$$

At the 1-gee stall speed, no turns can be made; wings must be held level – the turn radius is infinite and turn rate is zero.

As we increase airspeed above the stall speed, the allowable bank angle increases and the turn radius rapidly diminishes. The turn radius increases as a function of the true airspeed squared; the reader may examine the trade between load-factor and speed in FIGURE 4.

We may also consider the instantaneous rate-of-heading change capability. Recall that the arc length of a circle is 2π times its radius. Thus, if we know the turn radius in feet and we know the flight speed in true-airspeed we can infer the turn rate in terms of degrees-of-heading-change per second:

$$TURNRATE = 360/(2\,\pi\frac{TURNRADIUS}{VKTAS\frac{6076}{3600}}) \qquad (5)$$

The reader may examine the trade between load-factor and speed on the turn rate in FIGURE 5.

To put this in context, consider the implications of these equations as applied to a supersonic aircraft at 4-gees and 1,000 KTAS; it will commence a ~4-nM radius turn and will change compass heading at ~4°/sec. A Mach 3 aircraft pulling +4-gees at 1,980 KTAS will make a ~15-nM radius turn and will change heading at ~2°/sec. A hypersonic (Mach 5) airframe pulling 4-gees at 3,300 KTAS will embark on a ~40-nM radius turn and only change heading at ~1.3°/sec. Thus, to make a 90° course change at +4-gees, a hypersonic aircraft will take over 1-minute to comply and will cover ~65-nM ground distance.

The flip side is that a subsonic transport can fly the same course and make a 4-nM radius turn at 250 KTAS with ~12° bank angle and a barely perceptible load factor of 1.025-gees!

Turn to FIGURE 6 and consider a 25-nM radius turn circle centered on Edwards AFB in Southern California. To fly this circle, a hypersonic (Mach 5) airframe would need to maintain +6.4-gees of load factor at an ~80° bank angle.

This performance may be entirely theoretical as the such a high load factor may well prove both structurally and aerodynamically infeasible to achieve on a real airframe.

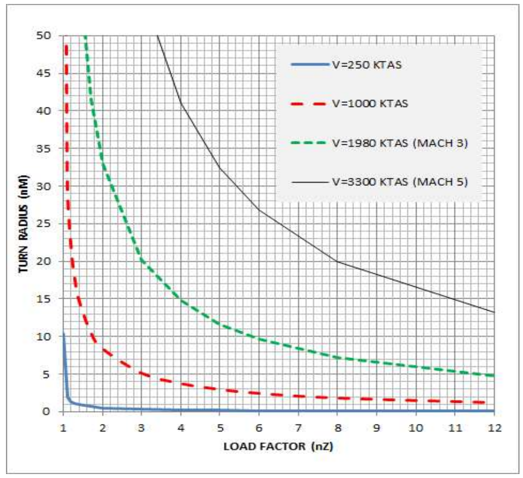

FIGURE 4 – Turn Radius / Speed / Load Factor relationship

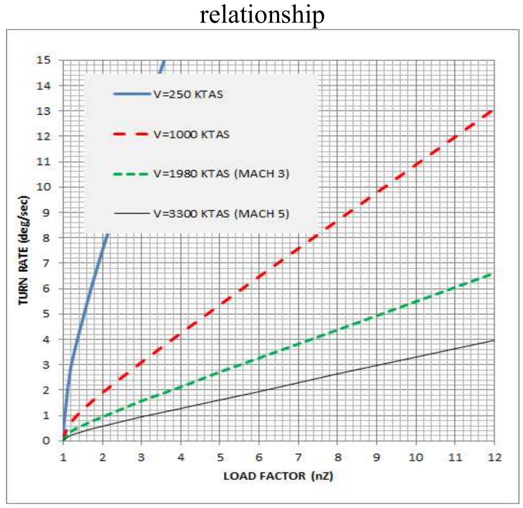

FIGURE 5 – Heading Rate Change Capability / Speed / Load Factor relationship

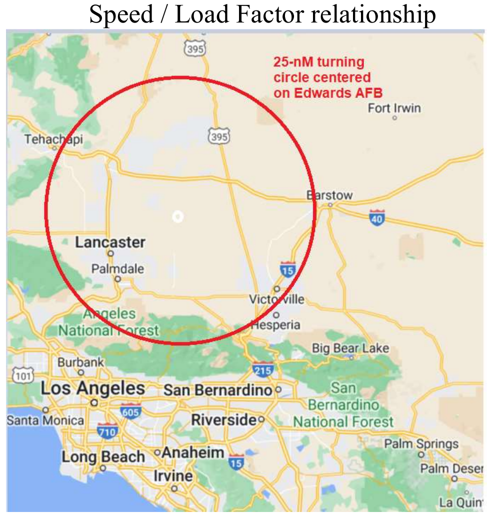

FIGURE 6 –Example 25nM turn circle centered on Edwards AFB, CA

B. Sustained Turn Radius and Rate

Performance engineers like to qualify the sustained turn capability inherent in an airframe. That is its ability to maintain a steady turn without loss of speed or altitude.

In order to compute sustained turn capability (both in terms of load factor, the implied bank angle, turn radius and turn rate) we must pay attention to the specific excess power of the airframe. Thus, sustained turn capability, *nZsustained*, reflects equation (8) where *CLmax* may also be limited by the lift coefficient associated with thrust equaling drag (*T=CD q Sref*) at a given power setting. The value of *nZsustained* is found using a computer program employing root-finding algorithm which attempts to balance thrust and drag for flight at a given speed/altitude pairing within the limits of the *CLmax*.

Once *nZsustained* has been established, we can use equations (9), (10) and (11) to compute the implied bank angle, turn radius and turn rate.

The Navy Test Pilot School Fixed Wing Performance Manual [15] presents some illustrative charts to describe typical combat aircraft sustained turn capability. These plots, seen in FIGURE 7, must be developed at a representative flight weight and altitude. We can see that for any given weight, speed and altitude combination, the sustained turn capability can never exceed the instantaneous turn capability of an airframe. The sustained turn capability tracks the instantaneous turn capability from stall speed up to some limiting speed; As the Mach number further increases, sustained turn capability diminishes.

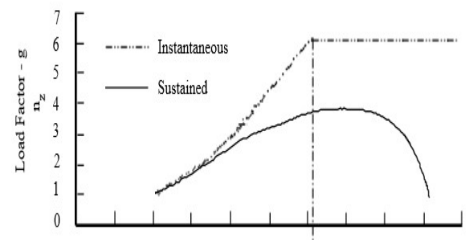

FIGURE 7 –Load factor as a function of Mach number schematic, after Referemce [15]

C. Unsteady Turning Flight

The Navy Test Pilot School Fixed Wing Performance Manual [15] suggests a number of metrics to document unsteady flight.

- The first area of interest is the 1-gee speed envelope for level flight; we seek to document the acceleration potential of the airplane in knots per second at full "military" thrust.
- The second area of interest comprises performance in windup turns. A windup turn involves a smooth and steady increase in load factor flown at constant Mach number beginning at 1-gee level flight and ending at the stall or buffet limit; the aircraft may climb or descent at various points in this maneuver. We will document this in terms of unaccelerated-rate-of-climb in ft/min across the flight envelope.
- The third area of interest involves turns at constant altitude. The "front side" technique documents the acceleration potential of the airplane in knots per degree heading change and full "military" thrust.
- The final area of interest involves turns at constant speed. The "back side" technique documents the unaccelerated-rate-of-climb in ft per degree heading change at full "military" thrust.

We calculate the acceleration potential is 1-gee level flight as:

$$ACCEL = 19.078\,\frac{(T - CD\ q\ Sref\,)}{W} \tag{6}$$

where *ACCEL* is in KTAS/sec, thrust, *T*, is given in lbf, dynamic pressure, *q*, in lbf/ft^2 and wing reference area, *Sref*, in ft^2. *CD* reflects flight where *CL = W / (q Sref)*.

The small-angle assumption work-energy-theorem based unaccelerated-rate-of-climb is:

$$ROC \approx 101.33\,\frac{(T - CD\ q\ Sref\,)}{W}\,KTAS \tag{7}$$

where *ROC* is in ft/min; the thrust, *T*, is given in lbf; the dynamic pressure, *q*, in lbf/ft^2 and the wing reference area, *Sref*, in ft^2. *CD* reflects flight at *CLmax* as limited by stall, buffet or structural limits.

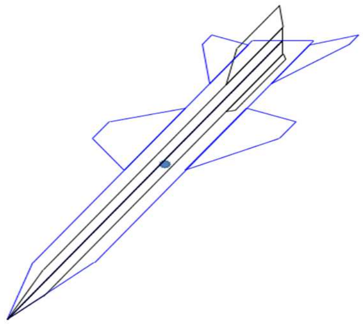

FIGURE 8 – VORLAX model of the X-15

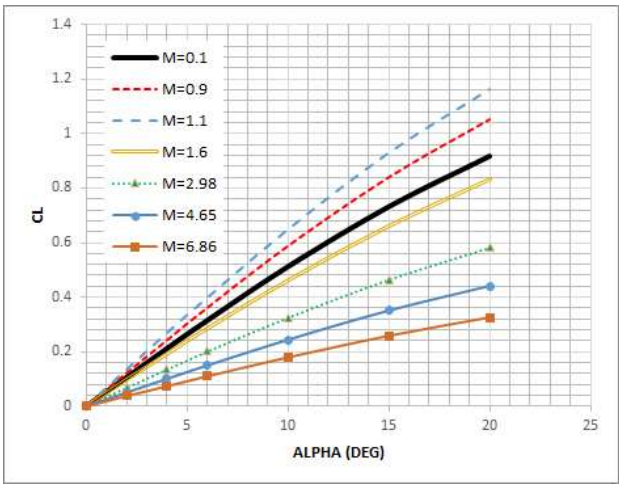

FIGURE 9 – CL vs alpha from VORLAX "cocktail" aero database

Table 1 Buffet CL

Mach	CLmax
0.1	0.488
0.6	0.411
0.9	0.360

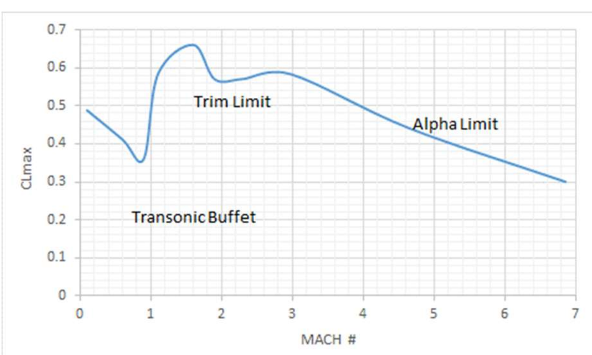

FIGURE 10 – *CLmax* vs Mach # from VORLAX "cocktail" aero database. *CLmax* limited by stall, transonic buffet, longitudinal trim (-30º< δelev <+30º and/or maximum angle-of-attack (α<20º) limits.

The "front side" acceleration potential is:

$$ACCEL_{FS} \approx {19.078\,\frac{(T-C\quad q\,Sref\,)}{W}}\Big/_{TURNRATE} \tag{8}$$

where $ACCEL_{FS}$ is in KTAS/deg-heading-change, thrust, T, is given in lbf, dynamic pressure, q, in lbf/ft^2 and wing reference area, *Sref*, in ft^2. *CD* reflects flight at *CLmax* as limited by structure, stall and/or buffet limits. TURNRATE is calculated using Eqn [5] in terms of degrees-heading-change per second.

IV. Developing the X-15 Aerodynamic Database

For this paper, we will study the implied turn performance of the North American X-15 rocketplane.

In order to estimate kinematic performance, we need a basic aero database. The contents of this database consist of tables of trimmed Lift and Drag as a function of Mach Number and angle-of-attack as well as a "Reynolds Number Correction" term for drag which is a function of Mach Number and Altitude.

Our main aerodynamic database derives from a cocktail approach using a Vortex Lattice model [17] of the X-15 in the small ventral tail configuration; see FIGURE 8. VORLAX is a vortex lattice potential flow solving CFD code written in FORTRAN [17] and recently received updates that drastically improve performance. [18] VORLAX develops influence coefficients for both subsonic and supersonic leading edge flow. We note that its supersonic model only accounts for shock waves developed at the leading and/or trailing edges; as such it is valid for "slender" shapes that do not develop off-body standing shock waves. In addition, VORLAX solutions fundamentally neglect thickness effects, and as such will under-predict the directional stabilizing effect of the X-15 wedge tail. It also cannot capture any sort of "real-gas-effects" of high temperature air. Despite these limitations, we demonstrate here how well it captures the essential aerodynamic properties of the X-15 from subsonic through the hypersonic.

Table 2 Vortex Lattice Zero-Lift Drag Correction

Mach	C_{D0}
0.1	0.054
0.7	0.06
0.9	0.07
1.1	0.13
1.6	0.09
1.9	0.08
2.29	0.07
2.98	0.06
4.65	0.045
6.86	0.035

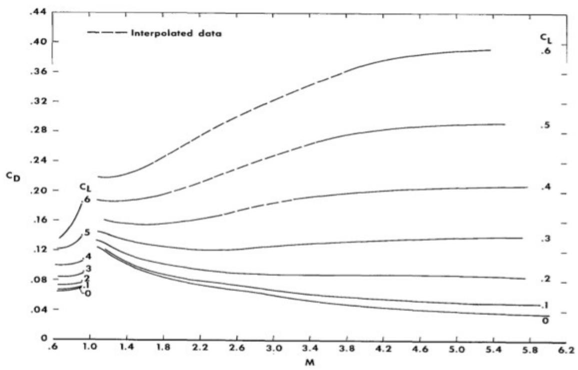

FIGURE 11 – *CD(CL, M*) from NASA TN D-3343 [20]

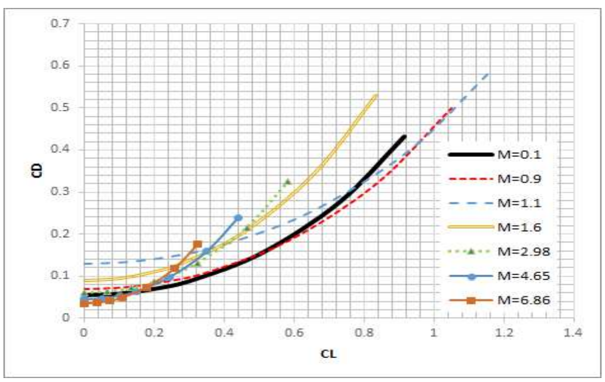

FIGURE 12 – *CD* vs α from VORLAX "cocktail" aero database (VORLAX with zero-lift-drag offset to match Flight Test data)

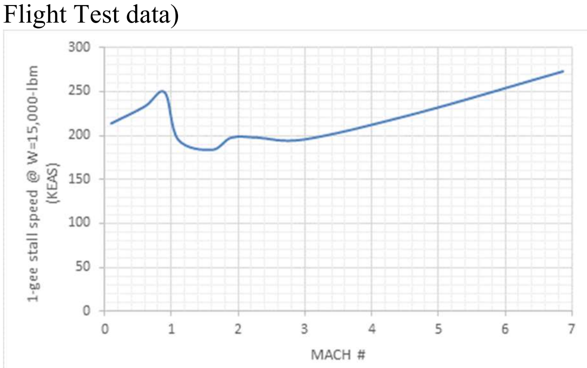

FIGURE 13 – 1-gee stall speed of the X-15 at *W*=15,000-lbm. *CLmax* follows the trend shown in FIGURE 10.

We built our X-15 aerodynamic database around our VORLAX model. FIGURE 9 plots VORLAX derived estimates of "trimmed" *CL* vs α; *Sref*=197.5-ft^2.

The maximum lift coefficient attained by the X-15 is governed by several physical phenomena. At low speeds, *CLmax* is governed by classical stall. At transonic speeds, by shock-wave induced flow separation ("buffet"). At supersonic and hypersonic speeds, it is limited by longitudinal trim capability (i.e. trimming with no more than 30^o elevator deflection) and/or angle of attack limits (i.e. trimming at no more than 20^o vehicle angle of attack). We used an EDET [19] model of the X-15 to establish buffet limits; see TABLE 1. The combined limits on *CLmax* as a function of Mach Number may be seen in FIGURE 10.

The *CD* values derive from both the Vortex Lattice model and a semi-empirical zero-lift drag correction. Altitude dependent Reynolds Number corrections, Δ*CD(*M,ALT), are derived from an EDET model of the X-15. [19] Basic zero-lift-drag corrections derive from Saltzman & Garringer [20] and Saltzman [21]; see Table 2 and FIGURE 11.

The "cocktail" database results for CL vs CD are shown in FIGURE 12

Propulsion system data is expressed as classic "five-column data;" that is thrust and thrust specific fuel consumption (TSFC) which are defined as functions of Mach number, altitude and power level angle (PLA). Data for the X-15's XLR-99 engine has been compiled by Maher, et al. [22] Absent a clear understanding of the minimum throttle characteristics of the rocket, this paper assumes that the XLR-99 can be fully throttled from zero to maximum thrust. We treat the smaller XLR-11 used in early X-15 test flights as a 30% thrust scale version of the XLR-99.

Griffin & Takahashi [13] demonstrated that this aerodynamic database, when used to drive a time-step integrating mission-performance code, closely matches the reported trajectories of a number of X-15 flights.[22] In this paper, the same data is used to compute instantaneous and sustained maneuverability capabilities.

V. X-15 Gliding Flight Maneuverability & Agility

We may now consider the gliding flight envelope of the X-15 aircraft at a flight weight, W=15,000-lbm. This represents the airframe with propellant tanks empty.

Particularly during ascent, pilots flew the X-15 along an essentially non-lifting, ballistic trajectory (CL~0).

During exo-atmospheric and re-entry conditions at very high altitudes, pilots flew the X-15 on a "quasi-ballistic" trajectory where ($L<W$). This sort of option is inevitable when the aircraft flies below its 1-gee stall speed; see FIGURE 13.

Consider for the X-15 at M=4.65, where *CLma*x ~ 0.441, it's 1-gee stall speed at W=15,000-lbm is ~225 *KEAS*. For "astronaut's wings" flights, the X-15 was flown out to the far edges of the atmosphere, where *KEAS* fell below 20-knots. [1][23] Over-the-top of those trajectories, even with the nose elevated to α=20-deg, wing lift would not begin to balance weight. Gliding and turning flight would have to await re-entry, where the aircraft was flying deeper into the atmosphere and dynamic pressure is great enough to allow the wings to develop enough lift to build appreciable load factor.

FIGURE 14 shows a "skymap" plot of the trimmed aerodynamic efficiency (L/D) of the X-15 at a typical re-entry weight plotted as a function of speed (Mach number) and pressure altitude (ft). We can see that a large portion of the flight envelope exceeds the 1-gee gliding capability of the airframe. For example, at M=4.5, gliding flight cannot be attained when ALT> 115,000-ft. At lower speeds, the maximum gliding altitude declines appreciable; at M=2.0 the X-15 cannot glide where ALT>80,000-ft. We see that the peak aerodynamic efficiency trends to occur at an altitude in between the high altitude CLmax limit and the low altitude maximum dynamic pressure limit.

Turn next to FIGURE 15 (overleaf) to consider the implied instantaneous gee capability of the X-15. Even modest turn capability, such as *nZ*=2-gees at M=3.3 can only be attained where ALT<90,000-ft. The aircraft aerodynamics reach its structural limit only at relatively low speeds and altitudes; ex. M=1.6 / ALT=35,000-ft. Thus, from the point of view of a traditional V-n diagram, the X-15's *VA* speed is above its 550-*KEAS VD* speed over almost the entire flight envelope.

	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																						2.2	2.3
90000																			2.1	2.2	2.4	2.6	2.7
85000																	2.3	2.5	2.4	2.5	2.4	2.6	2.7
80000														2.4	2.2	2.4	2.4	2.5	2.4	2.5	2.6	2.6	2.6
75000												2.3	2.4	2.3	2.2	2.4	2.6	2.6	2.5	2.4	2.3	2.3	2.3
70000										2.9	3.2	2.2	2.5	2.6	2.4	2.4	2.3	2.3	2.2	2.2	2.1	2.1	2.0
65000									2.9	2.9	2.8	2.4	2.4	2.2	2.1	2.1	2.1	2.1	2.0	1.9	1.8	1.7	1.7
60000								2.7	2.6	2.6	2.6	2.1	2.1	2.1	2.0	1.9	1.8	1.7	1.7	1.6	1.5	1.5	1.4
55000							2.5	2.3	2.3	2.2	2.2	1.9	1.8	1.8	1.6	1.6	1.5	1.5	1.4	1.3	1.2	1.2	1.1
50000						2.9	2.2	2.1	2.0	1.9	1.8	1.6	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.1			
45000						2.5	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0						
40000					3.2	2.3	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.0	0.9								
35000				3.2	3.0	1.9	1.3	1.2	1.1	1.0	1.0	0.9	0.8										
30000			3.5	3.1	2.6	1.6	1.1	1.0	0.9	0.8													
25000		3.6	3.4	2.7	2.2	1.3	0.9																
20000		3.3	3.0	2.4	1.9	1.1																	
15000	3.6	3.2	2.7	2.0	1.5	0.9																	
10000	3.4	2.8	2.4	1.7	1.3																		
5000	3.3	2.6	2.0	1.4	1.1																		
0	2.9	2.3	1.7	1.2																			

	2.8	2.9	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5
125000																							
120000																							
115000																		2.6	2.8	2.1	2.2	2.3	2.3
110000											2.5	2.5	2.4	2.6	2.8	3.0	3.2	3.3	3.3	2.3	2.5	2.6	2.7
105000						2.1	2.3	2.3	2.4	2.6	2.8	2.9	3.0	3.0	3.0	2.8	3.0	3.1	3.2	2.6	2.5	2.4	2.5
100000		2.4	2.1	2.2	2.2	2.4	2.6	2.7	2.8	2.8	2.6	2.8	2.9	3.0	3.1	3.1	3.1	3.1	3.1	2.6	2.6	2.6	2.6
95000	2.6	2.8	2.4	2.6	2.6	2.6	2.5	2.6	2.8	2.8	2.9	2.9	2.9	2.9	2.8	2.6	2.7	2.7	2.7	2.4	2.4	2.3	2.3
90000	2.6	2.7	2.4	2.5	2.6	2.7	2.7	2.7	2.7	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.5	2.4	2.4	2.1	2.1	2.1	2.1
85000	2.8	2.8	2.6	2.6	2.5	2.5	2.4	2.4	2.4	2.4	2.3	2.3	2.2	2.2	2.1	2.1	2.0	2.0	2.0	1.8	1.8	1.8	1.7
80000	2.5	2.4	2.3	2.3	2.3	2.2	2.2	2.1	2.1	2.0	1.9	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.7	1.6	1.5	1.5	1.5
75000	2.3	2.2	2.1	2.0	2.0	1.9	1.8	1.8	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4						
70000	1.9	1.9	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.3											
65000	1.6	1.6	1.5	1.4	1.4	1.3	1.3	1.2															
60000	1.3	1.3	1.2	1.2																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 14 – L/D ratio of the the X-15 at W=15,000-lbm limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max~+7.5-gees). 1-gee gliding flight.

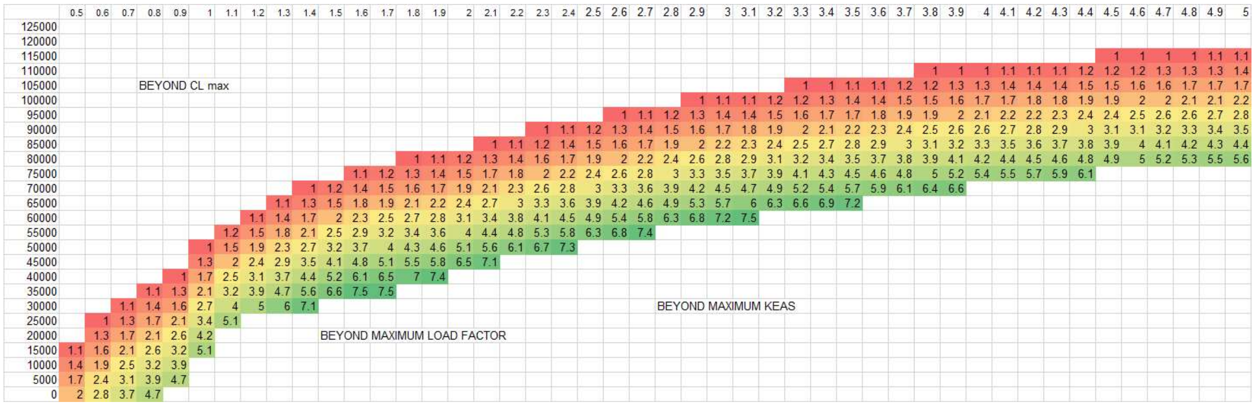

FIGURE 15 – Instantaneous Gee Capability of the X-15 at W=15,000-lbm limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max~+7.5-gees). Capability in gees.

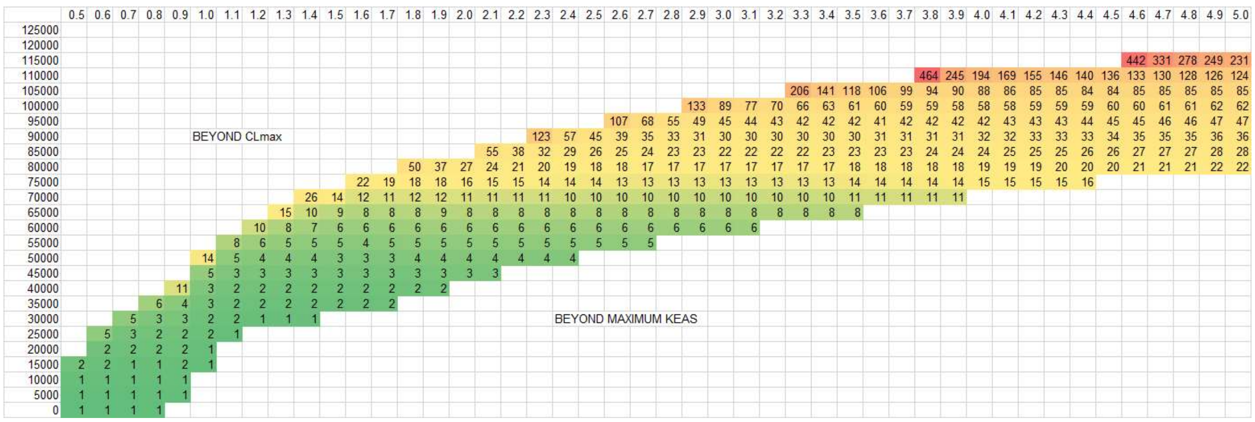

FIGURE 16 – Implied instantaneous turn radius capability of the X-15 at W=15,000-lbm limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max~+7.5-gees). Turn Radius in nM.

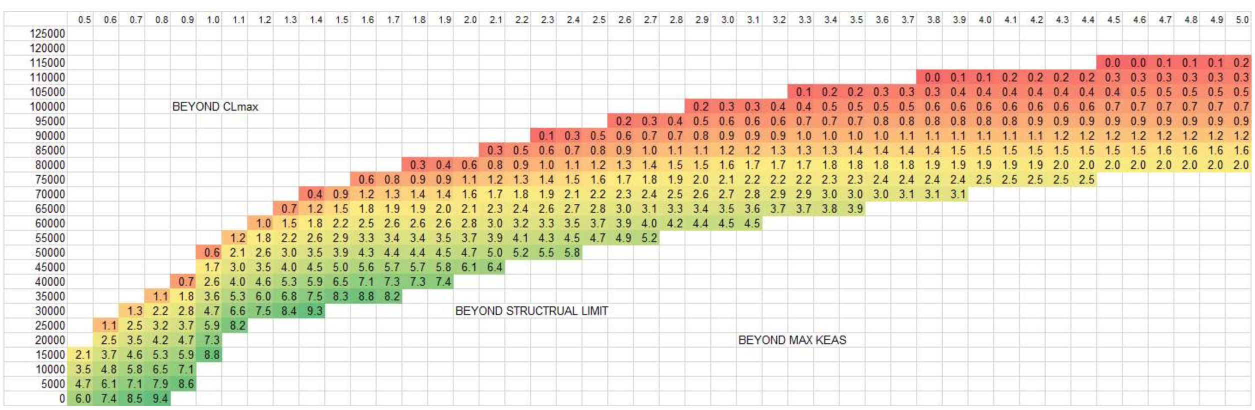

FIGURE 17 – Implied instantaneous heading rate change capability of the X-15 at W=15,000-lbm limited by dynamic pressure (*KEAS* < 550-KNOTS) and structural limits (*nZ*max~+7.5-gees). Heading Rate Change in compass-deg/sec.

FIGURE 16 shows the implied instantaneous turn radius of the X-15 at a typical re-entry weight plotted as a function of speed (Mach number) and pressure altitude (ft). Returning to that 2-gee turn point at M=3.3/ALT=90,000-ft, we can now see that a 2-gee turn at this speed implies a turn with radius ~ 30-nM.

FIGURE 17 shows the implied instantaneous heading rate change capability of the X-15 at a typical re-entry weight plotted as a function of speed (Mach number) and pressure altitude (ft). Returning once again to that 2-gee turn point at M=3.3/ALT=90,000-ft, we can now see that a 2-gee turn under these circumstances implies only 1-compass-degree per second change in heading.

These quasi-steady parameters may prove optimistic. Consider that the most aggressive heading rate change capability exists along the "bottom" of the skymap; at the maximum *KEAS* operating point. If, for example, we were to attempt a maximum gee turn at M=5/ALT=75,000-ft; the airframe could develop *nZ*=+5.6-gees of load factor. Yet this still implies only a 2-compass-degree per second change in heading. Consequently, any appreciable heading change will take a considerable amount of time, with a hypersonic *L/D* of ~2 at *CLmax* the X-15 must descend rapidly – so such a turning maneuver instigated near the maximum *KEAS* operating point must bleed off airspeed (and hence *KEAS*) rather than altitude to keep the airframe within its structural limits. As the airframe bleeds off *KEAS* without a loss of altitude, its heading rate change capability diminishes.

VI. X-15 Powered Flight Maneuverability & Agility

In this section, we will discuss the instantaneous and sustained turn capability of the X-15 under powered flight. We consider flight with the 18,000-lbf static thrust XLR-11 and the 54,000-lbf static thrust XLR-99 rocket motor. [1]

A. Maneuvering Capability at Light Weights, with the XLR-11 Rocket

At zero-fuel weight, the X-15 weighs about 15,000-lbm. Thus, powered flight performance at this weight represents the ultimate maneuvering capability of the airframe at motor cut-out.

Because the instantaneous turn capability of the airframe does not depend on thrust, the turn capability implied by FIGUREs 15,16 and 17 equally applies to powered flight. However, under full rocket power, we can assess the velocity gained or lost during a maximum effort "wind up turn." If we examine FIGURE 18, we can see plots of the front side acceleration potential of an XLR-11 powered X-15 aircraft at this light flight weight. Positive values indicate an ability to accelerate the airframe during maneuvering flight at *CLmax*; negative values indicate how the airframe will decelerate during the same conditions. If we return to the case discussed above, that is a maximum gee wind up turn at M=5/ALT=75,000-ft under full power from the XLR-11 rocket; the airframe could develop *nZ*=+5.6-gees of load factor. Yet this still implies only a 2-compass-degree per second change in heading. Even under full thrust, the airframe will still lose 14 knots true-air-speed per second (*dM/dt* ~ 0.02 /sec). Thus, even a modest 30-degree heading change under full rocket thrust implies an ~15 second maneuver where the airframe would lose M~0.4 in speed; i.e. decelerate from M~5.0 to M~4.6.

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																						75	48
90000																				46	26	21	17
85000																	51	29	21	16	13	11	9.3
80000														52	33	21	15	13	8.8	7.4	5.8	4.9	3.8
75000												22	16	15	11	9.2	6.8	6.5	3.7	2.6	1.6	0.9	0.2
70000										43	18	8.6	8.2	7.8	5.8	4.1	3.1	2.2	-0	-1	-1	-2	-3
65000									23	13	9.4	3.5	3.8	3.4	1.6	1.1	-0	-1	-3	-3	-4	-4	-5
60000								16	9.4	6.8	4.8	0.5	0.5	0.5	-1	-2	-2	-3	-4	-5	-5	-6	-6
55000							12	7.2	5.1	3.8	2.6	-1	-2	-1	-3	-4	-4	-5	-6	-6	-7	-7	-7
50000						28	6	3.9	2.6	1.7	0.7	-3	-3	-3	-5	-5	-5	-6	-7	-7			
45000						8.7	3	1.9	1	0.1	-1	-4	-4	-4	-5	-6	-6						
40000					25	4.7	1.4	0.4	-0	-1	-2	-5	-5	-5	-6								
35000				16	8.6	2.6	0.1	-1	-1	-2	-2	-5	-5										
30000			13	7	4.9	1.2	-1	-2	-2	-3													
25000		16	6.4	4.2	2.9	0.1	-2																
20000		6.3	4	2.6	1.6	-1																	
15000	7.8	3.7	2.5	1.5	0.6	-1																	
10000	4.1	2.5	1.6	0.7	-0																		
5000	2.7	1.5	0.9	0.1	-1																		
0	1.8	0.9	0.3	-0																			

	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																							
120000																							
115000																							71
110000														78	76	79	73	51	53	36	39	42	37
105000							77	72	50	47	48	34	35	34	31	34	31	33	25	16	14	16	18
100000		79	41	46	31	34	25	23	25	23	20	19	18	18	18	17	15	15	14	6.4	4.9	7.1	5.8
95000	35	27	15	18	16	13	12	14	11	11	11	11	10	9.5	6.8	6.2	5.7	7.5	7.1	-3	-1	-1	-2
90000	16	14	7.7	7.1	6.6	5.6	5.2	4.9	4.6	4	3.7	3.5	3.9	3.4	2.9	0.7	0.7	0.7	2.3	-6	-7	-7	-7
85000	7.5	7.2	0.7	0.9	0.9	1	-1	-0	-0	-0	-0	-0	-1	-1	-2	-2	-4	-3	-3	-11	-11	-10	-10
80000	2.8	2.1	-4	-3	-4	-3	-4	-3	-4	-4	-3	-4	-4	-4	-5	-6	-7	-6	-5	-15	-14	-14	-14
75000	-0	-1	-6	-6	-6	-7	-7	-7	-6	-6	-6	-7	-7	-7	-7	-7	-9						
70000	-3	-4	-9	-8	-8	-9	-8	-9	-8	-8	-9	-8											
65000	-5	-5	-10	-10	-10	-10	-10	-10															
60000	-7	-7	-11	-11																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 18 – Implied speed gain or loss in true airspeed due to flight at CLmax for the X-15 at W=15,000-lbm under full thrust from the XLR-11 rocket motor. Performance limited by dynamic pressure (*KEAS* < 550-KNOTS) and structural limits (*nZ*max~+7.5-gees). Airpseed gain (+) or loss (-) in terms of KTAS/sec.

FIGURE 19 – Sustained Gee Capability of the X-15 at W=15,000-lbm with an XLR-11 rocket motor. Performance limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max~+7.5-gees). Capability in gees.

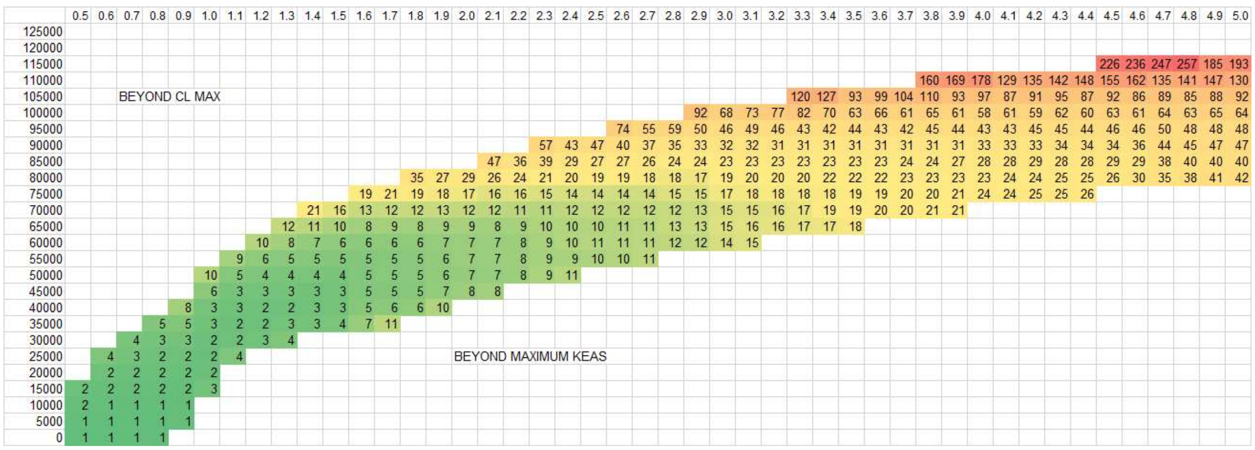

FIGURE 20 – Sustained Turn Radius of the X-15 at W=15,000-lbm with an XLR-11 rocket motor. Performance limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max~+7.5-gees). Radius in NM.

Turning next to FIGURE 19, we can see the sustained gee capability of the X-15 at typical re-entry weight. Compare and contrast these results with the peak instantaneous turn capacity shown above in FIGURE 15, above. Here we see that the XLR-11 rocket motor has sufficient thrust to overcome the drag at that M=3.3/ALT=90,000-ft turn point; that *nZ*~+2-gee aerodynamically limited maximum load factor can be maintained without loss of speed or altitude. At lower altitudes, drag will eventually exceed thrust. For example, at M=3.0/ALT=60,000-ft, the X-15 can develop a maximum instantaneous load factor of *nZ*~+5.7-gees (referring to FIGURE 15) but can only sustain *nZ*~+3.2-gees (referring to FIGURE 19) without loss of speed or altitude.

FIGURE 20 shows the sustained turn capability of the X-15 at a typical re-entry weight. Returning to that 2-gee turn point at M=3.3/ALT=90,000-ft, we can now see that a 2-gee turn at this speed implies a turn with radius ~ 30-nM without loss of speed or altitude. At M=3.0/ALT=60,000-ft the instantaneous turn capability implies a turn with an ~8-nM radius (refer back to FIGURE 16) and a sustained turn capability with a much broader ~14-nM radius.

FIGURE 21 (overleaf) shows the implied sustained heading rate change capability of the X-15 at a typical re-entry weight. Returning once again to the M=3.0/ALT=60,000-ft flight condition, we can now see that the sustained turn capability of the airframe enables at 1.9-compass-degree per second change in heading; considerably less than its instantaneous 3.5-compass-degree per second change capability (refer back to FIGURE 17).

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																						0.3	0.4
90000																			0.3	0.5	0.4	0.5	0.6
85000																	0.4	0.5	0.5	0.7	0.8	0.9	0.9
80000														0.4	0.6	0.6	0.7	0.8	1	1	1.2	1.2	1.3
75000												0.7	0.7	0.8	0.9	1	1.2	1.2	1.4	1.5	1.6	1.7	1.8
70000										0.6	0.8	1.1	1.2	1.3	1.3	1.5	1.6	1.7	1.9	1.9	1.9	1.9	1.9
65000									0.9	1.1	1.4	1.7	1.8	1.9	1.9	2	2.2	2.2	2.1	2.1	2.2	2.2	2.2
60000								1	1.4	1.8	2.2	2.4	2.5	2.6	2.4	2.4	2.5	2.6	2.3	2.1	2.1	2.2	2.2
55000							1.1	1.7	2.1	2.5	2.9	2.9	3	3.1	2.7	2.4	2.5	2.5	2.4	2.4	2.3	2.3	2.1
50000						0.8	1.9	2.5	3	3.4	3.8	3.1	2.9	2.9	2.7	2.6	2.7	2.6	2.2	2			
45000						1.5	3	3.4	3.9	4.5	4.6	3.2	3.2	3.2	2.6	2.3	2.2						
40000					0.9	2.6	3.9	4.6	4.9	4.8	4.7	2.8	2.8	2.5	1.7								
35000				1.5	1.7	3.5	5.2	5.1	4.1	3.9	3.7	2	1.3										
30000			1.7	2.2	2.5	4.6	4.2	3.8	2.7	0.6													
25000		1.3	2.1	3.1	3.7	5.9	2.4																
20000		2.4	3.4	4.1	4.7	5																	
15000	2.3	3.6	4.6	5.2	5.8	3.4																	
10000	3.3	4.6	5.6	6.5	7.1																		
5000	4.6	6.1	7	7.9	6.4																		
0	5.7	7.2	8.4	7.3																			

	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																							
120000																							
115000																		0.1	0.1	0.1	0.1	0.2	0.2
110000											0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
105000						0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.5	0.5	0.5
100000		0.2	0.4	0.3	0.3	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.7	0.7	0.7
95000	0.4	0.5	0.6	0.5	0.6	0.7	0.7	0.7	0.7	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.8	0.9	0.9	0.9
90000	0.7	0.8	0.8	0.9	0.9	0.9	1	1	1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.1	1	0.9	0.9	0.9
85000	1	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.1	1.1	1.1	1.1
80000	1.4	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.4	1.2	1.1	1	1.1
75000	1.6	1.7	1.5	1.5	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.6	1.5	1.5	1.5	1.5	1.5						
70000	2	2	1.8	1.8	1.8	1.8	1.6	1.6	1.6	1.6	1.6	1.6											
65000	1.9	1.9	1.7	1.8	1.8	1.8	1.8	1.7															
60000	2.2	2.2	1.9	1.8																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 21 – Implied sustained heading rate change capability of the X-15 at W=15,000-lbm lbm with an XLR-11 rocket motor. Performance limited by dynamic pressure (*KEAS* < 550-KNOTS) and structural limits (*nZ*max~+7.5-gees). Heading Rate Change in compass-deg/sec.

B. Maneuvering Capability at Heavy Weights, with the XLR-11 Rocket

Fully fueled, the X-15 weighed about 35,000-lbm. Thus, powered flight performance at this weight represents the maneuvering capability of the airframe early in its mission.

The instantaneous turn capability of the airframe degrades considerably with the increase in flight weight; see FIGUREs 22, 23 and 24 (overleaf). Firstly, the structural limits in terms of load factor are considerably reduced; *nZ*max is now limited by structural strength to +3.0-gees while the 550-*KEAS* (1,000-lbf/ft2) dynamic pressure limit remains in place. Together these two terms greatly restrict the gliding flight envelope; at any given speed the difference between the altitude limited by stall and that by maximum dynamic pressure holds at around 20,000-ft. For example, at M=2.8, if the X-15 could just attain *nZ*=+1.0 gliding flight at ALT=80,000-ft, the maximum dynamic pressure limit engages when ALT<60,000-ft. This holds both gliding and maneuvering flight into a narrow "window" in the skymap.

FIGURE 22 shows a "skymap" plot of the instantaneous gee capability of the X-15 with full fuel. As with the light weight analysis, above, we see once again that the X-15's *VA* speed is above its 550-*KEAS VD* speed over almost the entire flight envelope.

	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000							BEYOND CL MAX																
85000																							
80000																							
75000																					1	1.1	1.2
70000																		1	1.1	1.2	1.3	1.4	1.5
65000																1	1.1	1.2	1.4	1.5	1.6	1.8	1.9
60000												1	1	1.1	1.2	1.3	1.4	1.6	1.7	1.9	2.1	2.3	2.5
55000											1	1.2	1.3	1.4	1.5	1.7	1.9	2	2.2	2.4	2.7	2.9	3
50000										1.1	1.3	1.6	1.7	1.8	1.9	2.1	2.4	2.6	2.9	3			
45000								1	1.2	1.5	1.7	2	2.2	2.3	2.5	2.7	3						
40000							1	1.3	1.6	1.9	2.2	2.6	2.8	3					BEYOND STRUCTURAL LIMIT				
35000							1.3	1.6	2	2.4	2.8												
30000						1.1	1.7	2.1															
25000						1.4																	
20000					1.1	1.8																	
15000				1.1	1.3																		
10000			1.1	1.3	1.6			BEYOND MAXIMUM KEAS															
5000		1	1.3	1.6	2																		
0		1.2	1.6	2																			

	2.8	2.9	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																1	1	1	1	1.1	1.1	1.1	1.2
90000										1	1	1.1	1.1	1.1	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5
85000				1	1	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.7	1.7	1.8	1.8	1.9
80000	1	1.1	1.2	1.2	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.8	1.9	2	2	2.1	2.1	2.2	2.2	2.3	2.4
75000	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9	2	2	2.1	2.2	2.3	2.3	2.4	2.5	2.6						
70000	1.6	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8											
65000	2.1	2.2	2.4	2.5	2.7	2.8	2.9	3					BEYOND MAXIMUM KEAS										
60000	2.7	2.9	3	3																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 22 – Instantaneous Gee Capability of the X-15 at W=35,000-lbm limited by dynamic pressure < 1000-lbf/ft^2 (*KEAS* < 550 knots) and structural limits (*nZ*max ~ +3-gees). Capability in gees.

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																																														
120000																																														
115000																																														
110000																																														
105000																																														
100000																																														
95000																																								285	246	222	204	192	184
90000																																245	179	152	138	129	123	118	115	113	112	111	110	109	108
85000																											146	112	97	89	83	80	77	76	75	74	73	73	73	74	74	74	75	75	75
80000																							119	78	65	60	57	54	53	52	51	51	51	51	51	51	51	52	52	53	53	54	54	55	55
75000																				96	60	49	44	40	38	37	37	36	36	36	36	36	36	37	37	37	38	38	39							
70000																	112	51	40	34	31	29	28	27	26	26	26	26	26	26	27	27	27	28												
65000															50	34	28	25	23	22	21	20	20	19	19	19	19	20	20	21																
60000											97	33	26	24	21	19	18	17	16	16	15	15	15	15	15	16																				
55000										24	15	15	14	14	14	13	13	12	12	12	12	12																								
50000									15	11	10	10	10	10	10	10	9	9	10																											
45000							21	10	8	7	7	7	7	7	7	7																														
40000						13	8	6	6	5	5	5	5																																	
35000						6	5	5	4	4																																				
30000					8	4	4																																							
25000					5																																									
20000				8.8	3.6																																									
15000			6.7	4.9																																										
10000		6	3.9	3.6																																										
5000		9.1	3.4	2.9	2.8																																										
0		3.2	2.5	2.3																																											

FIGURE 23 – Instantaneous Turn Radius Capability of the X-15 at W=35,000-lbm limited by dynamic pressure < 1000-lbf/ft^2 (*KEAS* < 550 knots) and structural limits (*nZ*max ~ +3-gees). Radius in NM.

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																																														
120000																																														
115000																																														
110000																																														
105000																																														
100000																																														
95000																																						0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2
90000																																0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4
85000																										0.0	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6
80000																							0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8
75000																				0.2	0.3	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0							
70000																	0.1	0.4	0.5	0.6	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2												
65000															0.3	0.5	0.7	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.5	1.5	1.5																
60000											0.1	0.4	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.7	1.7																				
55000										0.5	0.9	1.0	1.1	1.1	1.3	1.4	1.5	1.7	1.8	1.9	2.0	1.9																								
50000									0.8	1.2	1.5	1.6	1.6	1.7	1.8	1.9	2.1	2.2	2.2																											
45000							0.5	1.1	1.5	1.8	2.1	2.2	2.2	2.3	2.4	2.5																														
40000						0.7	1.4	1.8	2.2	2.5	2.8	2.9	2.9																																	
35000						1.6	2.1	2.6	3.0	3.3																																				
30000					1.1	2.4	2.9																																							
25000					1.9																																									
20000				1	2.6																																									
15000			1.1	1.8																																										
10000		1.1	2	2.5																																										
5000		0.6	2.1	2.8	3.2																																										
0		2	2.9	3.6																																											

FIGURE 24 – Instantaneous Heading Rate Change Capability of the X-15 at W=35,000-lbm limited by dynamic pressure < 1000-lbf/ft^2 (*KEAS* < 550 knots) and structural limits (*nZ*max ~ +3-gees). Heading Rate Change in compass-deg/sec.

FIGURE 23 shows the implied instantaneous turn capability of the X-15 at heavy flight weight. Recall, at light weights M=3.3/ALT=90,000-ft implied a 2-gee turn capability. Note that this altitude now lies far above the ability for the airframe to attain a 1-gee level glide, let alone develop a gliding turn. To attain a gliding turn with radius ~ 30-nM at the heavy weight, the X-15 must now descend to ALT~72,000-ft. At higher speeds and altitudes, the radii grow larger. FIGURE 24 (prior page) shows the instantaneous heading-rate change capability of the X-15 at heavy flight weight. At M=3.3/ ALT~72,000-ft the X-15 can change course at ~1.1-compass-deg/sec. At higher speeds, performance degrades further; at M=5.0 / ALT=75,000-ft, it has ~0.8-compass-deg/sec ability to change course.

Once again, we can examine the velocity gained or lost during a maximum effort "wind up turn." Turning next to FIGURE 25 (overleaf), we can see envelope of the front side acceleration potential of an XLR-11 powered X-15 aircraft at heavy flight weight. Considering a maximum gee wind up turn at M=5/ALT=75,000-ft under full power from the XLR-11 rocket; the airframe could develop *nZ*=+2.4-gees of load factor and a ~0.8-compass-deg/sec heading rate change while losing 14 KTAS per second (*dM/dt* ~ 0.02 /sec). Thus, even a modest 30-degree heading change under full rocket thrust implies an ~40 second maneuver where the airframe would lose considerable speed.

Now consider FIGURE 26 (overleaf), we can see the sustained gee capability of the X-15 at a heavy flight weight.. Compare and contrast these results with the peak instantaneous turn capacity shown above in FIGURE 22, above. Here we see that the XLR-11 rocket motor lacks thrust to overcome drag at the M=5.0/ALT=75,000-ft turn point. Nowhere in the flight envelope can the X-15 even attain 2-gees of sustained turn capability.

FIGURE 27 (overleaf) shows the implied sustained turn radius of the X-15 at heavy weights; FIGURE 28 (overleaf), shows the sustained heading rate change capability. Note that turn radii exceed 50-nM at speeds in excess of M~3.2; and sustained heading rate change similarly falls below 0.5-compass-deg/sec at these speeds. These charts show that the maneuverability of the X-15 would improve greatly with a larger engine.

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000																							
85000																							
80000																							
75000																					6.5	2.5	0.4
70000																		15	0	-1	-2	-3	-3
65000																5.2	2	0.7	-3	-4	-4	-5	-5
60000												2.3	4.7	2.5	-2	-2	-2	-3	-5	-5	-6	-6	-7
55000											7.9	-1	-1	-1	-3	-4	-5	-4	-6	-6	-7	-7	-8
50000										3.8	1.7	-4	-3	-3	-4	-5	-6	-6	-8	-8			
45000								6.4	1.9	0.1	-0	-4	-4	-4	-6	-6	-7						
40000							4.1	0.8	-0	-1	-2	-6	-5	-5									
35000							0.5	-1	-1	-2	-2												
30000						2.4	-1	-2															
25000						0.4																	
20000					3.4	-1																	
15000				3.2	1.2																		
10000			3.6	1.1	0.1																		
5000		6.9	1.3	0.2	-1																		
0		1.4	0.4	-0																			

	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																	28	34	39	-8	0.2	3.3	-4
90000										23	24	9	9.4	8.5	4.6	4.2	0.2	3.2	5.6	-14	-7	-5	-8
85000					6	-0	2.9	-1	1.7	-1	0.4	-1	-1	-2	-4	-2	-4	-1	-3	-12	-15	-10	-12
80000	10	5	-6	-2	-4	-2	-4	-4	-3	-4	-5	-4	-5	-6	-5	-6	-6	-7	-5	-15	-12	-14	-14
75000	-1	-1	-8	-9	-5	-6	-7	-8	-7	-6	-7	-7	-8	-7	-7	-9	-10						
70000	-3	-5	-9	-10	-9	-9	-9	-8	-9	-9	-9	-9											
65000	-6	-5	-10	-10	-11	-10	-10	-10															
60000	-7	-7	-11	-10																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 25 – Implied speed gain or loss in true airspeed due to flight at CLmax for the X-15 at W=35,000-lbm under full thrust from the XLR-11 rocket motor. Performance limited by dynamic pressure (*KEAS* < 550-KNOTS) and structural limits (*nZ*max~+3.0-gees). Airpseed gain (+) or loss (-) in terms of KTAS/sec.

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000																							
85000																							
80000																							
75000																					1.1	1.2	1.2
70000																		1.1	1.2	1.2	1.1	1.2	1.3
65000																1.1	1.2	1.2	1.2	1.2	1.3	1.4	1.4
60000												1.1	1.1	1.2	1.2	1.3	1.4	1.3	1.3	1.2	1.3	1.3	1.4
55000											1.1	1.2	1.3	1.4	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4
50000										1.2	1.3	1.2	1.2	1.3	1.2	1.3	1.3	1.4	1.2	1.2			
45000								1.1	1.2	1.5	1.7	1.2	1.3	1.3	1.2	1.1	1.1						
40000							1.1	1.3	1.6	1.6	1.6	1.1	1.1	1.1									
35000							1.3	1.4	1.3	1.3	1.3												
30000						1.2	1.1	1.1															
25000						1.4																	
20000					1.2	1.3																	
15000				1.2	1.3																		
10000			1.2	1.3	1.6																		
5000		1.1	1.3	1.6	1.5																		
0		1.2	1.6	1.6																			

	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																1.1	1.1	1.1	1.1	1.0	1.2	1.2	1.2
90000										1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.1	1.1	1.1	1.2
85000				1.1	1.1	1.0	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.3	1.5	1.5	1.6	1.6	1.7	1.2	1.3	1.3	1.3
80000	1.1	1.2	1.2	1.2	1.1	1.3	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.6	1.6	1.6	1.7	1.7	1.3	1.3	1.3	1.3
75000	1.1	1.2	1.1	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.5	1.4	1.5	1.5	1.5	1.6						
70000	1.3	1.4	1.3	1.3	1.4	1.4	1.3	1.4	1.4	1.4	1.5	1.5											
65000	1.4	1.4	1.3	1.3	1.4	1.4	1.4	1.4															
60000	1.4	1.5	1.4	1.4																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 26 - Sustained Gee Capability of the X-15 at W=35,000-lbm with an XLR-11 rocket motor. Performance limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max~+3.0-gees). Capability in gees.

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000																							
85000																							
80000																							
75000																					66	49	53
70000																		51	38	42	66	49	42
65000																42	32	35	38	42	36	33	36
60000												27	30	23	26	23	22	28	31	42	36	39	36
55000											24	18	17	16	26	29	32	28	31	33	31	33	36
50000										14	13	18	21	19	26	23	25	24	38	42			
45000								15	12	8	8	18	17	19	26	42	46						
40000							13	8	6	8	9	27	30	34									
35000							7	7	10	11	13												
30000						8	13	16															
25000						5																	
20000					7	7																	
15000				6	6																		
10000			4	5	4																		
5000		5	4	3	4																		
0		3	2	3																			

	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000										148	156	114	119	125	132	138	115	121	126	239	249	259	187
85000							86	91	96	81	86	76	80	100	78	81	76	80	76	164	136	142	148
80000	84	62	66	71	109	64	85	90	76	81	72	76	70	73	69	72	76	72	75	130	135	141	147
75000	83	62	95	70	75	64	68	61	64	59	63	66	79	73	77	80	75						
70000	45	41	52	56	50	54	67	60	64	67	62	66											
65000	38	41	52	55	50	53	57	60															
60000	38	36	44	47																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 27 – Sustained Turn Radius Capability of the X-15 at W=35,000-lbm limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max ~ +3-gees). Radius in NM.

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000																							
85000																							
80000																							
75000																					0.3	0.4	0.4
70000																		0.3	0.5	0.5	0.3	0.4	0.5
65000																0.4	0.6	0.5	0.5	0.5	0.6	0.7	0.6
60000												0.5	0.5	0.7	0.6	0.7	0.8	0.7	0.6	0.5	0.6	0.6	0.6
55000											0.5	0.7	0.9	1	0.6	0.6	0.6	0.7	0.6	0.6	0.7	0.7	0.6
50000										0.9	1	0.7	0.7	0.8	0.6	0.7	0.7	0.8	0.5	0.5			
45000								0.7	0.9	1.5	1.7	0.7	0.9	0.8	0.6	0.4	0.4						
40000							0.7	1.3	1.8	1.7	1.5	0.5	0.5	0.4									
35000							1.4	1.5	1.2	1.1	1												
30000						1.2	0.7	0.7															
25000						1.7																	
20000					1.3	1.4																	
15000				1.4	1.6																		
10000			1.6	1.7	2.3																		
5000		1.2	1.9	2.6	2																		
0		1.8	2.9	2.5																			

	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000										0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.1	0.1	0.1	0.2
85000							0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.5	0.4	0.5	0.5	0.5	0.2	0.3	0.3	0.3
80000	0.3	0.4	0.4	0.4	0.2	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.3
75000	0.3	0.4	0.2	0.4	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.4	0.5						
70000	0.5	0.6	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.5											
65000	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5															
60000	0.6	0.7	0.6	0.6																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 28 – Sustained Heading Rate Change Capability of the X-15 at W=35,000-lbm limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max ~ +3-gees). Heading Rate Change in compass-deg/sec.\

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000																							
85000																							
80000																							
75000																					125	81	48
70000																		251	59	46	37	31	27
65000																84	49	35	26	23	20	17	15
60000												239	64	42	32	28	22	18	15	13	11	9.5	8.1
55000											55	25	23	21	18	14	12	11	7.9	6.7	5.4	4.6	4.6
50000										33	21	12	12	12	9.7	8.5	6.3	5.4	3.3	3			
45000								54	23	16	13	7	6.4	7	4.3	4	2.9						
40000							38	18	13	9.6	7.9	2.9	3	3.2	2.6								
35000							15	11	7.7	6	4.8	2.3	3.3										
30000						24	8.9	6.5	5.1	3.8	4.7												
25000						13	5.7	4.2	3.5														
20000					26	8.2	3.5	3.1															
15000				24	14	5.5	2.7																
10000			24	12	9.2	3.5																	
5000		43	12	8.1	6.4																		
0		12	7.9	5.7																			

	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																	265	271	275	228	118	121	114
90000										259	260	127	128	127	83	83	79	82	84	65	52	54	51
85000					124	118	82	78	81	58	59	58	58	46	44	46	44	46	44	35	33	30	28
80000	128	84	53	57	43	45	44	35	36	35	34	30	29	28	28	28	27	27	28	15	17	16	15
75000	47	38	26	25	24	24	23	22	19	20	20	19	19	17	16	14	14						
70000	23	22	14	14	13	13	12	11	11	11	11	11											
65000	14	13	6.7	7.1	5.1	5.5	5.8	5.9															
60000	7	6.1	2.5	4.3																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 29 – Implied speed gain or loss in true airspeed due to flight at CLmax for the X-15 at W=35,000-lbm under full thrust from the XLR-99 rocket motor. Performance limited by dynamic pressure (*KEAS* < 550-KNOTS) and structural limits (*nZ*max~+3.0-gees). Airpseed gain (+) or loss (-) in terms of KTAS/sec.

	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																							
90000																							
85000																							
80000																							
75000																					1.1	1.2	1.2
70000																		1.1	1.2	1.2	1.3	1.4	1.5
65000																1.1	1.2	1.2	1.4	1.5	1.6	1.8	1.9
60000												1.1	1.1	1.2	1.2	1.3	1.4	1.6	1.7	1.9	2.1	2.3	2.5
55000											1.1	1.2	1.3	1.4	1.5	1.7	1.9	2.0	2.2	2.4	2.7	2.9	3.0
50000										1.2	1.3	1.6	1.7	1.8	1.9	2.1	2.4	2.6	2.9	3.0			
45000								1.1	1.2	1.5	1.7	2.0	2.2	2.3	2.5	2.7	3.0						
40000							1.1	1.3	1.6	1.9	2.2	2.6	2.8	3.0	3.0								
35000							1.3	1.6	2.0	2.4	2.8	3.0	3.0										
30000						1.2	1.7	2.1	2.5	3.0	3.0												
25000						1.4	2.1	2.6	3.0														
20000					1.2	1.8	2.7	3.0															
15000				1.2	1.3	2.2	3.0																
10000			1.2	1.3	1.6	2.7																	
5000		1.1	1.3	1.6	2.0																		
0		1.2	1.6	2.0																			

	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0
125000																							
120000																							
115000																							
110000																							
105000																							
100000																							
95000																1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2
90000										1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.5
85000				1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.7	1.7	1.8	1.8	1.9
80000	1.1	1.2	1.2	1.2	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.8	1.9	2.0	2.0	2.1	2.1	2.2	2.2	2.3	2.4
75000	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9	2.0	2.0	2.1	2.2	2.3	2.3	2.4	2.5	2.6						
70000	1.6	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8											
65000	2.1	2.2	2.4	2.5	2.7	2.8	2.9	3.0															
60000	2.7	2.9	3.0	3.0																			
55000																							
50000																							
45000																							
40000																							
35000																							
30000																							
25000																							
20000																							
15000																							
10000																							
5000																							
0																							

FIGURE 30 - Sustained Gee Capability of the X-15 at W=35,000-lbm with an XLR-99 rocket motor. Performance limited by dynamic pressure (*KEAS* < 550 knots) and structural limits (*nZ*max~+3.0-gees). Capability in gees.

C. Maneuvering Capability at Heavy Weights, with the XLR-99 Rocket

We next consider the maneuvering performance of the fully fueled, the X-15 with the more powerful XLR-99 rocket. Analysis weight remains constant at 35,000-lbm to highlight the impacts of additional thrust.

The clear benefits of the larger rocket are immediately evident in the "wind up turn" plot. Examining FIGURE 29 (prior page), we can see envelope of the front side acceleration potential of an XLR-99 powered X-15 aircraft at heavy flight weight is positive all across its gliding flight envelope. FIGURE 30 (prior page) demonstrates how the sustained turn capability matches the instantaneous turn capability everywhere in the flight envelope. This is because the rocket has more than enough thrust to overcome drag at any *CL* anywhere in the wing-borne flight envelope. That said, the ability for the X-15 to rapidly make significant course changes remains severely limited at high speeds and altitudes.

VII. Summary & Conclusions

These plots show the very real maneuvering limitations of the X-15 rocket plane in either gliding or powered flight. Unlike maneuvering combat aircraft (i.e. F-16, F-18) or even lightly loaded transport category aircraft, which can attain 10-compass-degree-per-second turn capability, its high speed maneuverability is severely limited. Consider that the entire powered flight duration of an aircraft like the X-15 is measured in single digit minutes, relatively few course corrections can be made before it exhausts its propellant. In gliding flight, heading changes will directly impact downrange performance.

A very high thrust engine, like the XLR-99 (where T/W >> 1) helps maneuverability as it permits a turn without loss of speed or altitude.

These figures also show that maneuvering capabilities at high speeds improve as the aircraft descends in altitudes, although the best L/D for glide or endurance occurs at relatively high altitudes. In order to gain maneuvering capability, such an aircraft would need to be engineered to withstand the aerodynamic and aero-thermodynamic environments found where *KEAS* >> 1000-knots and would need a propulsion system capable of overcoming drag when the airframe is operated far below its best *L/D*.

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