Flying with Eyes Wide Shut - A Reflection on the Hollywood View of Real World Aircraft Performance

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This paper dissects the implied performance of both the "SR-72" and F/A-18E/F aircraft as depicted in Top Gun: Maverick. The overall configuration of the "SR-72," while flyable at subsonic speeds, is inappropriate for maneuvering flight at hypersonic speeds. In addition, the implied agility of both the "SR-72" and the USMC F/A-18E/F aircraft are unrealistically high. As aircraft flight speed increases, their agility in terms of both turn-radius and heading-rate-change-per-second decrease markedly.

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I. Introduction

TOP GUN / MAVERICK was one of 2022's most successful summer blockbuster films. As of October 23, 2022, Top Gun: Maverick has grossed $1.485 billion worldwide.[1] and is the highest-grossing film of Cruise's career. The film was widely praised by critics, with many citing the aviation sequences as the standout element, and deeming it superior to its predecessor. [2]

FIGURE 1 – The "Lockheed Skunk Works" fictionalized designers of the "SR-72" [3]

The plot of the film sees Tom Cruise reprise his youthful role as, the now 50-something, still buff, but increasingly craggy, Pete "Maverick" Mitchell. In the mid 1980's, United States Navy Captain Mitchell graduated from the TOPGUN strike fighter tactics instructor program at NAS Miramar in San Diego, CA. Shunning retirement from active duty, we see Mitchell working as an officer test pilot; his heroic yet erratic personality having held him back from flag rank and an associated desk job. Defying upper management in the face of imminent program cancellation, "Maverick" surreptitiously changes the flight plan in an upcoming test-flight of the hypersonic Lockheed Skunk Works "SR-72" scramjet aircraft and attempts to exceed the program's contract specification; see FIGUREs 1 and 2. The prototype is destroyed when its structure fails as "Maverick" pushes it beyond Mach 10. [4]


FIGURE 2 – Unauthorized take-off of the "SR-72" [4]

Once again, Mitchell's old rival, and now commanding officer, Tom "Iceman" Kazansky, saves Maverick's career ordering him to NAS North Island for his next assignment: to destroy an unsanctioned uranium enrichment plant in a rogue state in an "unannounced" attack. The target is located in a deep depression at the end of a canyon not far from the beach-head in arid region of the world. The site is defended by surface-to-air missiles (SAMs), GPS jammers, and some "fifth-generation fighters" that look a lot like Sukhoi Su-57s. Using a Navy cruise-missile barrage as a distraction, Mitchell plans to attack the target using two pairs of carrier launched F/A-18E/F Super Hornets. [4]

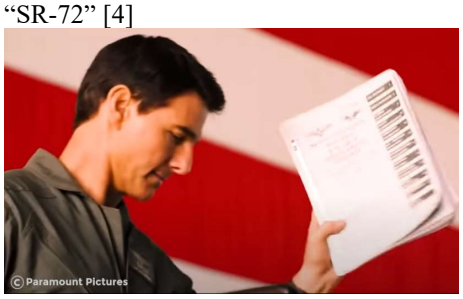

FIGURE 3 - Tom Cruise showing the kiddos how to "really" make friends with the aircraft performance engineers. [4]

To add dramatic tension, Mitchell learns that he is not supposed to take part in the strike; instead, he is to train an elite group of TOPGUN graduates. After Cruise throws the F/A-18E/F NATOPS in the trash can (see FIGURE 3), we watch an hour of dramatic in-flight footage where we learn that "old dogs" know "tricks" that today's youth cannot even conceptualize. At the same time, we learn that the training cohort has its own set of rivalries; these are aggravated when "Maverick" out flies his highly competitive but not-quite-battle-ready students which include the son of Mitchell's old back seat weapons officer Nick "Goose" Bradshaw, deceased. The further death of Kanzansky and a training accident which results in the crash of another F/A-18 (although without loss of life) further complicate matters for Mitchell. With his guardian angel gone, Mitchell is removed from duty. [4]

After his new Commanding Officer decides to relaxes the mission parameters to make the canyon run easier to fly, at the expense of greatly increased risk of interception during egress, "Maverick" decides to go rogue. Mitchell makes an unauthorized flight through the training course using his preferred "ignore the NATOPS" approach, proving that it can be done. [4]

In the end, Mitchell serves as the Rogue-One formation lead flying his bomb laden F/A-18E, accompanied by a two-seat F/A-18F. Bradley "Rooster" Bradshaw, the son of Mitchell's deceased buddy, leads the second strike pair in his F/A-18E along with a further F/A-18F. The teams successfully navigate the canyon run at "573 knots," destroy the plant but are engaged by SAMs during their escape. [4]

More drama ensues after "Rooster" runs out of countermeasures when "Maverick" sacrifices his jet to protect him. Eventually both "Maverick" and "Rooster" re-unite as they are both trapped behind enemy lines. Together they manage to commandeer a fully armed and fueled F-14 Tomcat and fight their way back home shooting down several enemy "fifth-generation fighters" along the way; see FIGURE 4. [4]

FIGURE 4 - Making it back home in a stolen F-14 [4]

In the coda, we see "Rooster" helping "Maverick" work on a P-51 Mustang. "Rooster" muses over a photo from their recent mission pinned alongside a photo of his late father and the young "Maverick" from the 1980s. Closing the film, Mitchell and his new/old girlfriend Penny fly off into the sunset in the P-51. [4]

All in all, I found the movie to be enjoyable as entertainment. The live action air-to-air combat scenes, filmed on real USMC F/A-18E/F aircraft are certainly preferred to CGI. At the same time, I find the "real footage" was framed within a story where considerable dramatic licence occurred regarding aircraft performance. Unlike some more hostile critiques, [5] I write this paper as a gentle, but serious, critique so that the engineering student (and possible future policy maker) will better grasp the blending of fact and fiction found in this film.

II. Performance of the Mysterious SR-72 "Dark Star" Hypersonic Aircraft

According to Popular Mechanics magazine, the production team behind *Top Gun: Maverick* contacted Lockheed Martin's Skunk Works division to assist with the SR-72 concept. [6] The Skunk Works is the division of Lockheed Martin that works on prototype, proprietary and other classified aircraft programs. The Skunk Works name is associated with the Lockheed XP-80 "Shooting Star" prototype, the U-2 spy plane of Francis Gary Powers fame, the A-12/YF-12/SR-71 "Blackbird," and the F-117 "Stealth Fighter," as well as the YF-22 and X-35 prototypes for the production "Raptor" and "Joint-Strike-Fighter" programs. [7][8]

I worked at Skunk Works in the mid 1990's, on the ill-fated unclassified prototype X-33 hypersonic space plane. [9] I presently teach and consult in the realm of aircraft design, performance and aerodynamics with a keen interest in stability & control issues exhibited by high-speed airframes. [10][11][12][13][14][15] I have no direct affiliation with Lockheed Martin, and certainly no connection to those who worked with the film unit to produce the fictionalized aircraft seen in the film and now on the air-show circuit.

According to an official video documentary released by the studio, the fictionalized "SR-72" was designed with a collaboration between members of the film and engineers from Lockheed Martin Skunk Works. Based on elements of the 1960's era SR-71 the film studio "lowered it… to make it look sleeker and faster" [3] Through an "invaluable" partnership with Lockheed engineers, the film studio learned how to make the aircraft "look angry, mean [and] insanely fast." [3]

A. The SR-72 Designation Seems Implausible for an Experimental Navy Aircraft

One obvious question which the movie leaves unanswered is this: Why is Mitchell, a Navy test pilot, is flying an apparently land-based USAF designated airplane (the "SR-72") out of what appears to be NAS China Lake? In the 1940's, the US Navy flight tested its D-558 Phase I and Phase II research aircraft out of Muroc Army Airfield (presently Edwards AFB) in California. [16] Today, the VX-9 air test and evaluation squadron for the F-35C has a home base at NAS China Lake and a detachment at Edwards AFB. [17] As a maritime platform, the US Navy does operate the Lockheed P-3 and Boeing P-8. It is not inconceivable for the US Navy to develop a large land-based "patrol" aircraft; if they were to do so, its designation would be XP-72. As a carrier-based strike platform, the

designation would have to be something like XF/A-72. Ultimately the location of the California runway for the flight test is less troubling than the designation of the test aircraft itself.

B. The Overall Size of the "SR-72" Is Reasonable for A Carrier Based Aircraft

The configuration of the "SR-72" appears to be an amalgamation of elements of the prototype ATF Northrop YF-23 and the famous Lockheed SR-71. [18][19] The physical size of the filming mock-up for the "SR-72" is quite small; see FIGURE 4. [20]

As dramatized in the movie, the "SR-72" appears considerably larger. [4] If the pilot in the image found in FIGURE 1 is ~6-ft tall, the "SR-72" would be just 70-ft long. Contrast this to an SR-71, which is 107.5-ft long. [19] Note that the elevator size on the USS Gerald Ford restricts an aircraft to <85-ft overall length by ~52-ft span. [21] Thus, the "SR-72" could conceivably be sized as a prototype for a future carrier based aircraft.

Looking at an image capture from the film, we see that the "SR-72" has a wingspan ~48% of its overall length; if its length were to be 70-ft, then wingspan would be ~34-ft from tip-to-tip. Once again, contrast to the SR-71 which had a 55.6-ft span.

The cropped delta wing appears to have ~55° leading edge sweep; this leads to a nominal *Sref* ~ 700-ft^2 with AR~1.65.

Maximum takeoff weight is likely to scale with the square of the linear-scale factor and/or linearly with the wing reference area. The SR-71 weighs 172,000-lbm fully loaded. [19] With a length ~65% of the SR-71, a span ~61% of the SR-71 and an Sref ~39% of the SR-71, I estimate the maximum takeoff weight of the SR-72 to be between 65,000 and 70,000-lbm. This is comparable to a Grumman F-14 "Tomcat;" [22] it is compatible with the elevator on a Nimitz class carrier.

C. Tail Size and Landing gear placement indicates CG positioned for positive static stability

A visual inspection of FIGURE 5 notes the main ground wheel contact point ~45-ft aft of the tip of the nose. To prevent tip-back, this would suggest that the fully fueled takeoff CG is located ~42-ft aft of the nose. Between the planform and a possible CG position, we can develop a simple VORLAX [23] model to assess longitudinal stability; see FIGURE 8.

Running this model at incompressible flow conditions reveals a three-axis stable configuration. The slope of *CL* vs. α is rather shallow ($dCL/d\alpha \sim 0.05/^{o}$) due to the low aspect ratio and substantial leading edge sweep; see FIGURE 9a. The vehicle appears quite stable in pitch, $dCm/dCL \sim -0.13$ (or 13% stable); see FIGURE 9b. The vehicle also demonstrates positive static directional stability, $dCn/d\beta > 0$; see FIGURE 9c. Due to the sweep, the vehicle also exhibits positive effective aerodynamic dihedral, $dCl/d\beta<0$ for $CL>0$; see FIGURE 9d.

FIGURE 5 – Children posing next to the filming mock-up of the "SR-72" [20]

FIGURE 6 – CGI rendering of the "full scale" "SR-72"

FIGURE 7 – "SR-72" ready for Takeoff [4]

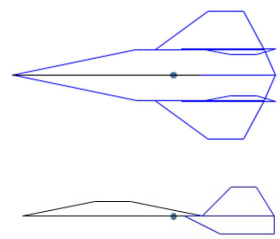

FIGURE 8 – Simple flat plate VORLAX model for initial stability assessment

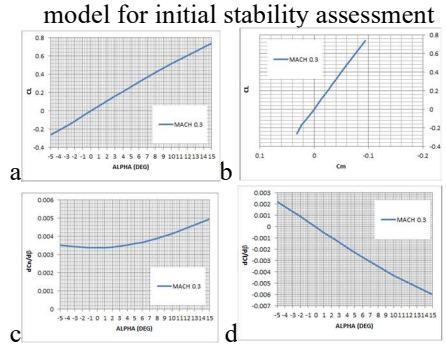

FIGURE 9 – Basic Incompressible Aerodynamics estimated using VORLAX

All taken together, a simple open-loop piloted RC model of the "SR-72" configuration balanced about the proposed landing gear position should prove stable and controllable in low-speed flight.

D. Aerodynamic Centre Shifts with Increasing Mach Number not accounted for in fuel system

While VORLAX neglects real-gas effects that are seen in Hypersonic flight, it does include a supersonic leading-edge panel formulation which captures the basic effects of flight at extremely high speeds. [23] The Mach number normal to the leading edge is governed by: $M_{LE} = M_{\infty}\cos(\Lambda)$. With the Λ~55° on the main wing and Λ~45° on the vertical tails, the transition to supersonic leading-edge aerodynamic surfaces will be complete by Mach 1.8.

Turning next to FIGURE 10a, we can see how the slope of *CL vs.* α declines with increasing Mach number. By Mach 8, $dCL/d\alpha$~0.015/°. Plotting longitudinal stability, see FIGURE 10b, we can see that the aerodynamic-centre has shifted aft; with all major aerodynamic surfaces having supersonic leading edges the aircraft is now 25% stable. With a reference chord, *c*, of 20.5-ft; this change in stability reflects an ~30-in shift in aerodynamic-centre positon.

FIGURE 11, a screen capture from the film, reveals the fuel tank disposition on the SR-72. [4] Lacking a nose-ballast tank, the vehicle would not be able to fly at low speeds with a forward CG fully fueled for takeoff, shift its CG aft for reduced trim drag at high-speed flight and then be able to return to a forward CG position for approach and landing. Without active CG management, and lacking an obvious body flap or discrete elevator attaining trimmed flight at hypersonic speeds with elevons alone may prove challenging.

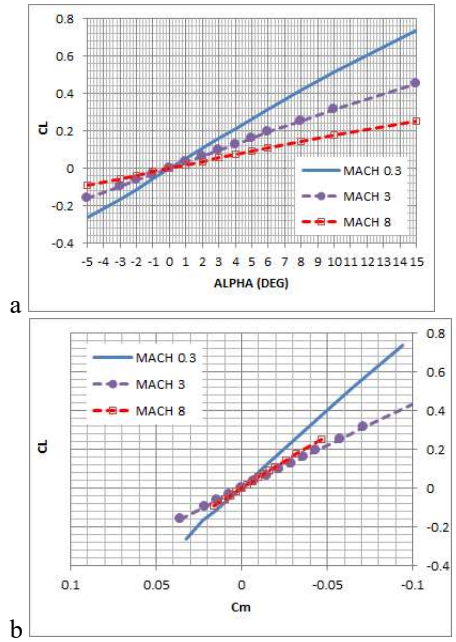

FIGURE 10 – Mach Number Effects on Lift Slope and Static Longitudinal Stability from VORLAX

FIGURE 11 – SR-72 Vehicle Health Display indicates a lack of a nose fuel tank for active CG management. [4]

E. Because directional stability degrades at Hypersonic speeds, the vertical tails are likely to be substantially undersized

The directional stabilizing effect of vertical tails are proportional to their effective area, their moment arm and also the size of the vehicle wing (its reference area and tip-to-tip span). These factors are often rolled up into a single parameter known as the vertical tail volume coefficient: $C_{VT} = \frac{S_{VT}\, l}{S_{ref}\, b}$. [11]

During the 1950's, engineers realized that the vertical tail loses ability to stabilize the airplane as speed increases. This all reached head when developing the North American X-15 rocket plane. During its inception, only two previous airplanes had flown above Mach ~2: The Bell X-1A and Bell X-2. Both of these aircraft experienced large decreases in stability that compromised stability & control. [24] In the case of the Bell X-2, attempted flight above Mach 3 led to a vehicle hull loss and pilot death. [12]

The initial solution, proposed by NACA, encouraged designers to incorporated large, wedge-shaped upper-and-lower vertical-tail surfaces. [24][25] The wedge shape was used because it is more effective than the conventional tail as a

stabilizing surface at hypersonic speeds. [25] Even so, a vertical-tail area equal to 60% of the wing area was required to give the Mach 6.7+ X-15 adequate directional stability; see FIGURE 11. [24]

Returning to the design of the SR-72, consider how the stabilizing effectiveness of the projected area of the vertical tail relates to the "lift-slope," $CL\alpha$, of the 2D airfoil section which defines the vertical stabilizing surface; see FIGURE 12. [24]

The SR-71 has thin-section tail sizes suitable for flight at around M~3, where $CL\alpha$ is ~ 0.025. The movie "SR-72" also appears to have a thin-section vertical tail; see FIGURE 13. Thus, its speed dependent stabilizing behavior should, at best, track the "0.05c Diamond Section" data found on FIGURE 12. Seeing that in the dramatization the vehicle held directional stability to Mach 10 (it crashed due to aero-thermal / structural issues), thin-section $CL\alpha$ would have declined to ~ 0.008; requiring the "SR-72" to have a three-fold larger vertical tail than did the SR-71. If the "SR-72" were to incorporate a 10° wedge (δ=5°) like the X-15, its tail surface section $CL\alpha$~0.017 at Mach 10; still necessitating vertical tail areas proportionally 1.5 times the size of the SR-71s.

F. Fixed Geometry Inlets are unsuitable for operation much above Mach 1.8 and too slow for transition in a combined cycle engine

If we return to FIGURE 13, and compare the inlets of the fictional "SR-72" to the Northrop YF-23 ATF prototype (see FIGURE 14) we see substantial similarity. Both geometries have fixed geometry, and function primarily as a "normal shock" inlet with only inefficient external compression, especially above Mach 1.8. As evidenced in the film, the "SR-72" is propelled by a dual flow-path turbine-based combined cycle system.[4] Other hypersonic research aircraft, such as the Boeing X-51, feature a rocket-based combined cycle system with a transition from rocket powered boost to ramjet/scramjet operation around Mach 4.5.[26] While other proposed dual-mode ramjet/scramjet systems might lower the transition speed to around Mach 3.0, it is extremely improbable that the transition speed could be reduced to the point where the low-speed turbine cycle used for takeoff and initial acceleration could function with a fixed geometry external compression inlet.[27][28]

FIGURE 11 - North American X-15 – note the very large vertical tail area needed to provide positive static directional stability at Mach 6.7+

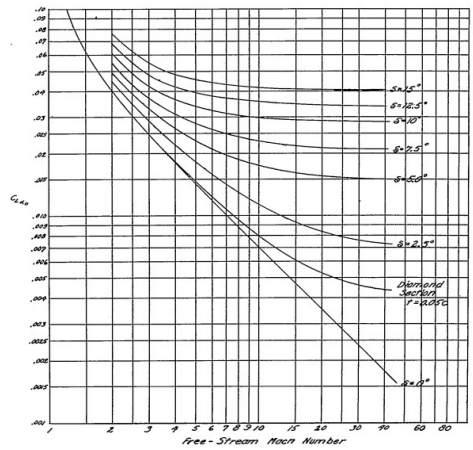

FIGURE 12 - 2D $dCL/d\alpha$ for various thin (δ=0°), conventional 5% t/c diamond, and various wedge airfoils (δ is the wedge half-angle). [24] The X-15 used a δ=5° wedge. [25]

FIGURE 13 – "SR-72" displaying its thin vertical tail sections and fixed geometry inlets. [4]

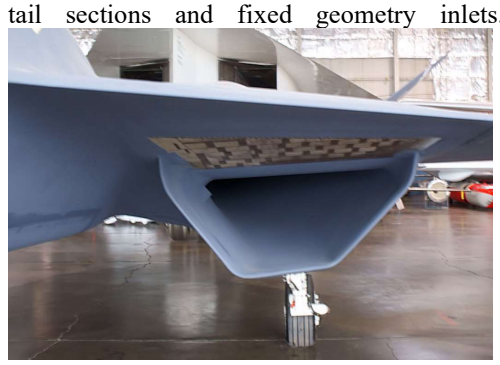

FIGURE 14 – YF-23 at the National Museum of the United States Air Force with its fixed geometry inlet clearly revealed. [18]

FIGURE 15 – "Maverick" flying a Mach 9 Turn in the "SR-72" [4]

G. The implied hypersonic maneuvering capabilities of the "SR-72" defy the most cursory analysis

In a particularly dramatic scene in the film, we see Mitchell piloting the "SR-72" through a 60° heading change at Mach 9. This occurs over ~3 seconds of film; it is flown without apparent loss of speed or altitude. This would indicate that the "SR-72" would be capable of maintain ~20° heading rate change/second sustained turn capability at this speed. Such a sustained turn rate is impressive in a modern fighter plan during air-to-air combat at subsonic speeds and at moderate altitude. In this section, we consider what does this dramatization imply about the flight performance of the "SR-72?"

To begin, let us assume that the maneuver is flown at ALT~100,000-ft MSL. If we refer to the extended standard atmosphere tables (see TABLE 1), we see that on a nominal day the speed of sound at 100,000-ft MSL is ~990 ft/sec; thus flight at Mach 9 reflects a velocity of ~8,900-ft/sec; or 5,280-KTAS. Despite the rarefied atmosphere, the dynamic pressure would be ~1260 lbf/ft^2; ~625 KEAS. With *Sref* ~ 700-ft^2 and a late-mission flight weight of ~35,000-lbm, 1-gee level flight would imply flight at *CL*~0.04 which needs α~2.7°; refer back to FIGURE 10. Superficially, this level flight point seems reasonable.

Next, we must consider the implication of sustained load factor, *nZ*, on turn radius, turn rate and bank angle. These fundamental relationships are dictated by simple physics and geometry and apply equally to low speed, supersonic as well as hypersonic flying machines.

TABLE 1 – Standard Atmosphere at High Altitudes

alt (ft)	T (deg R)	P (psf)	Rho (s/ft^3)	a (ft/s)	Mu (slugs/ft/sec)	q/M^2 (lb/ft^2)
0	518.67	2116.22	2.38E-03	1116.45	3.74E-07	1481.354
55000	389.97	191.8	2.86E-04	968.0757	2.97E-07	134.26
60000	389.97	151.027	2.26E-04	968.0757	2.97E-07	105.7186
65000	389.97	118.934	1.78E-04	968.0757	2.97E-07	83.25413
70000	392.2463	93.7271	1.39E-04	970.897	2.98E-07	65.60897
75000	394.9706	73.9906	1.09E-04	974.2627	3.00E-07	51.79339
80000	397.6935	58.5116	8.57E-05	977.6152	3.02E-07	40.95811
85000	400.4151	46.3501	6.74E-05	980.9547	3.04E-07	32.4451
90000	403.1354	36.7785	5.31E-05	984.2812	3.05E-07	25.74493
95000	405.8545	29.232	4.20E-05	987.595	3.07E-07	20.46243
100000	408.5722	23.2722	3.32E-05	990.8961	3.09E-07	16.29056

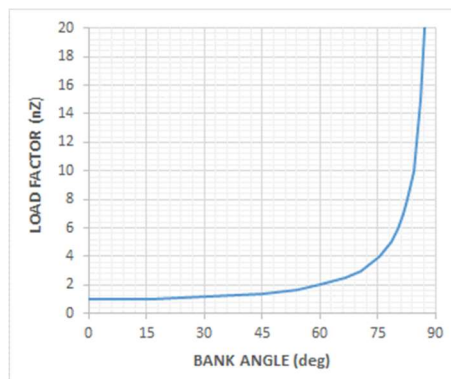

FIGURE 16 – Load Factor / Bank Angle Relationship for Sustained Turn

To begin, recall that the load factor, *nZ*, represents the magnitude by which lift exceeds weight. Geometry also implies a correlation between load factor, *nZ,* and bank angle, *Φ,* for a maneuver flown without loss of speed and altitude: $nZ = 1/\cos(\Phi)$; see FIGURE 16. [10][29]

The turn radius in nautical miles may be inferred from load factor, *nZ*, and flight speed in KTAS, where g = 32.2-ft/sec^2: $TURNRADIUS = \frac{(V)^2}{g\sqrt{nZ^2-1}} = \frac{(VKTAS\frac{6076}{3600})^2}{32.2\cdot\sqrt{nZ^2-1}} \Big/ 6076$. [10][29]

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 and the flight true-airspeed we can infer the turn rate in terms of degrees-of-heading-change per second: $TURNRATE = 360/(2\,\pi\,\frac{TURNRADIUS}{VKTAS/3600})$. [10][29]

As we increase load factor, *nZ*, the allowable bank angle increases and the turn radius rapidly diminishes. However, the turn radius also increases as a function of the true airspeed squared. [29]

Taken together, we may examine the true maneuverability of any Mach 9 airframe; see TABLE 2. The bank angle as implied in the movie is Φ~60° which implies a 2-gee turn without loss-of-speed or altitude. For the "SR-72," this would imply flight at α~5.4° which seems reasonable. Now, the problem here is that such a maneuver would result in a heading rate change of only 0.4°/sec and an implied turn radius of ~235-nM! It would take ~2.5-minutes for the "SR-72" to affect a 60° course heading change. This is clearly bad for the dramatic pacing of the film.

The movie, alternatively, shows Mitchell flying a 20°/sec heading-change maneuver. At Mach 9, that would imply a bank angle of Φ~89.4°; that requires *nZ* to be in excess of 100! Given the slope of $dCL/d\alpha$, this maneuver is completely impossible no matter how structurally sound the "SR-72" is and how physically fit the pilot is. Even a +6-gee sustained turn without loss of speed or altitude (that would be hard on a pilot) would take ~50-sec to execute at Mach 9.

TABLE 2 – Turn Radius / Rate and Bank Angle at Mach 9

Gee's	Turn Rad (nM)	Turn Rate (deg/sec)	Bank Angle (deg)
1.414	406.6	0.2	45.0
2	234.7	0.4	60.0
3.86	109.0	0.8	75.0
6	68.7	1.2	80.4
9	45.4	1.9	83.6
10	40.9	2.1	84.3
25	16.3	5.2	87.7
50	8.1	10.3	88.9
75	5.4	15.5	89.2
100	4.1	20.7	89.4

If the "SR-72" actually flew that ~100-gee maneuver as depicted in the film, Tom Cruise would have teleported himself into the script of *The Right Stuff* where Chuck Yeager quipped that astronauts were "spam in a can." [30]

III. Throwing the NATOPS in the trash – flying "fast" by sheer force-of-will

In the long buildup to the films denouement, we see Mitchell teaching his cohort of young pilots to push themselves and their planes to the edge (and beyond) of their physical limits. At one point, Mitchell throws the F/A-18E/F NATOPS (the certified flight performance flight manual) into the trash; return to FIGURE 3. [4] We hear discussions of 10-gee maneuvers (well above the advertised 7.5-gee limit of the F/A-18E/F) mixed with considerable Yoda-like advice: "don't think, do," – Mitchell instructs his cadets. [4] While this battle between past and future, old and young, intuition and technology, rigid rules and a human touch makes for great drama, does it begin to reflect how an experienced instructor-pilot would approach mission planning?

The strike mission is certainly challenging. It is an "unacknowledged operation" against a uranium enrichment facility in a hostile, but nameless country, well-armed with late-model Russian offensive and defensive technology. They must bomb a target, deep in a valley, all surrounded by steep mountains; this is supposedly beyond the capabilities of the Navy's Tomahawk missiles. An attack with USAF assets, i.e. B-1 or B-2, too conspicuous and provocative; plus it wouldn't fit the narrative since Tom Cruise/ "Maverick" Mitchell is a Navy Pilot. To my mind, the preferred equipment to fly this low-level penetration mission would be the TSR-2; except that's a cancelled British aircraft that never entered service. [31] Instead, our heroes must make do with F/A-18E/Fs that makes it a nearly impossible, "suicide" attack mission – survivable only if they access the target by flying deep through a sinuous canyon.

When Mitchell demonstrates the canyon attack, showing both his management and the youngsters how to really "fly it," we see ~20 separate turns flown within the canyon walls. Mitchell enters the canyon at ~580-KTAS with 2:15 time to target and exiting with ~0:40 to go; thus, the aircraft were in the canyon for about 95-sec making the canyon

about 15-nM long. Turning to FIGURE 16, another frame grab from the film, we confirm the airspeed and altitude and the sustained load-factor (*nZ*~5.0-gees) mid turn.

Movie buffs note that filming locations for the simulated attack include both the famous Star Wars Canyon near Death Valley as well as Feather River Canyon just to the east of Oroville, in Northern California. Posted you-tube videos show amateur pilots flying this canyon run using Microsoft Flight simulator and their F-18 model in the ~440-knot range, but staying fairly high in the canyon. [32] Turn radius at the road-bed level can be as tight as 500-ft, but flown deeper into the canyon – as depicted in the film - it seems that a trajectory could be assembled from segments between 2,000-ft and 4,000-ft radius; see FIGURE 17.

FIGURE 16 – Mitchell Flying the "Canyon" at ~580-KTAS [4]

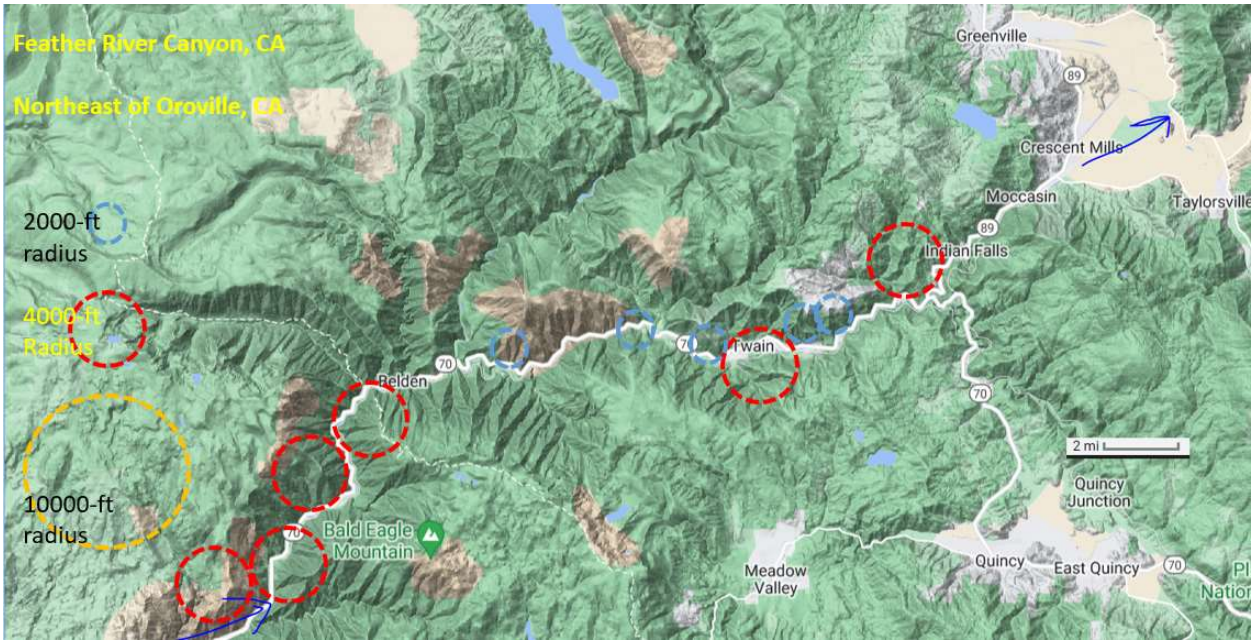

FIGURE 17 – Feather River Canyon in Northern California

Let us consider the performance of an F/A-18E/F with a tactical payload. Since the NATOPS is export controlled, I cannot use it for example in this general publication. [33] That notwithstanding, the NATOPS should contain a series of "Dog House" plots showing how flight speed, climb rate and sustained turn capability trade-off for various flight weights and stores. [34]

To continue the discussion, avoiding any export control concerns, let us consider the estimated performance of an Airbus A320 flown at very light weight (W=100,000-lbm); the raw data may be found in Takahashi's paper from.[29] This theoretical performance of the A320 is based purely on its aerodynamics and propulsion; it may be considerably better than the actual aircraft which has substantial envelope protection including bank-angle limits.

While the A320 clearly differs from an F/A-18E/F, the trends should make themselves clear.

FIGURE 18 shows both maximum instantaneous (solid black line) and sustained (dashed red line) turn capability of the airframe as a function of true airspeed near sea-level. At a light weight, the structural limit of an A320 should be ~+3.8-gees (recall it is certified to +2.5-gees at MTOW, not at W=100,000-lbm). The *VA* speed is the airspeed where the maximum instantaneous load-factor limited by stall equals the airframe structural limit. Below the *VA* speed, the airframe is limited by stall; above the *VA* speed it is limited by structure. Thrust limitations limit maximum sustained load factors to be less than the instantaneous in most cases. However, we can see here that the maximum sustained load factor exists at a specific airspeed: ~300-KTAS; if one flies faster or slower than the optimum, the-gee capability falls off.

Turning next to FIGURE 19, we can see that the Heading Rate-Change capability is also a strong function of speed. The instantaneous heading change peaks at the *VA* speed (250-KTAS); the sustained heading change capability peaks just as the aircraft develops its maximum sustained load factor: ~300-KTAS. Once again, if one flies faster or slower than the optimum, we see that the heading change capability declines.

Moving on to FIGURE 20, where we see that the turn radius is also a function of speed. The interplay between load factor and speed and drag plays out here. The basic trend is that the turn radius increases with the square of the airspeed, provided load factor is held constant; but below the *VA* speed, the load factor varies inversely proportionally to the airspeed cancelling out this effect. Taken together, it is clear that above a clearly defined speed, both instant and sustained turn radius widens considerably. We note that the A320 is incapable of flying a sustained 2,000-ft radius turn at any airspeed. To achieve a 2,000-ft radius turn it must dynamically shed energy; such a turn can be flown at constant altitude only if airspeed sags as the turn progresses.

Finally, we see in FIGURE 21 that the wings level acceleration capability of an aircraft declines with increasing airspeed. As the vehicle approaches its top-speed, its acceleration potential vanishes

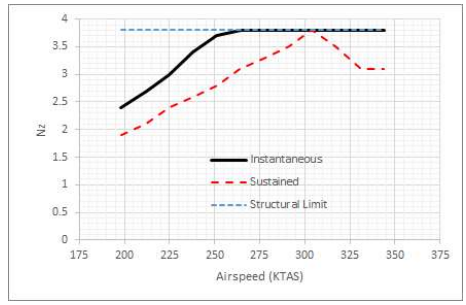

FIGURE 18 – Estimated Load Factor Capability of a generic transport aircraft flown in maneuvering flight at light weight.

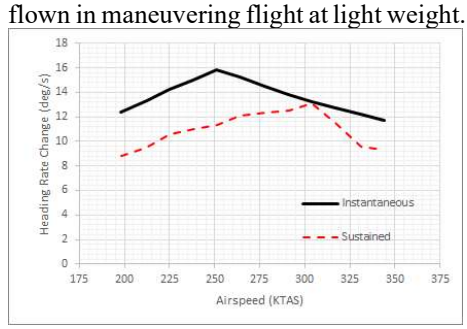

FIGURE 19 – Heading Rate Change of a generic transport aircraft flown in maneuvering flight at light weight.

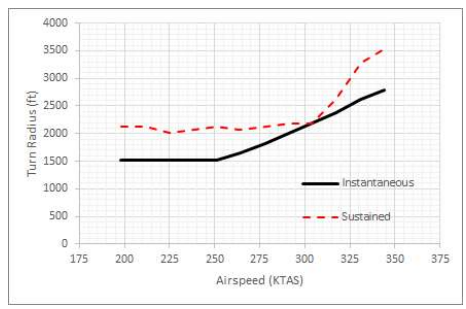

FIGURE 20 – Turn Radius of a generic transport aircraft flown in maneuvering flight at light weight.

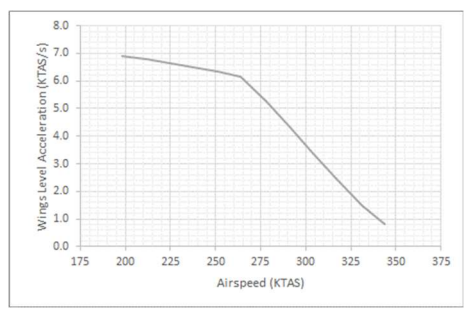

FIGURE 21 – Wings Level Acceleration Capability of a generic transport aircraft at light weight.

(along with its sustained turn or climb rate). Thus, an A320 at light weights throttle-lag notwithstanding, would take ~10-sec to accelerate from 300-KTAS to 325-KTAS flown wings-level; during this time it would cover ~1-nM ground distance. In the context of a flight through Feather River Canyon, this is not an insignificant distance as the straight-line distance between many turns is on the order of 1-nM and the aircraft would need to decelerate to enter subsequent turns in order to maintain the required radius.

We may also note from TABLE 3, that the aircraft will need to bank over to Φ~75° to negotiate these turns. The time-to-roll from wings-level to this bank angle is not insubstantial; the peak roll rates $d\Phi/dt$ can only be attained mid-maneuver. Thus, an aircraft with a peak roll rate $d\Phi/dt$=60°/sec may well take 2-sec to transition from wings-level to peak bank angle.

Since an F/A-18E/F must obey the same laws of physics as the A320, we should expect broadly similar trends although its roll rates, specific excess thrust, maximum instantaneous *Nz* and maximum sustained *Nz* likely exceed the A320 by substantial margins.

While an F/A-18E may be able to initiate a +7.5-gee instantaneous load factor, it seems that a bomb-laden aircraft on a tactical mission would be unlikely to sustain even +6.0-gees load factor without loss of speed or altitude. Thus, to fly a tight course as quickly as possible, pilots must fly at an airspeed commensurate with the expected turn radii. They must also pay close attention to their linear acceleration and deceleration capabilities; if they enter a turn "too hot" – they may not achieve the radius and end up as a dark spot on the side of a canyon wall. Consider the fatal crash of a US Navy F/A-18E in 2019; the Navy reports that the pilot entered the canyon around 550-KTAS before misjudging the deceleration and left turn; see FIGURE 22. [35]

TABLE 3 – Bank Angle associated with a 2,000-ft radius turn without loss of speed or altitude

V (KTAS)	gee's	bank angle (deg)
200	2.03	60.5
250	2.94	70.1
275	3.49	73.3
296	4.00	75.5
332	5.00	78.5
365	6.00	80.4
400	7.14	81.9

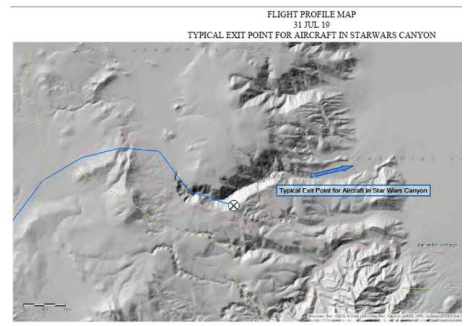

FIGURE 22 – Flight track of an F/A-18E/F which entered "Star Wars Canyon" at an estimated 550-KTAS. [35]

Flying deep within a canyon, a pilot cannot permit a loss of altitude as a result of excessive turn-rate, or even permit a turn radius to exceed limits without contact with terrain. Consider that with heavy fuel loads and external stores an F/A-18E/F pair **might** be able to sustain +5 to +6-gees load factors. If so, the actual flight speeds the pilot needs to schedule to fly the canyon at without crashing into a wall will critically depends upon flying the aircraft to not exceed engineer produced data; analogous to FIGUREs 18 through 21 for the actual military configuration.

We can further speculate on the actual flight speeds needed to fly Feather River Canyon. If we were to enter the canyon following CA 70 just east of Bald Eagle mountain, we must navigate north east through a series of ~4,000-ft radius turns. The canyon briefly opens east of Belden followed by a series of tighter turns, around ~2,000-ft radius until just east of Twain, CA. At flight altitude, the canyon may be just wide enough to avoid the narrow switchbacks that the road must take as we approach Indian Falls, CA. The aircraft will then take a left turn and follow CA 89 through Indian Falls, CA to Moccasin, CA and exit for the final sprint across the desert to the target.

Looking at the A320 data (return to FIGUREs 18 through 21), we see that with limited acceleration capabilities we would need to keep flight speeds at or below ~300-KTAS for the sharpest turns. Since the aircraft has marginal capability to achieve the tightest turns, we would realize that there is no room for error. Tighter radii might exceed the structural limit of the airframe; they will most certainly result in a loss of speed and/or altitude. During the broader turns earlier and later in the canyon, we could let the airspeed increase. In no way would we expect the aircraft be able to exceed 350-KTAS, its drag limited top speed near sea-level.

Consider a hypothetical F/A-18E/F unit flying this mission. TABLE 4 lets us hypothesize the required performance to fly 2,000 to 4,000-ft radius turns at 583-KTAS. Note that +5-gee sustained turns imply a radius of ~6,200-ft which is considerably broader than flight deep within Feather River Canyon would permit. To achieve a ~4,000-ft radius turns requires +7.5-gees sustained turn capability; ~2,000-ft radius turns require +15-gees sustained turn capability. Thus, we are posed with the fact that high-speed flight through the canyon must be flown at a much lower speed than dramatized in the film. [4]

If the F/A-18E/F unit were able to sustain +5-gee's without loss of speed or altitude, they would need to enter the canyon around 470-KTAS slowing down to ~330-KTAS for the tightest turns; see TABLE 5. This seems to be consistent with the sorts of flight speeds seen in the amateur Microsoft Flight Simulator videos. If the F-18s were able to sustain a full +6-gee's without loss of speed or altitude, they would need to enter the canyon around 520-KTAS slowing down to ~360-KTAS for the tightest turns; see TABLE 6.

As with the A320, acceleration capabilities of aircraft limit performance in the canyon. Even with full afterburner, an F/A-18E/F cannot accelerate that quickly. Anecdotally, it takes at least 15-sec for it to accelerate from 360 to 520 KTAS. While that is an impressive speed gain of more than 10-KTAS per second (about double the acceleration of the lightweight A320), the aircraft will still traverse ~1.75-nM in doing so. Thus, I would suspect that the F/A-18E/F unit wouldn't begin to regain their full flight speed until after they passed the final 2,000-ft radius turn, and wouldn't attain full speed until they were over Indian Falls and on its way to exit the canyon system.

We see in such a "realistic" scenario flying such a real-world canyon that aircraft will be forced to decelerate to take the tightest of turns. Even with afterburners, many subsequent maneuvers would be "throw-aways" because the F/A-18E/F lacked an ability to accelerate to a speed where it would need its +5 or +6-gee aerodynamic capability to fly the needed turn.

Examining TABLEs 5 and 6, we see that the aircraft will need to bank as much as Φ~80° to negotiate these turns. Remember that the time-to-roll from wings-level to a prescribed bank angle is longer than the published peak roll rates capability implies since $d\Phi/dt$ can only be attained mid-maneuver; by definition $d\Phi/dt$=0°/sec at both wings-level turn initiation and at the final bank angle. While it is said that an F/A-18E has a peak roll rate $d\Phi/dt$=~120°/sec; [36] it may take ~1-sec to transition from wings-level to peak bank angle and ~2-sec to transition from a left-turning +6-gee turn to a right-turning +6-gee turn.

TABLE 4 –Nz vs Turn Radius Performance at 583-KTAS

gee's	bank angle (deg)	turn radius (ft)	turn rate (deg/sec)
1.155	30.0	52028	1.08
1.414	45.0	30079	1.87
2	60.0	17361	3.25
2.5	66.4	13123	4.30
3	70.5	10631	5.30
4	75.5	7764	7.26
5	78.5	6138	9.19
6	80.4	5083	11.09
7	81.8	4340	12.99
8	82.8	3788	14.88
10	84.3	3022	18.66
12	85.2	2515	22.42
15	86.2	2009	28.06

TABLE 5 – Nz vs Turn Radius Performance at 330-KTAS

gee's	bank angle (deg)	turn radius (ft)	turn rate (deg/sec)
1.155	30.0	16670	1.91
1.414	45.0	9637	3.31
2	60.0	5562	5.74
2.5	66.4	4205	7.59
3	70.5	3406	9.37
3.5	73.4	2872	11.11
4	75.5	2488	12.83
5	78.5	1967	16.23
6	80.4	1628	19.60

TABLE 6 – Nz vs Turn Radius at 360-KTAS

gee's	bank angle (deg)	turn radius (ft)	turn rate (deg/sec)
1.155	30.0	19838	1.75
1.414	45.0	11469	3.04
2	60.0	6620	5.26
2.5	66.4	5004	6.96
3	70.5	4054	8.59
3.5	73.4	3418	10.18
4	75.5	2960	11.76
5	78.5	2340	14.88
6	80.4	1938	17.96

IV.Summary and Conclusions

This commentary on Hollywood representations of aircraft performance serves to highlight the disconnect between cinematic drama and "real-world" performance of hypothetical and current production military aircraft.

Hypersonic systems, limited by aerodynamics and structural strength, will be incapable of rapid heading changes. Whether designed by friend or foe, this class of airframes will always "look like a fish, move like a fish and steer like a cow." [37]

Conversely, subsonic aircraft equally limited by aerodynamics and structural strength are capable of rapid heading changes. However, to properly plan flight in dangerously confined spaces like a canyon requires pilots to pay keen attention to aircraft performance data prepared by skilled engineers. While this sort of data is not included in most general aviation and transport category aircraft flight manuals, it **should be** found in export-controlled combat aircraft flight manuals. The key takeaway here is that all aircraft have an optimum flight speed for turn performance that is likely to be far below their top speed. Flying by the seat-of-the-pants reliant on your craggy good looks and ego is a sure recipe to end up as a "dark spot on the down side of a canyon wall." [38]

Ultimately, I found Top Gun: Maverick to be an enjoyable cinematic experience. I just would warn any student of aircraft performance not to take it too seriously.

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