Try to point at and shoot well flown MiG-21!

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Maneuverability of modern fighter is measured by how slow it can fly and how high angle of attack it can sustain and still turn. During some war situations, US evaluation and Aggressor use, MiG-21 has shown it can keep pace with modern planes in this area. Aircraft manufacturer at one time considered this irrelevant and imposed restrictions on angle of attack. Flying above allowed 28-33 degrees local angle of attack at low speeds makes possible to relatively safely achieve a maneuverability once considered privilege of modern fighters.

Couple years ago reports and testimonies appeared in the media about a dogfight during the Israeli-Arab War '73. when the Egyptian MiG-21 pilot managed to do a Split-S maneuver at the start altitude of 3000 feet, less than half minimum airspace the manual says (about 6750 ft). Appropriate simulation can be found on the internet:

http://www.youtube.com/watch?v=bQMzK2WfYYM&feature=player_embedded

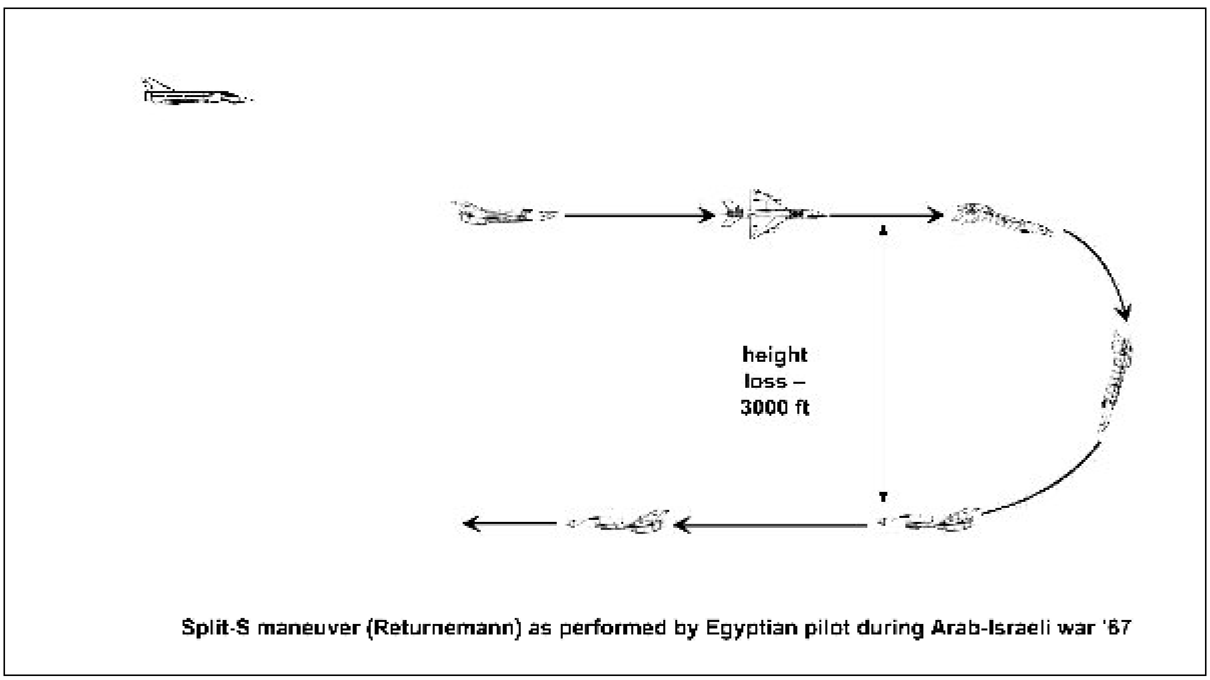


Figure 1.

Initiated by this event, some American and Israeli enthusiasts (once pilots of their AF fighters), one of which has a private squadron of various Russian fighters, attempted to replicate that minimum altitude needed to complete Split-S figure in the two-seater MiG-21. Previous consultation with Israeli ace, who participated in that dogfight in '73. war, did not help test to be successful. Attempts were carried out at the higher altitude (5 km) and the height loss during the figure was in accordance with flight manual. It remained unclear whether ’73 event was result of "special skills or superhuman strength of the Egyptian pilot needed to withstand the required g-loads”.

Recently disclosed files of the official MiG-21 evaluation in the U.S. revealed some unexpected capabilities that can be correlated with the "inexplicable" ’73. maneuver. MiGs were brought to America via Israel, in the late '60s as a result of pilot error or fled from Iraq and Algeria. Later they were bought from Indonesia. The MiG-21 in the U.S. Air Force is designated YF-110.

The report of a MiG-21F shows nothing particularly unusual, except for maneuvering capabilities and behavior/handling at low speeds described as "class above competition”. Besides that, if competitors tried to follow MiG-21F at high alpha, their engine experienced shutdown or compressor stall. MiG could perform "hammerhead" turn (wing over/stall turn/renversement) at 100 knots (knot = 1.853 km/h), figure where at the end of the vertical climb pilot add rudder (with the opposite aileron and forward stick) to push the plane in the dive. Rudder is effective from 30 knots. With the stick fully backward, the plane flies at 210 km/h, the rolling oscillations are present, but there is no lift breakdown or the tendency towards spin. If during the evaluation, loss of control due to uncoordinated controls occurred, it was in the form of roll-off (usually for 180°) instead of much more dangerous yaw-off. To put the plane back under control it was necessary only to release controls. MiG-21 proved to be docile, safer to fly than MIG-17. During the hundred flight tests engine compressor stall was never experienced.

U.S. of course, used MiGs in dogfight evaluation against their aircraft. Latter, they formed "Aggressor" squadron of MiGs and other fighters for the dogfight simulation with regular American aircraft.

Figure 2, 3. MiG-21 on testing in the U.S.

During MiG testing, it was clear that U.S. pilots have not relied on Soviet pilot's manuals or they did not have one at the beginning. That is why the aircraft ability was fully exploited. Test pilots had thousands of flight hours experience on dozens of types of aircraft. Those who have survived the testing of U.S. supersonic fighters F-100/101/104/4 (many of planes were called "widow makers"), learned to recognize the pre-stall/spin signs and use rudder for rolling the aircraft at higher angles of attack.

What we learned

■ G-load factor	8gs without stores, 6 with stores
■ Max indicated airspeed	595 kt below 15,000 ft, 640 kt above 15,000 ft
■ Maximum indicated Mach	2.05 without stores, 1.6 with stores
■ Strike radius	370 NM with external fuel
■ Poor forward and rearward visibility	F-4 acquired at 3-5 miles range
■ Low Q limit	Below 15,000 limited to .98 Mach or 595kt – severe buffe
■ Afterburner puff	Above 15,000 FISHBED E produces a puff in/out of AB
■ Engine response	Extremely slow
■ Cockpit noise	Extremely low
■ Gunsight capabilities	3.7NM, missile mode; 1.6NM, gun. Gun/missile target tracking impossible over 3gs
■ Slow speed	The MiG-21 could maneuver at 115 KIAS

MiG-21 Good Features

- Simplicity; Ease of Flying – It's a good, honest aircraft!
- Reliability and Maintainability (20 minute turn around)
- Cross-Sectional Area
- Engine Exhaust Smoke
- 3-wheel brake concept

AFFTC Lessons Learned on MiG-21F-13 TAC Evaluation borrowed from Israel '68.
(Foreign Technogy Division of USAF Systems Command)

Figure 4. Some of the results of MiG-21 testing in the United States

Reportedly, if Vietnamese pilots had adequate training, the U.S. fighter shot-down ratio figures would be much worse in that war. In the hands of the well trained pilots, MiG would always outmaneuvered Phantom. US unveils graphs depicting not only far better instantaneous turn performance of Fishbed C compared to F-4D but also better sustained maneuverability. MiG-21 Aggressor pilots respected only the most modern fighters because they do not lose so much speed in turn even at low speeds. However, appearance of all-aspect infrared missiles reduced the importance of sustained turns (M2000, F-18E, Gripen …are not brilliant in the maintaining speed in turn). If MiG-21 had R-73 missile, it could easily take advantage of first shoot opportunity at close range against any new fighter.

The F-5E, fighter which does not fly above Mach 1.5, MiG-21 simulator, reportedly has shade better subsonic sustained turn maneuverability, but inferior controllability at low speeds. Maneuverability is the ability to change speed and direction of flight path (velocity vector pointing) and controllability - ability of change aircraft attitude (pitch/roll/yaw - nose pointing) and thrust (engine response - spool up time matters). When the aircraft initial flight path in dogfight is anti-parallel flyby, combat will inevitably develop so that someone goes in a climb with rolling scissors - turn reversals along the opponent's flight path to remain behind the opponent. If the F-5E does not gain an advantage before the speed drops below 200 knots, MiG will start winning. First look at the configuration of the aircraft, MiG – delta with the sweep near 60°, and Tiger with nearly straight wings, would suggest the opposite, that MiG is in trouble at low speed.

Even the mighty F-15 Eagle had no solution in dogfight below 150-250 knots against MiG-21 in US Aggressor hands. At the beginning of dogfight, at the speed of 400-500 knots MiG-21 will turn at max g loosing 70 knots per second, ending at the speed of 70 knots in less than 90º of turn (deceleration of 3.5 g, more intensive than Harrier's VIFF turn). Reportedly, no other aircraft can do that. This way MiG will remain behind every opponent still having sufficient controllability for gun tracking using rudder rolls. Opponents would think that at this speed MiG can only bring down the nose and dive, but the MiG at less than 100 knots has sufficient pitch authority to raise the nose at enemy. If F-15 tries to follow, '21 should execute 'barrel-roll ' to remain behind the Eagle.

It is obvious that MiG-21 'Aggressor' pilots pulled full aft stick in turn regardless of the lateral oscillations, roll-off and temporary loss of control.

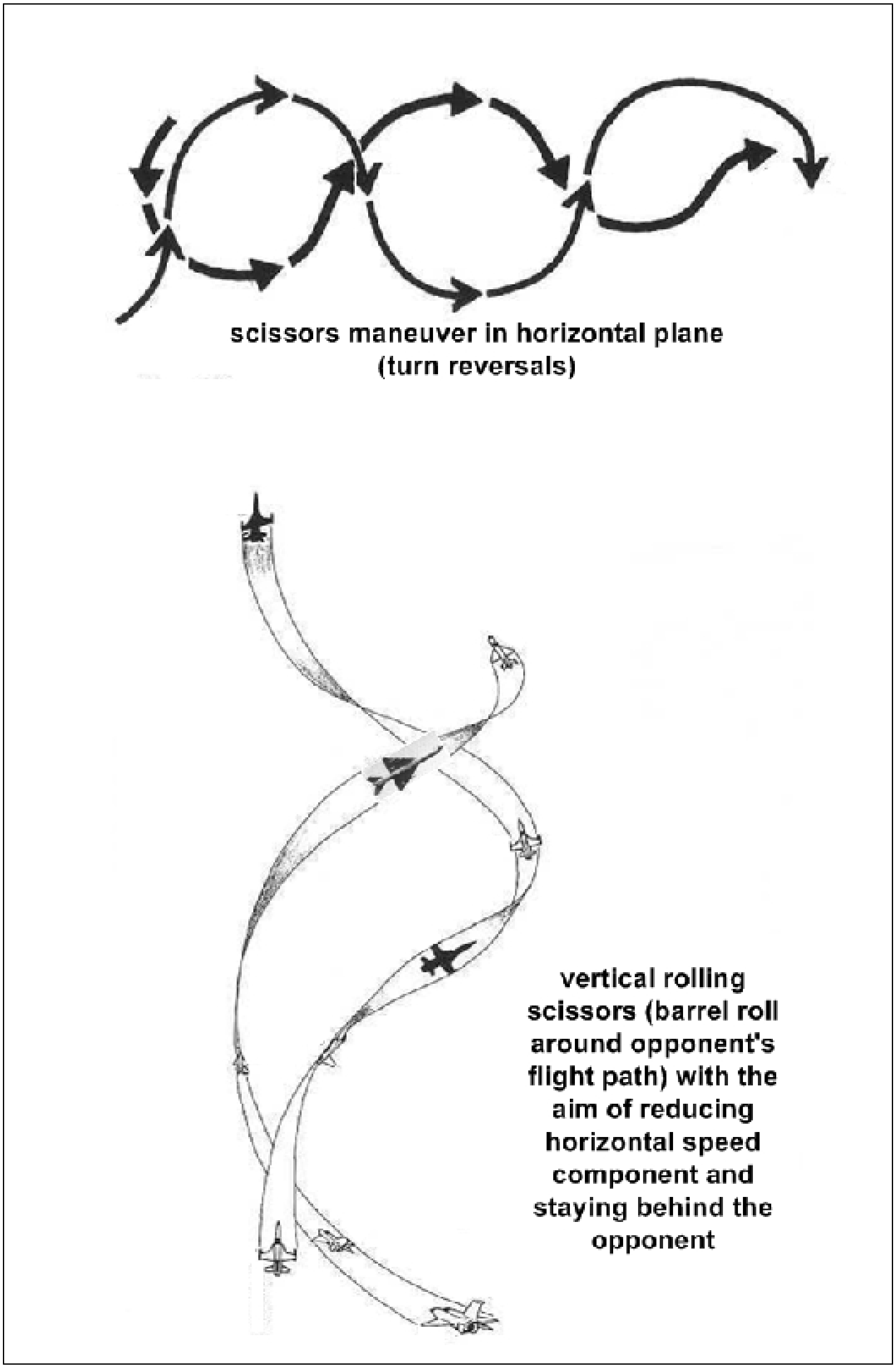


Figure 5. Scissors maneuver

Latter, the F-15 pilots learned (in a hard way) not to accept maneuvering at slow speeds, not to allow to be drown into a series of turn reversals, but to withdraw and re-attack at higher speeds using 3D turns and it's higher thrust/weight ratio. F-15 with 45º swept wing and low horizontal tail, at higher angle of attack becomes longitudinally superstable, so it can not achieve more than about 30º angle of attack.

On the example of lift and stability of the aircraft with the 45º swept wing and high-set horizontal tail it can be seen that the lift begins to decline at 10º (buffeting starts), the wings are stalled at the 20º (the airflow separates from the wing), and max body lift is at 35-40º after which it decreases. Delta wing of MiG-21 with sweep of 57 º retains stable airflow to very high angles of attack.
Longitudinal stability is positive where the curve has a downward slope. In this case, the position of the horizontal tail is causing longitudinal instability at 15º, and at 35-40º angle of attack aircraft is trimmed without tail deflection. MiG-21 has no problem with longitudinal stability (except with air to ground armament with low fuel) and the plane in the example would have a limit at 15º angle of attack.
Yaw stability curve shows that the aircraft is unstable at 15º, what is not uncommon. Few modern fighters are stable at over 20º, but it is not a problem if the aircraft maintains lateral stability i.e. roll due to yaw. Roll stability curve is increasing as the lift increase, so it similarly comes to the instability, in this case at about 20º angle of attack. Shall the plane have a tendency toward spin (at no deflection of the control surfaces!) show the curve of dynamic directional stability where factors are static yaw and roll stability along the inertial characteristics of the aircraft. In this example, the plane is at stall just above 20º angle of attack, while MiG-21 is stable at well over 30º at low Mach numbers.
Curves correspond to a particular Mach number, at some other speed they can vary significantly.

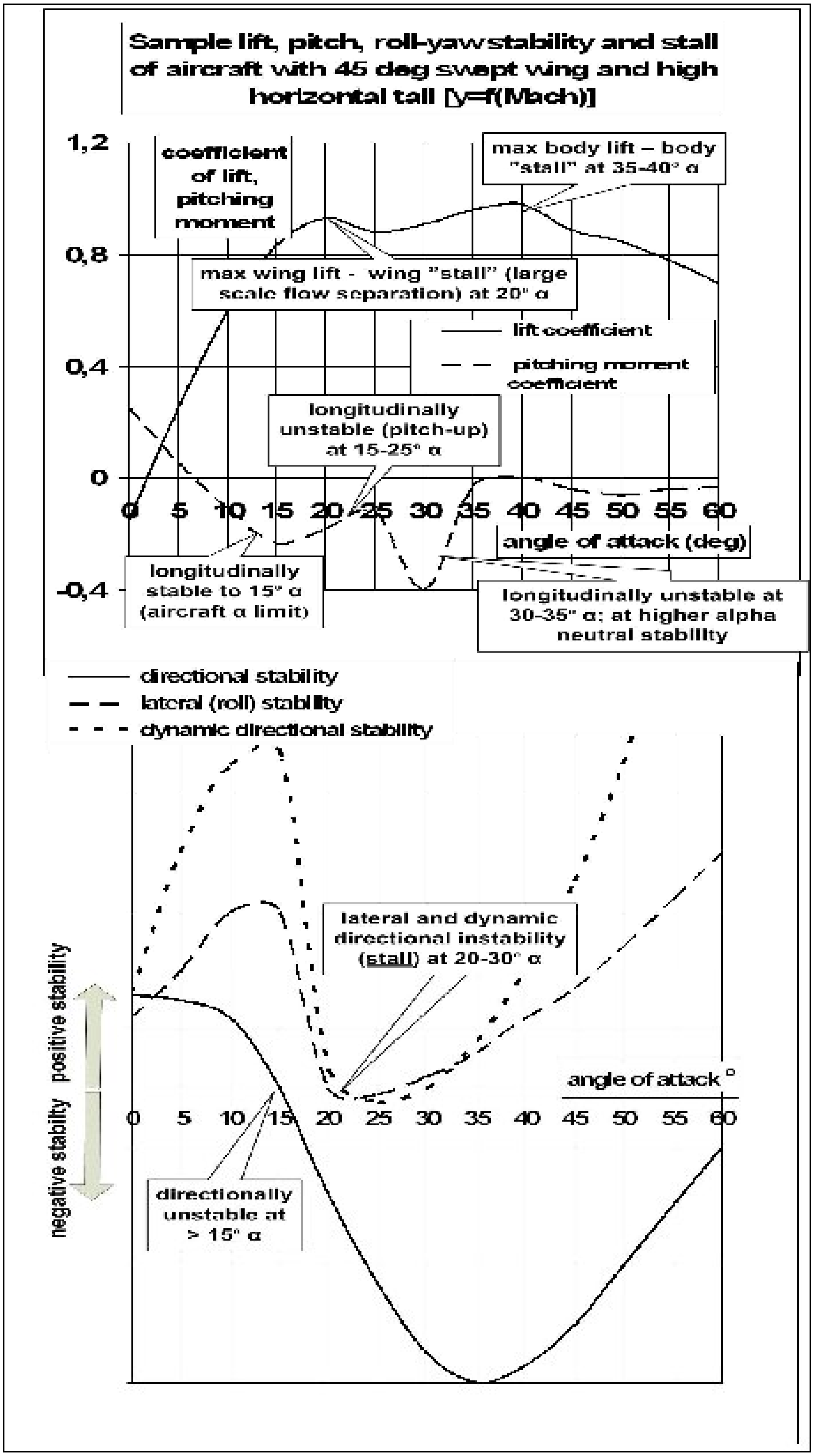


Figure 6. Example lift and stability of aircraft

Soviet training was based on a relatively small number of flight hours on a MiG, which is used for training the primary purpose of aircraft, interception of fighters-bombers, under ground control. Pilots are not encouraged to explore the flight envelope. The aircraft is designed to fly faster and higher. Slow speeds were irrelevant, except for landing. In the first combat manuals, the performance at altitudes only above 5 km were presented. Later, it turned out that there are many practical constraints due to which the projected max altitudes and speeds are rarely used.
MiG-21 wing has no camber or twist along span. The relative thickness of the higher end of the wing than in the root. There are few prestall signs. Prestall buffet begins much earlier (at 50-100 km/h higher speed), its intensity is light and slightly decreases at higher α. Below Mach 0.4 buffet does not develop. Just before stall α, aircraft nose would start wandering accompanied by more noticeable wing rocking (roll oscillations that intensify thru the stall), symptoms of dynamic directional instability.
Stalling proceeds more vigorously with fewer signs at higher subsonic speeds.

Ailerons are ineffective in countering roll oscillations and rudder would push aircraft into a spin. Setting control surfaces to the neutral position immediately after the onset of stall would restore normal flight conditions. The aircraft is longitudinally stable in air combat configuration at any internal fuel quantity.

Aircraft's stall speed (speed at which dynamic directional stability breakdown occurs) is function of Mach number, because directional and lateral static stability usually decreases with speed. Stall angle of attack decreases from above 30º (far beyond indicated α) at Mach 0.2 to 20º (i.e. 33 units local angle of attack on indicator) at Mach 0.95.

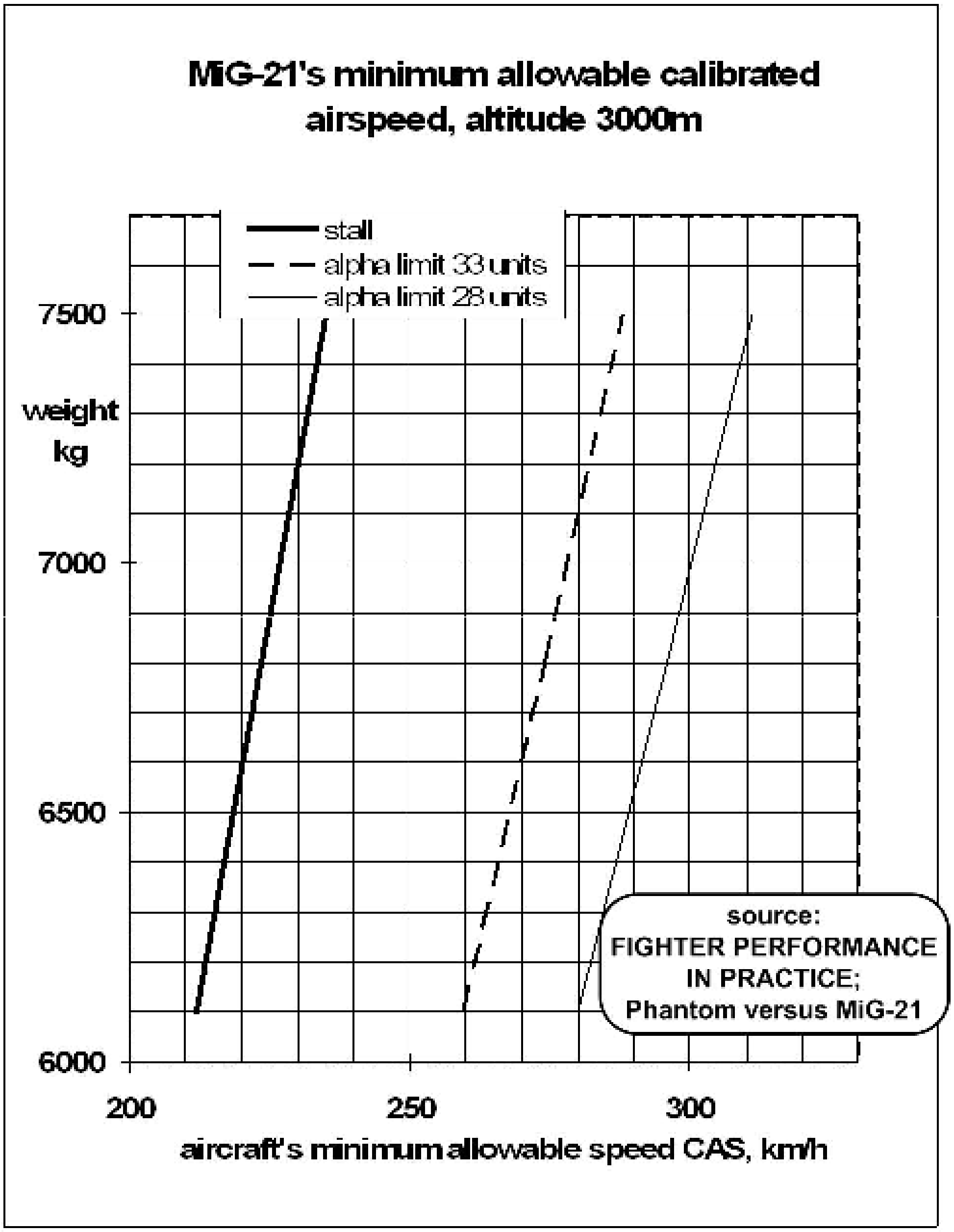
In those days when MiG-21 was designed, electronic flight controls to limit the angle of attack in function of Mach number didn't exist. A fighter was built primarily for high speeds, high altitude interceptions. At slower speeds previous generations MiG-19/17 were better.

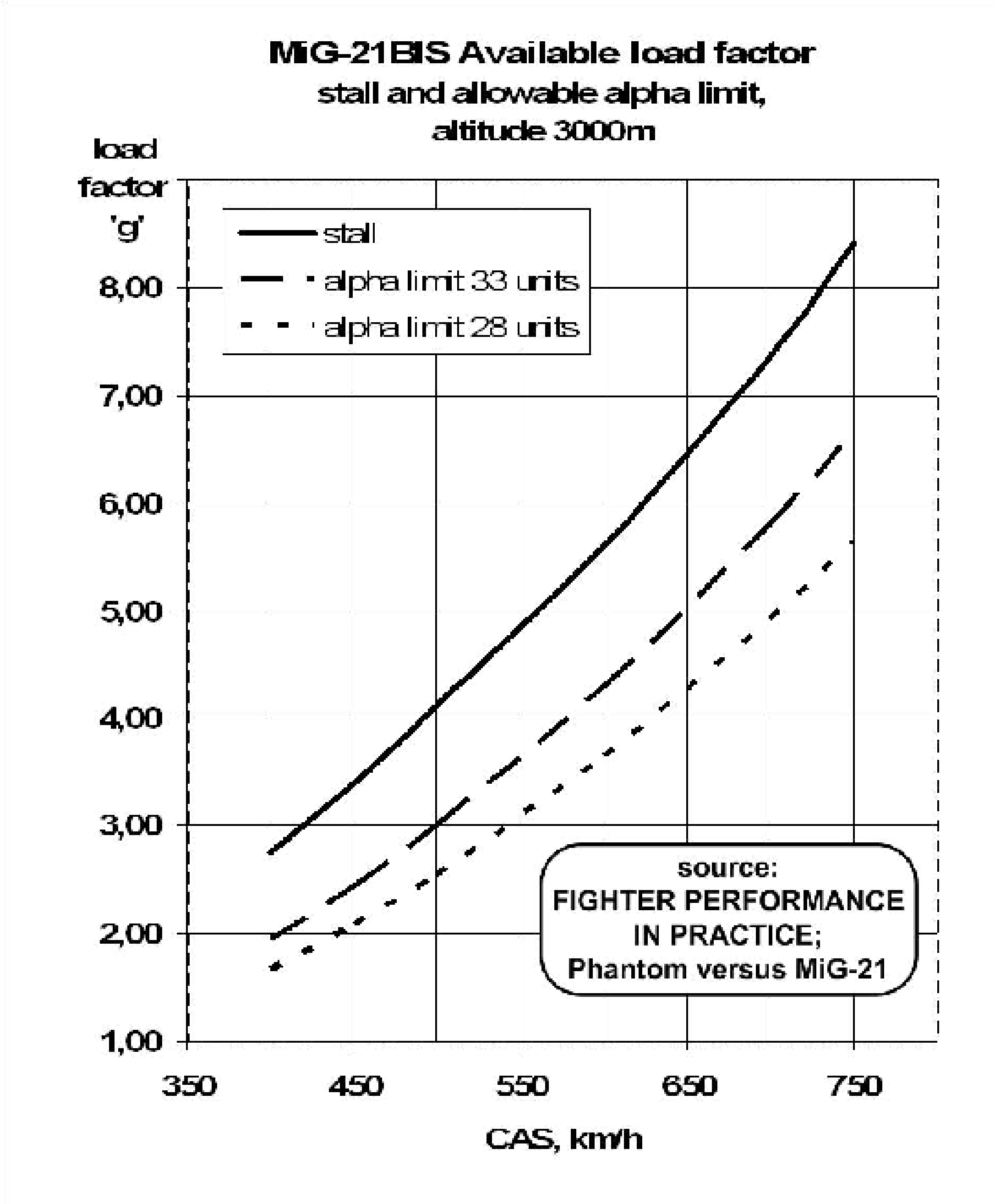
Designers put the angle of attack indicator, calibrated in local angle of attack, to warn the pilot of approaching stall limit. At recommended and allowed limit 28 units (about 17º true angle of attack) safety margin to stall is from 13º at Mach 0.2 to 3º at Mach 0.95.
So there is large margin between allowed angle of attack and stall angles of attack especially at lower Mach numbers.
At higher speeds, the angle of attack is limited by tail pitching power.

Mach number	0.2	0.7	0.8	0.95
Stall angle of attack (α)	> 30º	~ 25º	~ 23º	~ 20º
Stall speed weight = 7500 kg	233 km/h	254 km/h	260 km/h	267 km/h
Speed at 33 units local α (~20º α)	287 km/h	287 km/h	282 km/h	267 km/h (stall)
Speed at 28 units local α (~17º α)	311 km/h	311 km/h	305 km/h	291 km/h

So, the low speed turning capabilities were not fully exploited. If situation comes, like it happened to that Egyptian pilot during war, there is an additional lift potential.

During the Split-S figure, speed should not be increased. The closer to stall α is, the lesser the altitude loss is during figure. Below 600 km/h CAS entry speed aircraft cannot aerodynamically reach the allowed structural load factor so there is no need for superhuman physical stress. At higher speeds height loss in split-S at stall angle of attack is much more than 3000 ft.


MiG-21's minimum allowable calibrated airspeed, altitude 3000m
stall
alpha limit 33 units
alpha limit 28 units
weight kg
7500
7000
6500
6000
200
250
300
aircraft's minimum allowable speed CAS, km/h
source:
FIGHTER PERFORMANCE IN PRACTICE;
Phantom versus MiG-21


MiG-21BIS Available load factor
stall and allowable alpha limit,
altitude 3000m
load factor 'g'
stall
alpha limit 33 units
alpha limit 28 units
8,00
7,00
6,00
5,00
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3,00
2,00
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350
450
550
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CAS, km/h
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FIGHTER PERFORMANCE
IN PRACTICE;
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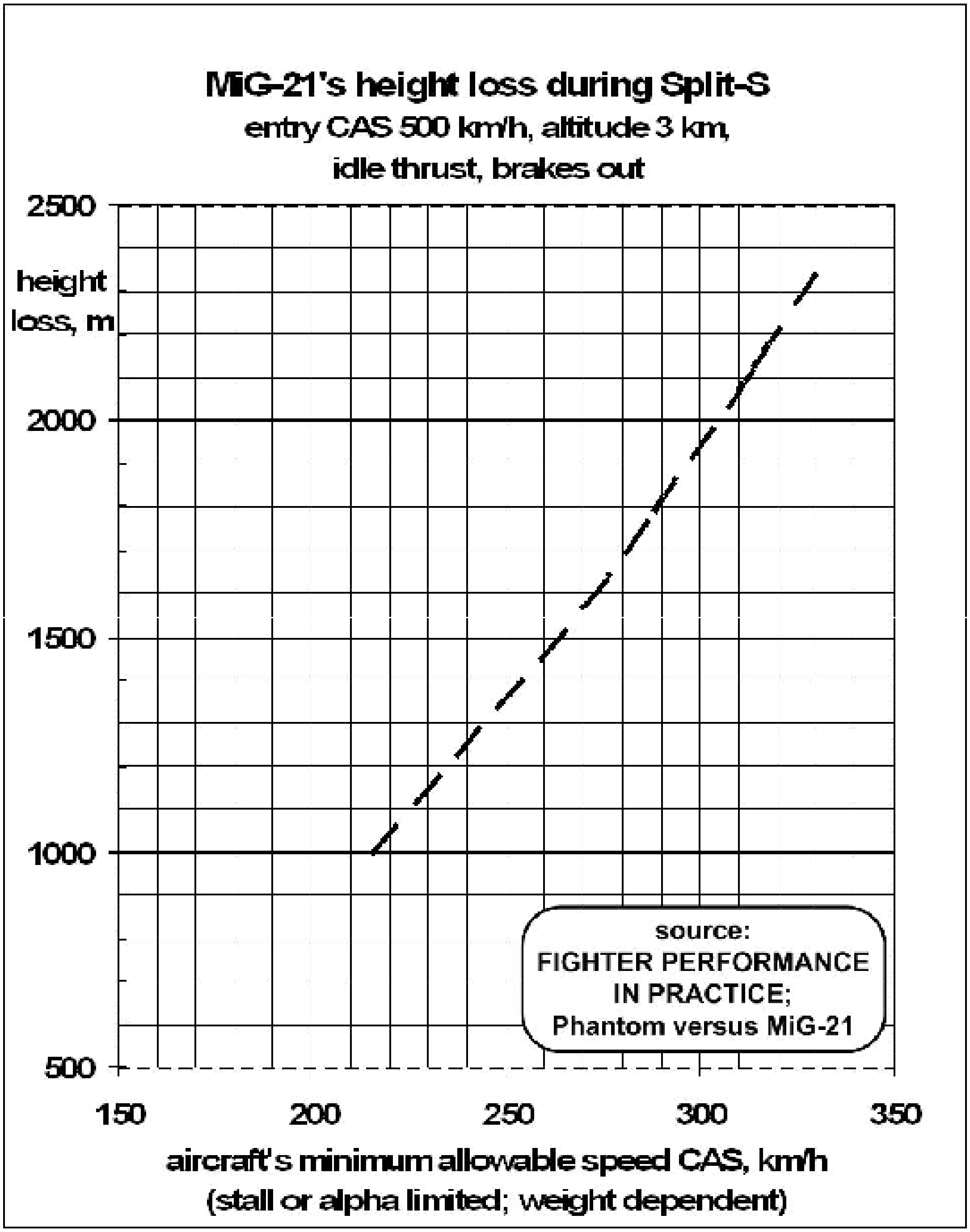
MiG-21's height loss during Split-S
entry CAS 500 km/h, altitude 3 km,
idle thrust, brakes out
2500
height
loss, m
2000
1500
1000
500
150
200
250
300
350
aircraft's minimum allowable speed CAS, km/h
(stall or alpha limited; weight dependent)
source:
FIGHTER PERFORMANCE
IN PRACTICE;
Phantom versus MiG-21

Figure 7, 8, 9.

Because of its very high stall angle of attack at lower Mach numbers and good pitch control authority (large wing leading edge sweep produces strong vortical flow which shifts aerodynamic centre forward at high alpha, reducing stability thus allowing the tail to easily trim aircraft at more than 30° alpha), aircraft has a great point and shoot potential with modern IR missiles.

Although it is often said that the MiG-21 looses a lot of energy in turn, the truth is also that it has better sustained turn performance than most aircraft of its generation. Tumansky engine proved almost stall/surge free at speeds far below minimums quoted in conservative Soviet flight manuals. All U.S. and European contemporary designs flamed out under same conditions. Engine has two shafts for optimized - different rotational speeds of low and high pressure compressors stages for a compressor blade stall resistance, feature that allows more compressors stages to be added for lowering specific fuel consumption. But it has unusually low number of compressor stages for a two-shaft design, contributing to reliability. Bad side of this philosophy is higher fuel consumption. Despite the resistance of the compressor to the extreme conditions of airflow at the inlet, if afterburner is engaged at almost zero speed (well below the conservative engine envelope) other undesirable phenomena are possible. Distortions of the inlet airflow causes disruption of relations of air and fuel in the AB chamber, which changes the speed of combustion. Pressure fluctuations coupled to acoustic velocity fluctuation (AB chamber is also exposed to sound fatigue, the noise is up to 180 decibels) associated with combustion instability (called rumbling), can cause extreme resonant structural vibrations of the engine with subsequent engine destruction and the loss of the aircraft.

The published results of American evaluation relates to the F/PF models. BIS model has 15-20% higher ratio of inertia moments in yaw to roll. It certainly results in more sideslip during rolls and somewhat lower stall angle of attack, angle when breakdown of dynamic directional stability occurs. But the prevailing factor in this equation is the dihedral effect i.e. roll stability and it is the same in all models because it depends on airflow around the delta wing, so it can be expected good behavior of BIS model at low speeds also.

It should be borne in mind that prevailing effects at high angles of attack are dihedral and adverse yaw due to aileron deflection. Rudder is used for rolling and if the sideslip angle or yaw rate (induced in this way) crosses critical, result is the spin. Opposite aileron increases the roll rate through an additional sideslip angle i.e. 'adverse yaw'. In most modern aircraft application of such cross controls for 5-15 seconds, usually causes spin.

Figure 10. MiG-21 derivatives J-7G and JL-9

In general, the plane that has a lower stall speed is more maneuverable. At some speed, it will be able to achieve g-load equal to the square of the mentioned speeds quotient. The U.S. experience from simulated dogfights during exercises indicates the importance of the minimum speed and controllability at high angles of attack. That is why F-18 gets F-15/16 although its performances are considerably lower. Latest F-18E has still weaker performance, but better controllability. Angle of attack, at low speeds, of the F-16 and

Gripen is limited to about 26º (Rafale and the Typhoon to a shade more). F-15 has max trimmed angle of attack 30-33º with poor roll response here. Against 'stealth' fighters F-22/35 and corresponding new Russian (whose all planform contour lines are parallel to a few main sweep angles - cm wavelength radar return angles, in addition to other 'stealth' measures and cost of 50 MiG-21), none of the listed has significant chances at medium range. Analysts agree that the close combat will remain inevitable, and that each aircraft armed with missiles cued by helmet sight has a chance, especially if it can reach high angles of attack. Even stealth fighters do not destroy opponents with death rays. Every component of the fire control/weapon system chain has limitations, from fighter radar to missile fuze. Towed mini decoy (laterally separated) with monopulse deception jammer/repeater or just simple towed corner reflector can draw away radar return signal centroid from towing aircraft. It could help surviving medium range combat even against stealth fighters.

The main disadvantages of MiG-21 are poor cockpit downward visibility, a proportionally small (but inline to generation) wingspan i.e. large induced drag (afterburner is needed for level flight at the absolute minimum speed, as at max allowed Mach number) and relatively slow response of two-shaft engine. All this causes poor performance on landing, especially in the case of go-around. Small fighter size means limited mission equipment carriage capacity.

It turns out that only important is to have a reliable and economical aircraft, a platform for carrying payload, with attack speed in the Mach 1.5+ class (that's why a 15-20 years younger A-10 was withdrawn prematurely). The modern nav-attack equipment (simplified inertial system, GPS, displays…) is now relatively inexpensive to install even in a small propeller planes. MiG-21 operators missed opportunity to realize fact that with helmet cued, large acquisition angle R-73 missile that was available upgrade, MiG could achieve 50:1 kill ratio in dogfight against F-18/Gripen/Typhoon class fighters just because latter were 10-15 years late with similar weapon system. Instead of making best of it, MiG-21 operators opted to admire newer fighters.
Because of its good characteristics, even 50 years after MiG-21 became operational, some of its modifications are still in production in Asia.

Reference:

- Fighter Performance in Practice, Phantom versus MiG-21, Predrag and Nenad Pavlović, eBay.com;
- Test and Evaluation Squadron, Nellis Air Force Base, Interviews;

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As of Last Complete Printing
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Number of Words: 4,626 (approx.)
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