TRENDS IN MILITARY AVIATION TECHNOLOGY

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INTRODUCTION

It is essential for any Air Force that desires to become a force to be reckoned with to independently analyse the possible and most likely future trends in aviation technology and to work in a dedicated manner in close liaison with the nation's scientific community and its own in-house engineering expertise. It must also update its basic and operational doctrines to develop and field the most promising technologies that are expected to rule the field of military aviation in the foreseeable future. An Air Force that fails to do so, is likely to be reduced to an expendable adjunct to the nation's military forces and become an undesirable liability in place of being an asset. Looking ahead to discern trends in military aviation technology, in the near to medium term future, is hence a vital requirement for any Air Force that desires to carry out its responsibilities to the nation in an effective manner. The evolution of aircraft technology from the dawn of modern military aviation to the present day reveals some interesting facts.

To this end, this paper examines the historical playoff between two major variables in aircraft design, manoeuvrability vs speed, which have remained important in determining ascendancy of one over the other in aerial warfare

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since the dawn of modern aviation. The paper then makes an educated guess on the way they might play out in the future, looking at about three to six decades ahead. Such an analysis would form the bedrock of medium to long-term equipping policies for retaining effective air delivered capability.

While artificial divisions into blocks of years have been made, all serious students of military aviation are aware and understand that there is considerable overflow and overlap between such divisions, given that the typical operational service life of a fighter aircraft is about 40 years; the venerable MiG-21 that first flew in the early 1950s is still on active-duty status in several Air Forces.[1] However, such divisions help in placing the arguments in a more cogent fashion, and hence these artificial divisions have been retained here.

THE EARLY YEARS: 1903 TO 1930

At the dawn of military aviation, the then current technology in airframe structures as well as power plants and other systems limited aircraft to very low speeds of close to a few tens of kilometres per hour. This increased over time to a few hundred kilometres per hour. The best German fighter in World War I (WWI) was the Fokker D.VII of 1918. Its steel tubing-based fuselage was attached to a fabric covered biplane configuration fighter that was powered by an engine from Mercedes delivering 160 horse power (hp) and could reach speeds of 188 kilometres per hour (kmph).[2] The Bristol f.2b was best and most powerful British fighter, capable of reaching a top speed of 200 kmph courtesy its 220 hp water cooled Rolls Royce (RR) 'Falcon' V12 engine.[3]

In order to understand the implications of these performance parameters, a quick but brief look at some basic mathematics is needed.

1. Snehesh Alex Philip, "11 Down in 5 yrs, 3 in 2021, but Many in IAF Still Swear by MiG-21s Despite its 'Safety Record'", May 24, 2021, at https://theprint.in/defence/11-down-in-5-yrs-3-in-2021-but-many-in-iaf-still-swear-by-mig-21s-despite-its-safety-record/663813/. Accessed on May 25, 2021.
2. Britannica.com, "World War I Fighters", at https://www.britannica.com/technology/military-aircraft/World-War-I. Accessed on April 15, 2021.
3. Ibid.

The formula for radius of turn is: $\mathbf{R=V^2/(gTan\Theta)}$, where R is radius of turn in meters; V is speed of the aircraft in meters per second; g is a constant and denotes acceleration due to gravity or 9.81 metres/ second^2; and θ is the angle of bank.

The formula for rate of turn is: $\mathbf{\acute{\Omega}=V/R}$; where $\acute{\Omega}$ is rate of turn in radians per second (2π radians=360 degrees; 01 Radian=57.2958 degrees $\approx$ 60 degrees); V is the speed in meters per second and R is the radius of turn in meters.

The aerodynamic ability of its airframe and the power output from its engine limits an aircraft's ability to carry out small radius and high rate of turn manoeuvres.

The interested reader can use speeds approaching those of the Fokker D.VII and Bristol f.2b to work out the radii and rates of turn common at that time. These, assuming a bank angle of 70-80 degrees, are typically about 100-120 metres radius of turn and close to half radian per second in rate of turn. It becomes evident that at the very low (as per today's standards) speeds that existed at the time, almost all aircraft in use had turn radii about 100-150 metres and could thus turn in very small spaces and at relatively high rates of turn.

There are additional complications. For instance, the aircraft must have sufficient power available from its engine and adequate lift producing ability from its wings to enable the machine to maintain the high bank angles needed for very small radii of turn and high rates of turn. Thus, the aerodynamic ability of its airframe and the power output from its engine limits an aircraft's ability to carry out small radius and high rate of turn manoeuvres. A more detailed explanation is beyond the scope of this paper save to bring out the end results mentioned here. Due to the limitations in strength imposed by the widely used, then state of the art, wooden or metal frame fuselage and wings with doped fabric or thin light wood (lightweight balsa wood) covered skins, as well as the limited power output from their engines, and relatively limited understanding of the principles of flight and aerofoil sections, there was little room for differentiation in these parameters of radius and rate of turn between most fighter aircraft of the time.

At the then prevalent relatively low speeds, turn radii were quite small, and close in turning fights were the norm for aerial combat. The difference in turning performance of most aircraft between rival nations was not really significant, and did not give significant combat advantage; a few attempts were made by some designers to improve turning performance through innovative design layouts. The most common layout at the time of WWI was the biplane with two lifting aerofoil surfaces tied or held together through struts and bracing wires, apart from independent anchoring to the fuselage. A few designs incorporated three aerofoil lifting surfaces to give the triplane configuration. When the drag penalties of multiple lifting surfaces became more apparent, the braced monoplane and eventually the cantilever monoplane configuration (which comprised a single lifting surface as is common today) became increasingly popular.

In the initial years, aerial combatants utilised crude missiles, such as rocks and grenades thrown at each other, which were eventually replaced by hand-held small arms such as pistols, revolvers and even rifles. Technological progress led to incorporation of forward firing fixed guns mounted in line with the fuselage. To avoid catastrophic self-damage during the early years of this endeavour, the guns were mounted so as to fire from outside the propeller disk. This led to gross inaccuracies in weapon employment as the sight and weapon barrel had a large gap between them. Invention of the interrupter gear allowed the fixed guns to be mounted closer to the sighting system as these gears prevented the gun from firing a round when its own propeller blade was immediately in the line of fire.[4] The term "dogfight" was born at this time. This was accomplished by drawing a connection between packs of dogs fighting each other in very close proximity using their teeth and the then rudimentary aircraft engaged in close combat in very close proximity due to small turn radii,

4. Jeremy Hsu, "The Red Baron & Aerial Weapons of World War I | The Most Amazing Flying Machines Ever", at https://www.space.com/16605-red-baron-wwi-aerial-weapons.html. Accessed on May 12, 2021.

all trying to get their weapons to bear on each other. Without technological assistance in the early years, deflection shooting required to hit a moving target from a moving platform relied entirely on individual deflection shooting skills.

In these early years, once engaged in aerial combat, pilots found themselves in a close-range melee of aircraft turning to obtain the desired position behind the enemy to carry out effective deflection shooting at the opponent. Rates of fire, calibre and numbers of weapons mounted on the aircraft differentiated the opponents.

The biggest advantage that could be sought at a time when the opponents' turning performance was comparable to that of weapons and sighting systems was the ability to choose to fight or flee. This situation was delivered by more powerful powerplants with greater power being delivered either through use of bigger and heavier engines or by incorporating superchargers to develop greater power output by increasing the mass flow by compressing the input charge. This increased capability enabled the pilot to climb higher or fly faster than his opponent, to chase and catch up with enemy aircraft, or to elect to disengage from a combat and return to his base at will. Hence, speed delivered by more powerful engines became the differentiator to gain ascendency over the 'other' side. For instance, an aircraft capable of 200 kmph would be flying at about 55 metres per second while one flying at say 180 kmph would be at 50 metres per second. Thus, in less than a minute, the faster of these two aircraft would be able to close or open up the distance from the other by about 300 metres, a most significant distance given the very short-range weapons available at the time.

In the very infancy of modern military aviation, the earlier importance of ability to turn tightly or to manoeuvre quickly in order to gain an advantageous weapon firing position gave way to the ability to fly faster than the opponent. This was also because, even as engines became more powerful, the materials used to make aircraft fuselage and wings were still wooden frames covered with fabric and held stressed by bracing wires and struts. In some cases, the skin comprised sheets of light but relatively strong plywood. These materials resulted in aircraft structures that had severe limitations in the centripetal and centrifugal acceleration, or 'g' forces they could withstand, before getting distorted or suffering catastrophic failures. These structural constraints also limited the aircraft's potential to improve its manoeuvrability further, leaving higher speeds as the only variable available for exploiting the technological and tactical advantage. It is good to remind oneself that at this time audio-only radio was at the cutting edge of scientific research and television. Long-range video transmission lay in the realm of science fiction. The Germans appear to have seized upon these basics first, and the historical accounts from that time tell us that the British and allied pilots, were cautioned to look for the 'Hun from the Sun' indicating German tactics of climbing higher and using the glare of the sun to remain concealed till it was too late for the target to escape 'high speed slashing dive attacks' on Allied aircraft.[5]

Hence in the early years of modern military aviation, speed took precedence over manoeuvrability or manoeuvre agility as the predominant parameter for success in aerial engagements. This remained the case for several years after World WarI (WWI).

1930 TO 1950

By combining the lightweight but strong aluminium alloy duralumin with the development of stressed skin semi-monocoque and monocoque building techniques, significantly stronger aircraft structures capable of withstanding higher levels of centripetal acceleration were created. Parallel progress in the science of aerodynamics and powerplant technology led to the shift of performance primacy to manoeuvrability. Aircraft became stronger and engines more powerful. Many fighters in the 1940s had maximum speeds close to 650-700 kilometres per hour (kmph) and service ceilings of between 10-12 km above mean sea level (AMSL).[6] At the same time, as speeds approached the speed of sound, control issues and power output irregularities were experienced due to the then-mysterious effects

5. "Voices of the First World War: War In The Air", at https://www.iwm.org.uk/history/voices-of-the-first-world-war-war-in-the-air. Accessed on May 3, 2021.
6. History.nasa.gov., "Quest for Performance: The Evolution of Modern Aircraft", at https://history.nasa.gov/SP-468/ch5-3.htm. Accessed on May 1, 2021.

of compressibility. The propeller tips moved at much higher speeds than the aircraft in a spiral path and these experienced higher increases in drag affecting the power available.[7]

These technical and technological issues restricted the amount to which speeds could be increased and led to manoeuvrability or manoeuvre agility becoming the most important attribute for success in aerial engagements for most of WWII.

Since WWI, the art of deflection shooting had become well established, and addition of graticules to the fixed sights of the time enabled a greater number of pilots to carry out effective attacks. During WW II, the reflector sight and the gyro stabilised gunsight were developed, and these when combined made the earlier inaccurate burst of gunfire much more effective. Lethality of aerial engagements increased. The furball dominated. Noted dogfighters of the time included the British Spitfire, Hurricane (to a lesser extent) and the Typhoon. The German Messerschmitt (Me)Bf-109, Focke Wulf Fw-190, American P-51 "Mustang", and Japanese Mitsubishi -A6M"Zero".[8]

While aerial combat was dominated by highly manoeuvrable fighters, special needs led to a few high speed fighters being especially developed. The British Mosquito twin engine fighter/bomber was one of them and could fly at above 760 kmph using speed and altitude to evade the enemy. Later, fighters exceeded this speed but the focus remained on manoeuvrability as the prime need. In the closing years of WWII, a shift towards speed as the prime requirement was seen. Later model Spitfires, especially in dives, could reach up to 900 kmph while the innovative Germans fielded the first axial flow jet engines and their jet-powered fighters including the Me-262 that could exceed 900 kmph. The 'specially designed to kill bombers' Me-163 "Komet" rocket propelled fighter interceptor could reach speeds of 1130 kmph.[9] In the later

7. Ibid.
8. www.aircraftaces.com, "oTp 10 best aircraft", at http://www.aircraftaces.com/best-aircraft.htm. Accessed on April 2, 2021; Khalid Elhassan, "Dogfights: Top 10 Fighter Planes of World War II", July 28, 2017, at https://historycollection.com/dogfights-top-10-fighter-planes-world-war-ii/. Accessed on April, 3, 2021.
9. Peter Suciu, March 22, 2021, "World War II aircraft by the numbers—from fastest to longest range", at https://nationalinterest.org/blog/buzz/world-war-ii-aircraft-numbers%e2%80%94-fastest-longest-range-180826. Accessed on May 2, 2021.

Despite the development of more powerful jet engines, more streamlined designs, and advances in aerodynamics, maximum speeds came to be limited by the then theorised 'sound barrier' approach resulting in severe control problems, buffeting and unstable flight. Designers therefore shifted to achieving respectable top speeds in the transonic range and emphasising high manoeuvrability.

part of the 1940s, all the leading aviation powers followed the lead of the Germans to develop jet-powered aircraft. These were freed from the constraints of the propellor tip speed and attendant issues. Moreover, more streamlined designs enabled ever higher speeds being achieved. The Lockheed P-80 "Shooting Star" could reach 1,004 kmph and won the first ever jet vs jet aerial combat when on November 10, 1950, it shot down a Soviet designed MiG-15 in Korea. Lacking in many performance parameters against the superlative MiG-15 it was soon removed from front line combat service.[10]

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In this period the ideal remained a mix of high manoeuvrability and the highest achievable speeds with the former taking precedence.

1950 TO 1970

Jet engines were the preferred powerplant for fighters after WWII. New developments delivered stronger airframes but these were still below the human threshold of tolerance to 'gz', the F-86 "Sabre Jet"[11] and Hawker

10. "Lockheed P -80 shooting star", at http://www.aviation-history.com/lockheed/p80.html. Accessed on May 3, 2021.
11. Digital Combat Simulator, "F-86F Sabre Flight Manual", at http://cdn.akamai.steamstatic.com/steam/apps/306240/manuals/DCS_F-86F_Flight_Manual_EN.pdf. Accessed on May 12, 2021.

Hunter had 'gz' limits of about +7/ (-)3,[12] while the Folland/ HAL Gnat had a 'gz' of about +5 to +5.6[13] only and as per accounts, Gnats, however, successfully engaged better turning Sabre Jets through use of the vertical by executing upward 'yo-yo's.[14] The machine determined the limit of manoeuvre as it was at the time possible for a pilot to overstress the airframe during manoeuvres. Technological progress delivered new techniques such as manoeuvre flaps, leading edge flaps and slats "all flying tail", etc. to improve turning performance.[15] The 1950s were initially dominated by highly manoeuvrable fighters; however, as the aerodynamics of supersonic flight and design parameters became clearer, speed became a much sought-after attribute with speeds of just above Mach 2.0 achieved by the mid-1950s by legendary fighters such as the American F-104 "Starfighter" and Soviet MiG-21.

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At this time, the top aviation nations developed and fielded the air-to-air missiles (AAMs) first introduced by the Germans in rudimentary form towards the close of WWII. The airborne 'Missile Carrier' concept was a diversion from the main trend. The Vietnam war demonstrated the fallacy of this concept, as early generation AAMs were extremely unreliable in combat. MiG-21s, originally designed to climb fast, accelerate to the rear quarters of

12. Atacusa.com, "Mk-58 Hawker Hunter", at https://atacusa.com/mk-58-hawker-hunter.html. Accessed on May 12, 2021.
13. "HAL Ajeet", at https://en.wikipedia.org/wiki/HAL_Ajeet#Specifications_(HAL_Ajeet). Accessed on May 12, 2021.
14. Late AVM Viney Kapila, VrC talk, describing his shooting down a Sabre Jet in 1965 war, during a panel discussion at the National Seminar on 1965 Indo-Pak War (Air Force Auditorium, Subroto Park), on September 5, 2014. A yo-yo involves using the third dimension of the vertical to shorten the arc travelled in two dimensions.
15. Boeing.com, "Historical Snapshot", at https://www.boeing.com/history/products/f-86-sabre-jet.page. Accessed on May 2, 2021.

high and fast bombers and fire their missiles or/and guns to destroy them, were used in high-speed slashing attacks that leveraged the MiG's small size especially from head on and tail on and its high-speed capability due to a sleek design. The MiG-21 initially designed as an interceptor of high and fast bombers, due to its relatively high reserve of power/thrust proved to be a nimble dogfighter as well, especially against the over technologised, heavy and relatively underpowered American fighters in the theatre, mostly F-105 "Thunderchief", F-4 "Phantom-IIs", A-7 "Corsair-IIs", B-57 "Canberra", F-100 "Super Sabre" and the like.[16]

The Vietnam War muddied the waters a bit as regards speed vs manoeuvrability, as both elements when combined showed the most promise, as in the case of the MiG-21. This war's main takeaway was that new and novel technologies need time to settle in before becoming totally trustworthy. The US arming of its fighters with early generation Air Intercept Missile (AIM)-9A/B "Sidewinders" and AIM-7 "Sparrow" Air-to-Air Missiles (AAMS) to the exclusion of guns proved detrimental and led to the US since then including the onboard gun/cannon as an essential feature on all fighters, even the currently cutting edge and superlatively expensive F-22 "Raptor" and F-35 "Lightning-II".

Speed became the prime need in this period. The Delta series of fighters from the US, and mirroring these the Soviet MiG-19, 21 Sukhoi (Su)- 7, 9, 15, etc., showed this trend of high speeds. A most desirable additional characteristic at this time was the possession of high manoeuvrability; manoeuvre flaps and leading-edge flaps were developed to increase manoeuvrability. Bombers or strategic attack aircraft opted to fly higher and at high speeds to avoid tangling with these agile fighters. This led to development of high-speed supersonic interceptors to catch and engage these bombers. The MiG-21, Su-9, 11 and the Delta or "Century" series of American fighters (F-100, F-101, F-102 F-103, F-104, F-105, F-106, etc.) fall in this category. These fast fighters had the choice of engaging in combat

16. "Vietnam War Fighter Aircraft Aviation | Vietnam Conflict", at https://www.militaryfactory.com/aircraft/vietnam-war-fighter-aircraft.php. Accessed on May 13, 2021.

or denying an engagement by utilising their superior speed. High speeds were the result of research into high-speed aerodynamics which had run parallel to research into means of improving manoeuvrability. Sleeker low drag airframe designs coupled with powerful turbojet and turbofan engines using reheat or afterburners to augment the engine thrust for short periods of time while keeping the engine's weight in check delivered speeds of up to a shade above Mach 2.0 or over two times the speed of sound. Once again, attempts were made to mate different roles together through the multi-role aircraft design such as the F-4 "Phantom-II", which was capable of performing both air-to-air as well as air-to-ground missions. Further advances led to development of the swing-wing or variable sweep design, allowing the pilot, in flight, to modify the aerodynamic layout of his aircraft to better suit the role being executed at the time such as on the F-14 "Tomcat" and F-111 "Aardvark".[17] Throughout the 1950s and 1960s the emphasis remained on delivering good manoeuvrability combined with respectable top speeds; nonetheless, there was a shift towards role-specific aircraft. Examples are the ground attack role dedicated SEPECAT "Jaguar", A-10 "Thunderbolt-II", Sukhoi (Su)-7BMK and the interception or air-to-air role dedicated MiG-21F and other early model MiG-21s and F-104 "Starfighter". Both functions were distinct, with the former demanding a more stable platform for accurate weapon delivery, and the latter emphasising high acceleration, high top speeds and good manoeuvrability, all of which were attempted to be incorporated in the former types to a lesser extent.

A few specialised programmes were outliers in this trend. The US developed the A-12 later SR-71 "Blackbird" tri-sonic reconnaissance aircraft to overfly enemy airspace on spy missions with impunity. The US also planned a new tri-sonic bomber, the B-70 "Valkyrie" that never entered service, but to counter which the Soviets developed the MiG-25 near tri-sonic fighter. These eschewed manoeuvrability in favour of raw speed.

17. Joe Pappalardo, "Swing Wings It's all done with computers (and good old-fashioned hydraulics)", September 2006, at https://www.airspacemag.com/flight-today/swing-wings-9189621/. Accessed on May 5, 2021.

The overall trend was towards high speed followed by manoeuvre agility in this period.

1970 TO 2000

In this period, the earlier trends towards respectable speed remained, as did the emphasis on high manoeuvrability. High speeds, however, were seen as difficult to attain and maintain and less useful due to the very large radii of turns and low turn rates at high speeds. The high fuel burns due to the engine technology available and very large radii of turn at high Mach numbers made combat difficult, if not impossible with the then technology of onboard gun/cannon and AAMs. This led to exploration of other means of dominance. This emerged to be high manoeuvre agility coupled with new high off-boresight launch AAMs[18] and helmet-mounted weapon cueing systems. New technologies such as fly by wire and relaxed static stability designs enabled extremely high manoeuvrability and manoeuvre agility. It also enabled the same airframe to be more easily utilised for the very different air-to-air and air-to-ground roles. Thus, truly multirole aircraft such as the Swedish AJ-37 "Viggen", French Mirage 2000, and later blocks of the F-16 entered service; though a bias towards manoeuvre agility was clearly discernible in that many of these aircraft accepted somewhat lower top speeds of under Mach 2.0 in their agile multirole airframes. True multirole ability and high agility were seen as force multipliers. This was helped by a much better understanding of aerodynamics, high angle of attack performance, behaviour of vortices and the ability to position them where most desirable. Speeds of Mach 2.0 due to the very large radii of turn and low turn rates were seen as un-usable in combat, so top speeds of about M1.6 to M1.8 were accepted in several designs that delivered superlative manoeuvrability. Alongside advances in sensors and electronics led to true multi-role capability in fighters. The F-16, Mirage-2000, MiG-29, Su-27 represent this era of fighter aircraft design. The trends of desirable

18. This refers to the ability to launch the AAM at a target that is as much as 45 degrees to 60 degrees removed from the fore-aft axis of the AAM launch aircraft.

characteristics that had swung from high manoeuvrability towards high speed in the late 1950s and early 1960s now swung back towards very high manoeuvrability and true multi-role capability. Later developments continued to emphasise extremely good manoeuvrability over speed and pushed towards the newly coined term "omnirole capability". Multirole aircraft could be configured and loaded on the ground for a specific role, such as an F-16 carrying a full bomb load for ground strike or configured with only AAMs for an air-to-air-role with the limited ability to, in the ground attack role to carry say two to four AAMs for self-defence. Omni role refers to the ability of the aircraft to be equipped on the ground such that once airborne it can execute both air-to-air or/and air-to-ground, or other specialist roles in the same sortie due to its inherent high aerodynamic and engine performance, avionics systems on board and weapon mix carrying ability, two outstanding examples of this are the Eurofighter "Typhoon" and the Dassault "Rafale". However, the trend in this period was positively towards high manoeuvre agility and multi-role capability, with speed getting lesser importance in comparison.

2000–TILL DATE

This period witnessed the culmination of previous tendencies towards accepting maximum speeds of around Mach 2.0 or even lower in favour of high manoeuvrability and multi-role to omnirole capability.

Another diversion from the main trend that started in earlier decades was the endeavour to achieve invulnerability from enemy defences by reducing own aircraft signature in important parts of the electromagnetic (EM) spectrum to small values, thus delaying enemy's detection and tracking of own aircraft. This technology is actually that of low observability (LO), though popularly called "Stealth" technology. The US led these efforts and fielded the F-117 "Nighthawk" 'Stealth fighter' publicly in the late 1980s. Strangely, this aircraft saw service as a bomber rather than as a fighter, and has since retired from active service.[19] The B-2 "Spirit" Stealth bomber continues

19. "F-117A Nighthawk Stealth Fighter", at https://www.airforce-technology.com/projects/f117/. Accessed on May 5, 2021.

F-35 has been called the most complex and expensive fighter program ever attempted. Despite the high costs and well-established aerospace majors working on it, delivered F-35s suffer from several shortcomings such as bug afflicted software, poor supply of spare parts, inaccurate gun firing which also causes cracks in the airframe, low engine reliability, engine blade failures, and problems with supersonic flight.

to be in service and has been used in several live operations. Though very advanced it is possibly the most expensive military aircraft ever at over US$ 2 billion per aircraft.[20] New LO fighters, dubbed "Fifth Generation" fighters from the US, include the F-22 "Raptor" which is a mainly air-to-air-machine costing about US$ 334 million per piece and US$ 60,000 per hour to operate[21]. The F-35 "Lightning-II" is a multi-role LO project from the United States that costs approximately US$ 91 million per piece at large purchase volumes and about US$ 67,000 per hour to operate.[22] These exotic aircraft are far too expensive to be affordable in reasonable numbers by most nations. Despite their high cost, both these suffer from serious shortfalls. The F-22 has suffered from persistent problems with its On Board Oxygen Generating System (OBOGS) resulting in hypoxia and aircrew physiological issues.[23] Moreover, Raptors have been suffering from degradation of their high technology radar energy absorbing outer skin, pointing towards major airframe problems ahead.[24] The USAF has 185 of the originally 195 F-22 built left with it, having lost four aircraft in crashes during the F-22's 16-

20. Jacopo Prisco, "B-2 Spirit: The $2 billion flying wing", January 29, 2020, at https://edition.cnn.com/style/article/b-2-spirit-stealth-bomber/index.html. Accessed on May 5, 2021.
21. Colin Ritsick, "F-22 Raptor vs F-35 Lightning II", February 28, 2020, at https://militarymachine.com/f-22-raptor-vs-f-35-lightning-ii/. Accessed on May 6, 2021.
22. Ibid.
23. Dina Rasor, "Pilots as Lab Rats: The Reprehensible Risk-Taking on the F-22 Raptor", May 17, 2012, at https://www.defense-aerospace.com/articles-view/feature/5/135359/are-stealth-fumes-causing-f_22-%E2%80%9Chypoxia%E2%80%9D%3F.html. Accessed on May 7, 2021.
24. Tyler Rogoway, "These Images Of An F-22 Raptor's Crumbling Radar Absorbent Skin Are Fascinating", July 30, 2019, at https://www.thedrive.com/the-war-zone/29218/these-images-of-an-f-22-raptors-crumbling-radar-absorbent-skin-are-fascinating. Accessed on May 7, 2021.

year service with the USAF.[25] The F-35 has been called the most complex and expensive fighter programme ever attempted. Despite the high costs and well-established aerospace majors working on it, delivered F-35s suffer from several shortcomings such as bug afflicted software, poor supply of spare parts, inaccurate gun firing which also causes cracks in the airframe, low engine reliability, engine blade failures, and problems with supersonic flight to name a few.[26]

Given the attributes of a fifth-generation fighter that include LO, supercruise (the ability to fly at sustained supersonic speeds without use of afterburner), high agility and advanced multispectral sensors and sensor fusion (the ability to combine the inputs of many sensors to project a combined complete air situation),[27] these projects also appear to be headed for considerable technology shortfalls alongside time and cost overruns, with high per unit cost of the end product. That would make them rather expensive projects to achieve defined military ends.

There are fifth generation fighter projects underway at various stages in Russia (Su-57), Peoples Republic of China (J-20, J-31), Japan (Mitsubishi ATD-X [Shinshin]), South Korea (KAI KF-X), Turkey (TAI TFX/F-X), and India (AMCA). However, given the cost and complexity, as well as the fact that technologies for detecting and engaging these LO aircraft are already in service, these LO technologies are likely to be more of a temporary detour from the path of pursuing speed and manoeuvre agility in near-alternating manner.

25. David Axe, "A U.S. Air Force F-22 Stealth Fighter Just Crashed. How Many Are Left?", May 16, 2020, at https://www.forbes.com/sites/davidaxe/2020/05/15/an-f-22-stealth-fighter-just-crashed-how-many-are-left/?sh=73a3cfc454c3. Accessed on May 7, 2021.
26. Kyle Mizokami, "The F-35 Is Still Full of Must-Fix Flaws", at https://www.popularmechanics.com/military/aviation/a30718538/f-35-flaws/, January 31, 2020. Accessed on May 7, 2021; Valerie Insinna, "Inside America's Dysfunctional Trillion-Dollar Fighter-Jet Program", at https://www.nytimes.com/2019/08/21/magazine/f35-joint-strike-fighter-program.html. Accessed on May 7, 2021.
27. Jeffrey Hood, "Defining the 5th Generation Fighter Jet", March 14, 2017, at https://www.jble.af.mil/News/Commentaries/Display/Article/1112351/defining-the-5th-generation-fighter-jet/. Accessed on May 7, 2021.

The utilisation of very high speeds in the hypersonic range (above Mach 5.0) appears to be the next major trend. Almost all advanced countries, the US, Russia, PRC, etc., have hypersonic programs underway alongside development of DEW.

PROJECTIONS FOR THE FUTURE

An Air Force and its equipment exist to carry out certain real-world tasks. It is not a ceremonial appendage. This basic fact begs the simple question "what is it for?" Let's see what LO is for. The military aim is likely to be to change the condition of some chosen targets within enemy territory. In order to do this LO technology gives its operators the means to reach this target relatively unmolested by the enemy's Air Defence systems. The cost of LO technology as seen above is, however, prohibitive. So, is there any other manner to achieve the desired end? Fortunately, there is.

In the interplay between speed and manoeuvrability, another barrier hit has been that of human tolerance. Earlier fighters could sustain in the range of about +7 to 8 'gz'. The highly manoeuvrable fighter developed in more recent times can sustain a +'gz' of 9 which is the human limit of tolerance. Hence, with no reliable solution other than the old 'anti-g' suits and slight tilt back of the pilot's seat being discovered there is a serious impediment to achieving even higher manoeuvrability due to aircrew limitations.[28] This leaves speed as the only variable available that can be used to achieve an advantage.

First, to recap the discussion on the play off between manoeuvre agility and speed. We have seen that at the infancy of military aviation speed dominated. Thereafter in a sine curve fashion these attributes switched in primacy for success in aerial engagements. In the most recent period, we have seen manoeuvre agility to be the most desirable or ascendant attribute for almost three decades or more. However, in this same period aircraft have become stronger and now are able to sustain 'gz' of up to +9, which is the human tolerance limit to 'gz'. This limits the prospects of further increases in manoeuvrability unless there is some medical breakthrough that

28. M Khan, et al., "A review of high G-stress induced problems and their solutions", *International Journal of Medical Engineering and Informatics*, Vol. 9, No. 1, 2017, pp. 51–57.

enables humans to sustain higher 'gz'. At the same time AAM technology has matured considerably. Today's AAMs have matured and have much greater reliability, performance and single shot kill probability (SSKP) than their ancestors. Further, great advances have been made in Directed Energy Weapons (DEW).

The utilisation of very high speeds in the hypersonic range (above Mach 5.0) appears to be the next major trend. Almost all advanced countries, the US, Russia, PRC, etc., have hypersonic programs underway alongside development of DEW.

India's aircraft industry has long suffered from the drawback of not possessing cutting-edge jet engine technology. However, with this current trend towards hypersonic speeds and DEW India is particularly well placed. India has successfully tested supersonic combustion ramjet (scramjet) engines and hypersonic craft body shaped and high temperature materials through multiple agencies, such as the Defence Research and Development Organisation (DRDO) and Indian Space Research Organisation (ISRO).[29] It has also demonstrated the Kilo Ampere Linear Injector (KALI)[30] and is working further on the Tactical High Energy Laser System (THELS),[31] Directionally Unrestricted Ray-Gun Array Two (DURGA II) amongst other projects.[32] This gives India the much-missed powerplant in rocket booster coupled to scramjet hypersonic vehicles technology with possible integration of the GTRE Kaveri K-9 and later Kaveri K-10[33] jet engines to give

29. Sushant Kulkarni, "Scramjet vehicle: The significance and capability of the HSTDV", September 13, 2020, at https://indianexpress.com/article/explained/explained-significance-and-capability-of-scramjet-vehicle-that-drdo-tested-6586748/. Accessed on May 9, 2021; Express News Service, "DRDO successfully flight tests hypersonic technology vehicle", September 7, 2020, at https://indianexpress.com/article/india/india-test-fires-hypersonic-technology-demonstrator-vehicle-6586487/. Accessed on May 9, 2021.
30. Rajeswari Pillai Rajagopalan, "What Are India's Plans for Directed Energy Weapons?", September 24, 2020, at https://thediplomat.com/2020/09/what-are-indias-plans-for-directed-energy-weapons/. Accessed on May 8, 2021.
31. Ibid.
32. Mike Yeo, Nigel Pittaway, Usman Ansari, et al., "Hypersonic and directed-energy weapons: Who has them, and who's winning the race in the Asia-Pacific?", March 15, 2021, at https://www.defensenews.com/global/asia-pacific/2021/03/15/hypersonic-and-directed-energy-weapons-who-has-them-and-whos-winning-the-race-in-the-asia-pacific/. Accessed on May 8, 2021.
33. Defence Update, "KAVERI Engine: The Dawn of Jet Engine indigenization in India", at http://defenceupdate.in/dawn-jet-engine-indigenization-india-kaveri/. Accessed on May 14, 2021.

a Turbojet/ scramjet high speed capability. Development of DEW could arm the projected hypersonic combat vehicle with cutting-edge weapons. Given the publicly available data from ISRO on its technology development costs, these high-speed projects should be eminently affordable in comparison to Fifth Generation Fighter projects, while also carrying much lower costs and risks in delays, in view of the fact that all these technologies have already been demonstrated in tests.

A study of the interplay of technologies brings out that the current trend is unmistakably towards high speed and DEW. All intercept missiles, AAMs, surface to air missiles (SAMs) and Ballistic Missile Defence (BMD) missiles head out towards a predicted point of impact (PPI) after analysing the tracked and projected path of the incoming target in order to utilise their capabilities to the fullest. An incoming target flying at hypersonic speeds would require a very quick reaction, very high acceleration hypersonic speed interceptor to enable an intercept at all. Further, if the incoming vehicle changes its path by even a few degrees, the PPI would shift by a very large amount defeating the defensive system. Hence, the probability of guaranteed ingress into even heavily defended airspace, even if equipped with a BMD system, with impunity is guaranteed by hypersonic speeds capable craft.

Thus, investment in hypersonic technology alongside DEW or even hypersonic speed glide weapons could deliver the desired assured penetration and target destruction capabilities against all possible opponents. The probability of effective intercept of hypersonic vehicles is infinitesimally low as on date, and the probability of intercepting such vehicles that can alter their path even slightly is non-existent. In comparison, technologies to effectively detect, intercept and destroy fifth generation fighters exist and are becoming more robust. In fact, one F-117 was shot down by a Serbian SAM-6 weapon system.[34]

34. Mansij Asthana, "How US' Stealth Aircraft – F-117 Nighthawk Was Shot-Down By Russian Missile Defense System In The Spring Of 1999?", December 27, 2020, at https://eurasiantimes.com/how-us-stealth-aircraft-f-117-nighthawk-was-shot-down-by-russian-missile-defense-system-in-the-spring-of-1999/. Accessed on May 10, 2021.

CONCLUSION

This paper has examined the history of military aviation since 1903 till date on the two main parameters of speed vs manoeuvrability to examine their interplay. The study revealed that these two parameters have followed a sine curve path in relation to each other as regards their relative ascendancy in determining effective application of air power. During and after WWI, speed was the main determinant of this change to manoeuvre agility just prior to and during most of WWII, with the emphasis shifting back to speed only by the late 1950s. Since then manoeuvre agility combined with ever increasing multirole capability has held sway. The limits of human endurance to 'gz' have led to a stop in this trend and brought speed to the fore again. In the next few decades high speeds are expected to be the main parameter to determine ascendancy in aerial warfare. Every major aerospace player has a hypersonic program at some level of completion towards a deployable hypersonic military capability.[35]

Given the Research and Development (R&D) already undertaken independently by the DRDO and ISRO, India finds itself in an enviable position of having at least two parallel lines of technology development available in the country to effectively claim pole position in the new technology determining 'top of the totem pole' in military aviation.

What is needed is the doctrinal and operational understanding of this and its implementation by the IAF.

35. EurAsian Times Desk, "China Unveils Camouflaged DF-17 Hypersonic Missiles That Could Be Invisible To Enemy Surveillance Systems", January 4, 2021, at https://eurasiantimes.com/china-unveils-upgraded-df-17-hypersonic-missile-with-shield-against-enemy-surveillance/. Accessed on May 10, 2021. Blake Stilwell, "Why Russia's Hypersonic Missiles Can't Be Seen on Radar", at https://www.military.com/equipment/weapons/why-russias-hypersonic-missiles-cant-be-seen-radar.html, Accessed on May 10, 2021.