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The biodynamic and physiological implications of supermanoeuvrable flight [1]

by

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Abstract

Fighter aircraft are by design highly agile and manoeuvrable weapon platforms. A high degree of agility is essential in the three-dimensional environment of air combat manoeuvring (ACM). Supermanoeuvrability (SM) is the term used to describe the ability of a fighter aircraft to exploit more of its flight envelope through advanced aerodynamic features, including thrust vectoring and advanced flight control systems. SM allows the aircraft to operate effectively at much lower airspeeds, well into the post-stall region of the flight envelope, and to manoeuvre at high angles of attack with full control authority. After examining SM aerodynamics, flight test results and the performance characteristics of current SM aircraft, the paper will then centre on the biodynamic and physiological implications of human exposure to the SM flight environment. SM aircraft will operate in a much more complex acceleration environment than ever before. Exposure of the human occupant of such an aircraft to this environment raises serious questions in terms of the potential for spatial disorientation, the performance requirements of assisted escape systems and tolerance of the cardiovascular system and cervical spine to complex G loads.

"A big aerial barge is too clumsy for fighting. Agility is needed. "

\- Baron Manfred von Richthofen[1]

Fighter aircraft are designed to be agile and manoeuvrable weapons platforms. A high degree of manoeuvrability is essential in the three-dimensional, highly fluid environment of air combat manoeuvring (ACM), in order to achieve and maintain an offensive position relative to the target aircraft. In general terms, the generation of an optimal firing solution requires that the nose of the aircraft be pointed at the target. In the one-versus-one situation, the more agile fighter will be able to achieve such a position first, thus being able to take the initiative, control the development of the engagement and effect a valid shot at the opponent first. With the development of advanced all-aspect air-to-air missiles, the need to obtain a first-shot firing position has become even more critical. Manoeuvrability thus holds the key to success in modem air combat.

Modern fighter aircraft are much more manoeuvrable than their predecessors. Improvements to materials technology and flight control systems have produced new fighter aircraft that demonstrate what have become known as "supermanoeuvrable" capabilities. Supermanoeuvrability (SM) is the term used to describe the ability of a fighter aircraft to exploit more of its flight envelope through advanced aerodynamic features.[2.3.4] It represents a quantum leap in fighter aircraft technology and is destined for incorporation into the next generation of combat fighter aircraft. As an aerodynamic concept, SM allows the aircraft to operate effectively at much lower airspeeds, well into the post-stall region of the flight envelope, and to manoeuvre at high angles of attack (AOA) with full control authority. SM thus significantly expands the useful portion of the fighter aircraft's operating envelope, making it a far more formidable airborne weapons platform than ever before.

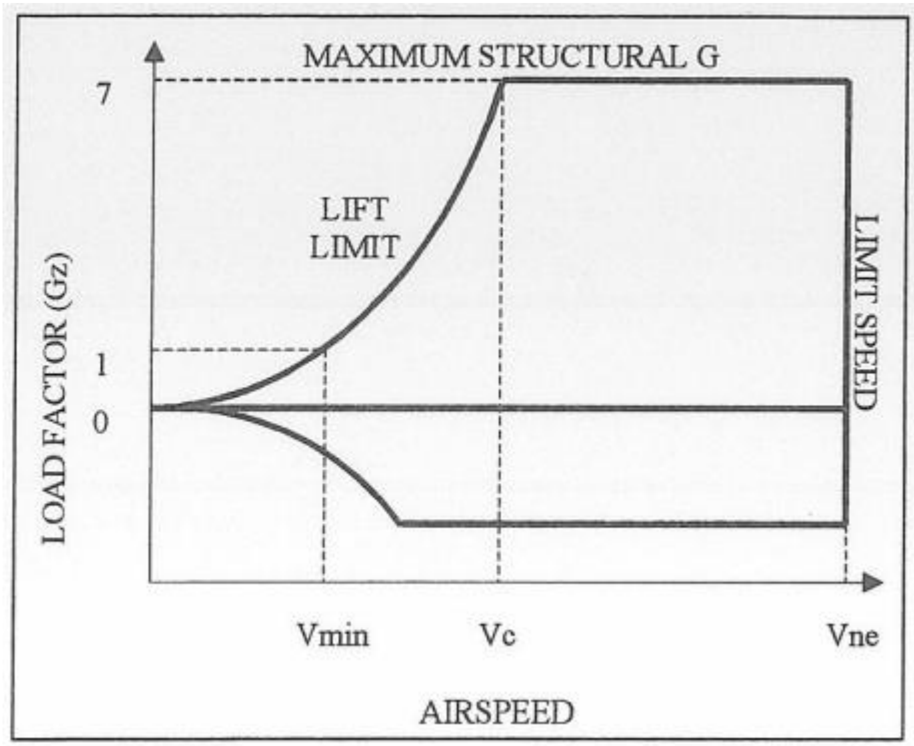

Figure 1. V-n diagram of generic fighter aircraft. Vmin = stall speed, Vc = corner speed, Vne = limit or never-exceed speed (Adapted from Shaw RL. Fighter combat: tactics and manoeuvring. Annapolis: Naval Institute Press; 1985)

As a result of their extreme degree of agility, these aircraft operate in a particularly complex acceleration environment. This environment is now not limited to the Gz axis as is largely the case with current fighter: W.-craft. Previously unheard-of accelerations in the Gx (front-to-hack) and Gy (lateral) axes can be generated by SM fighter aircraft, which reflects their unorthodox manoeuvring abilities. Exposure of the human occupant of such an aircraft to this environment raises serious questions in terms of the potential for spatial disorientation, the performance requirements of assisted escape systems and tolerance of the cardiovascular system and cervical spine to complex G loads.

This paper will examine the aerodynamic concept of SM before addressing the significant biodynamic and physiological implications of human exposure to the SM flight environment.

The Concept of Supermanoeuvrabillty

Early fighter aircraft were limited in their effectiveness by engine performance, structural strength and the weapons that they carried. These aircraft had relatively poor performance envelopes, particularly in terms of turning ability. Their main armaments were guns, and in order to shoot their opponent they were forced to manoeuvre their aircraft into the rear quarter of the target aircraft. A circular chase would then develop, with both aircraft attempting to achieve this rear position first and maintain it long enough to fire effectively on their opponent. Traditional ACM tactics have consistently been based on this need to get behind the enemy aircraft in order to shoot.[1,5]

The advent of the jet fighter and the introduction of the air-to-air missile changed the nature of air combat. The jet-powered fighter of today is a very capable aircraft. It is immensely strong, incredibly powerful and agile. It exploits modern materials technology and is designed in accordance with relaxed stability criteria. It can carry a multitude of weapons, and in the case of the multi-role F/A-18 can be loaded with both air-to-air and air-to-ground weapons.

Air-to-air missiles have a Weapon Employment Zone (WEZ) much larger than that of the gun. WEZ refers to the area around a target aircraft that will result in a high prob- ability of success for a missile fired within that zone. A missile fired outside its WEZ has a low probability of achieving a kill solution. The size of the WEZ varies between different types of air-to-air missiles, depending on the missile's onboard avionics, propulsion and guidance systems, fuel load and turning ability. The larger the WEZ, the greater the area and number of options that are available to the offensive aircraft for a missile shot. In order to win an air-to-air engagement, the offensive aircraft has only to manoeuvre in such a way that the target aircraft falls into the WEZ for the particular missile that is being carried at the time. This position may not necessarily be directly behind the target. Indeed, with the development of advanced all- aspect air-to-air missiles combining high turning performance with high off-boresight capability, the requirement to position one's aircraft to the rear of the opponent in order to fire a shot has diminished to a significant ex- tent. Successful shots can now be taken with the opponent aircraft approaching head-on or at off-boresight angles of up to 90^{o}.

The dominant principle in modern air combat is that of "first look, first shoot, first kill." This principle has driven the development of increasingly powerful and capable airborne radar systems and air-to-air missiles. An aircraft with SM characteristics is in a better position to achieve first look, first shoot, and first kill than a less agile opponent. In order to get the first shot off, SM allows the fighter aircraft to bring the opponent aircraft more quickly into the WEZ of the desired weapon. In addition, SM may arguably be of use in a defensive scenario, by allowing the aircraft to evade an incoming all-aspect missile (i.e. by driving the missile to gimbal lock). The increasing potency of modem air- to-air missiles and the increasing complexity of the modem aerial battlefield makes SM an important addition to the manoeuvring inventory of the fighter pilot.

A certain level of manoeuvring is, of course, still required in the air combat environment, particularly during a close-quarters within visual range engagement. With conventional fighter aircraft, heavy manoeuvring at high G loads bleeds off airspeed, and the aircraft subsequently approaches minimum flying speed, Vmin. One way to offset this is to provide more engine thrust, but there is still only a finite amount of thrust available from a given powerplant. Below Vmin, the aircraft stalls due to lack of effective lift and aerodynamic control. Vmin thus becomes an important limiting factor in manoeuvring flight. Figure 1 is a typical V-n diagram for a generic fighter aircraft, which plots load factor versus airspeed. The stall speed (or Vmin) is clearly shown. Conventional fighters cannot operate in the region to the left of this limit.[1]

Nose-pointing ability, particularly during tracking of the opponent for a guns-kill, requires the ability to rapidly pitch the nose up at the target. Such a manoeuvre will generate a high AOA relative to the aircraft's velocity vector. AOA is the angle formed between the chord line of the wing and the velocity vector of the aircraft and is expressed as units or degrees of alpha or AOA. [1.4] At high AOA, the aircraft's energy state rapidly decays as airspeed is bled off. The limiting lift speed is approached, and if the manoeuvre is maintained, the aircraft will stall and lose aerodynamic control in all three primary axes. The control surfaces (elevators, ailerons, and rudders) become ineffective due to the presence of low-energy airflow and wake shed from the wings and forward fuselage. Aircraft such as the F/A-18 can generate relatively large AOAs (in the order of 35°) but at the expense of some controllability and agility.

SM can be defined as full control authority at high AOA in the post-stall region of the manoeuvring envelope (see Fig 1). As such, the SM fighter can operate safely with full control at airspeeds and AOAs that are denied to a conventional aircraft. At low air- speeds and high AOA, the SM aircraft can point its nose at the target and rapidly achieve a satisfactory firing solution. The SM aircraft has the ability to effectively roll around its velocity vector at high AOA and point the nose in the desired direction. Additionally, this high pitch rate capability and nose authority allow the aircraft to continuously track the opponent aircraft despite any defensive manoeuvring the latter may employ. In tactical terms, constantly threatening the target aircraft (by exploiting the SM aircraft's nose-pointing ability) will be inherently intimidating. Furthermore, conventional clues as to an opponent's energy state will be denied to the target aircraft, as aspect, AOA and nose position will no longer have the same meaning.[1,4]

SM is achieved by designing an aircraft according to extremely relaxed stability criteria.[4] The inherently unstable airframe is able to fly in a controlled fashion only through the use of sophisticated digital flight control systems (FCS) with high-speed processing capability. The flight control systems provide a digital interface between the pilot and the aircraft's control surfaces and are heavily dependent on the quality and sensitivity of the control laws written and incorporated into the flight control computers. The performance of the aircraft can be significantly altered or enhanced by modifications to these control laws. Indeed, flaws in the software can result in the loss of the aircraft, as occurred with one of the prototype SAAB JAS39 Gripen air- craft, which departed controlled flight at an airshow forcing the pilot to eject. Thrust vectoring control (TVC) systems and advanced aerodynamic features (such as powered canard foreplanes) provide the appropriate control authority in all regions of the flight envelope.

TVC allows flight at very low Vmin values. In the case of the British Aerospace/McDonnell Douglas Harrier jet, TVC allows a Vmin of 0 knots of forward airspeed to be achieved in the hover mode of vertical flight. In addition, this VfSTOL jet is capable of vectoring in forward flight by rotating the engine nozzles fully forward. This can produce rapid decelerations in the Gx axis, with a relatively rapid transition therefore between conventional forward flight and vertical flight. This has considerable potential for tactical advantage, particularly against a less agile aircraft, as it forces the other aircraft to over- shoot and instantly become defensive rather than offensive.[1,5]

The Harrier's TVC system is mounted mid-fuselage, and as such does not allow it to achieve or sustain a particularly high AOA. Positioning the TVC aft of the engine nozzles allows the jet efflux to be deflected, which will produce a high pitch moment relative to the aircraft's velocity vector. Given enough engine thrust, the aircraft can achieve and maintain a high AOA, effectively using the thrust as an aerodynamic control force.[4] In this way, the SM aircraft can operate beyond the stall barrier at previously unimaginable AOAs with no loss of control authority.

Current Supermanoeuvrable Aircraft

A number of experimental aircraft have been designed, built and test flown in order to investigate the supermanoeuvrability concept. Perhaps the best known of these is the Rock- well fMBB X-31 program. This aircraft first flew on October 11, 1990 and flew with thrust vectoring paddles on February 14, 1991.[2.5.6] The single-engined X-31 has a cranked delta wing with powered canard fore planes and a fly-by-wire flight control system. The three thrust vectoring paddles can deflect the jet exhaust by up to 10.[2.5.6.7.8] It has achieved an AOA of 70" during ACM, as well as demonstrating full post-stall controllability.[2] It became the first aircraft to execute a minimal-radius 180" turn.[6]

Several existing fighter aircraft have been modified as part of various SM technology flight test programs. These programs are the F-16 AFTI (Advanced Fighter Technology integration),[9,10] the F-16 MATV (Multi-Axis Thrust Vectoring), J the F-15 STOL/MTD (Short Takeoff and Landing/Manoeuvre Technology Demonstrator),[11] the F-158 ACTIVE (Advanced Control Technology for Integrated Vehicles)[11] and NASA's F/ A-18 HARV (High Alpha Research Vehicle). All of these programs are aimed at investigating the characteristics of advanced thrust vectoring and high AOA capabilities. AOAs of 70" and beyond have been achieved, with the aircraft remaining fully controllable.[2]

The Russian-designed Sukhoi Su-37 Super Flanker is an extremely manoeuvrable aircraft, which ably demonstrated its capabilities at the 1996 Famborough airshow. It was first flown on April 2, 1996 under the code "Project 711." This formidable fighter aircraft has canard foreplanes, thrust vectoring via fully steerable engine nozzles (maximum deflection of±. 15" at 30"s-I) and a quadruplex digital fly-by-wire active flight control system.[3,6,8,12,13,14] Presently the nozzles are steerable in pitch only, but vectoring in yaw is being considered.

Manoeuvres

The Su-37 has demonstrated a number of manoeuvres that characterise the performance of a SM fighter aircraft. The "Cobra" and "Super Cobra" manoeuvres involve rapid pitch up to a high AOA while the aircraft continues on a horizontal forward flightpath. The high AOA is maintained (greater than 130" in the case of the Super Cobra - in this configuration the aircraft is effectively flying back- wards) for several seconds as airspeed decays rapidly, before the TVC is used to pitch the nose forward to allow recovery. Very little altitude change occurs with these manoeuvers.[3,13]

The "Kulbit" manoeuvre is essentially a backward somersault through 360", using thrust vectoring for rapid pitch rotation, again with very little change in altitude. During the manoeuvre the aircraft continues to fly along its forward flight path. Effectively a vertical loop has been completed in little more than the length of the aircraft.[3] A variation on this manoeuvre is the "bell turn," in which a Cobra-style rapid pitch up is used to generate a high AOA (approximately 90") that is maintained until forward airspeed is effectively zero. Thrust vectoring is then used to rotate the aircraft backward about its tail, with a subsequent roll to normal flight from the recovery drive. This manoeuvre is effectively a minimal-radius 180" reversal. Another variant of this minimal-radius 180" reversal is the "J turn," in which the aircraft pitches up to approximately 50-55", then rolls rapidly about 160" around the velocity vector to ultimately roll out heading in the opposite direction. This particular manoeuvre is also called the "Herbst Manoeuvre," after Dr Wolfgang B. Herbst, one of the initiators of the X-31 program.[2,3,13]

The "helicopter turn" involves the air- craft, in a low-speed, high-AOA state, descending rapidly while turning at a high rate around the horizon. The aircraft's velocity vector is essentially pointed down, with the aircraft rotating around it. Using this manoeuvre the aircraft can lose height quickly while still tracking the opponent aircraft.[2,3]

The F-16 AFI'I technology demonstrator aircraft was unique in that it was capable of two additional manoeuvring parameters: direct side force and direct lift, by exploiting advanced integrated aerodynamic control technologies (including decoupled rudders). Direct side force allowed the AFTI pilot to laterally translate the aircraft at up to ±. 2 Gy with no corresponding pitch or roll change. To an observer watching the manoeuvre, the aircraft would appear to suddenly move side- ways while maintaining the original attitude. Similarly, the aircraft had the capacity for direct lift, allowing it to climb during forward flight with no change in aircraft attitude (much like the Harrier).[9,15]

The combat validity of these manoeuvres is still the subject of much controversy. "Speed is life" is an axiom of air combat. Exploiting SM characteristics tends to put the aircraft into a low-speed, low-energy state. If the target aircraft is not eliminated with the SM-generated shot, it then has a significant manoeuvring advantage over the lower- energy SM aircraft. The SM aircraft becomes in effect a ripe target, until it can regenerate its energy state. Thus, the pilot of a SM fighter must ensure he gets a kill when exploiting the manoeuvring characteristics of his aircraft.

Nonetheless, there appear to be a number of tactical advantages with SM technology, as mentioned above. These include consistent and continuous high-alpha nose- tracking ability, denial of conventional energy state clues to the opponent, and the ability to use the post-stall region of the envelope against a conventional opponent. In using the latter feature, the SM aircraft can convert a defensive situation to an offensive one by executing a minimal-radius 180 turn or by forcing the opponent to overshoot. This gives the SM aircraft the upperhand in a low-speed air combat engagement. Furthermore, the SM aircraft is likely to be able to achieve first look, first shoot, and first kill much earlier and more effectively than a conventional fighter aircraft.

In order to demonstrate this, the X-31 took part in a series of ACM evaluation trials against conventional fighter aircraft including the F/A-18 and F-14. The results were impressive: in close-in ACM, the X-31 was the victor in 104 out of 116 engagements. This represents an air superiority factor in favour of the X-31 of 8 to 1.2

The Implications of Human Exposure

Supermanoeuvrable flight is therefore characterised by high +Gz onset rates, high angular accelerations in all three primary axes (X, Y and Z) and rapid changes in attitude and orientation.[2,3,4,15,16,17,18] Such a complex acceleration environment has significant biodynamic and physiological implications for the human occupant of such an aircraft. Specifically, these relate to problems of cardiovascular tolerance to high rates of applied +Gz the tolerance of the cervical spine to the complex acceleration environment, the potential for spatial disorientation (SD) of the pilot during such unorthodox manoeuvring, and the additional requirements of assisted escape systems.

Cardiovascular tolerance

Current fighter aircraft are capable of very high +Gz loads, in the region of +7.5 to +9 Gz. Future fighter aircraft such as the F-22 and the Eurofighter 2000 are projected to be capable of at least +10 Gz (peak) and +9 Gz (sustained). Furthermore, the +Gz onset rates of these aircraft are very high, in the order of 15 Gs-1 in the case of the Eurofighter 2000.

SM aircraft will at the very least be capable of similar load factors and +Gz onset rates. The use of vectored thrust technology may allow high +Gz loads to be sustained for more protracted periods of time. Clearly the potential for G-LOC (G-induced loss of consciousness) to occur in the pilot of a SM aircraft is much greater. 19 While there is evidence that fighter pilots develop a degree of cardiovascular adaptation to their repetitive exposure to high +Gz this will not help the novice pilot.[20.21.22] Over time it is likely that a pilot will adapt to the +Gz envelope of the SM fighter, but until this occurs there is the not inconsiderable risk that the physiological capacity of the novice pilot will be exceeded by the extreme performance capability of the aircraft. G-LOC will thus remain an omnipresent threat to the fighter pilot.[19,23,24,25,26]

It will be imperative then to accurately map and profile the G environment of the SM fighter aircraft, as has been done with other fighter aircraft, including the F/A-18 Hornet.[27,28] Only by conducting this research will the aerospace medicine community be able to fully establish the extent of the biodynamic challenge facing the pilot of the SM fighter aircraft. Current anti-G countermeasures will not offer the required level of protection.[16] ls A greater understanding of the magnitude of the challenge may well lead to more effective countermeasures to protect the pilot from the environment he or she must operate in.

<u>Cervical spine</u>

+Gz - induced neck Injuries are a frequently reported phenomenon in pilots of high-performance fighter aircraft.[29,30,31] A study among RAAF fighter pilots found a +Gz- induced neck injury prevalence rate of 85%.[30] several causal factors have been identified, such as the level of +Gz experienced, movements of the head under high applied +Gz loads, and the weight of the head-helmet complex. The position of the centre of gravity of the head is also important. This tends to be forced forward when helmet-mounted equipment such as night vision goggles or helmet- mounted sights and display systems are used.[30]

With SM fighter aircraft, the G loads will be multi-axial.[16.17] G-induced neck injuries in pilots of SM aircraft will therefore be the result of a complex vectorial sum of G loads. Of particular concern here in the pathogenesis of such injuries is the magnitude of the lateral or Gy component. These can be significant with SM fighters and can clearly result in considerable potential for injury to the neck when the unsupported and unrestrained head is subjected to these high Gy loads. There is a clear compromise be- tween protecting the neck by head restraint or support systems and the requirement for the pilot to have adequate all-round (especially rear-quarter) vision.

The problem is likely to be compounded even further by the incorporation of helmet-mounted sighting systems for use with the newer all-aspect air-to-air missiles. These systems are destined to be standard operating equipment for the pilot of a SM aircraft, in order to maximise the combat effectiveness of the aircraft as a weapons system. However, the price to be paid for increased utility of the aircraft is a greater incidence of +Gz-induced neck injuries. Indeed, this type of injury is likely to be reported far more frequently and/or to be of greater severity in the SM fighter pilot than it is in pilots of current fighter aircraft.

Spatial disorientation

The very nature of SM flight creates an extremely dynamic motion environment that could lead to spatial disorientation of the pilot, with the concomitant flight safety implications.[16.17] At high AOAs, the pilot will lose the horizon as a major visual reference and orientation cue. This, combined with rapid attitude changes and high angular accelerations in several axes, theoretically increases the potential for SD. This can readily be appreciated when one considers the type of manoeuvres that SM fighter aircraft are capable of, as discussed above. Most of these manoeuvres involve significant reduction in forward speed (Gx deceleration), rapid pitch-up, and in most cases a high rate of roll around the velocity vector and/ or rotation around the aircraft's centre of gravity (i.e. the helicopter turn). The neurovestibular integration product of the resultant sensory inputs is likely to be unfamiliar to the pilot, tending to disorient him as a result. At the very least, maintaining situational awareness will be much more of a challenge.[16,17] There have been reports from the various SM flight test programs of disorientation and loss of situational awareness occurring in some of the test pilots.[16]

SM flight will subject the semicircular canals (Sees) to multi-directional stimulation at suprathreshold levels. The 3 matched pairs of sees transduce angular accelerations, and with SM flight each pair of canals is likely to be detecting such angular excursions. The threshold limit for detection of angular acceleration by the sees is described by Mulder's constant, which has a value of 2.s.1. This constant is an angular acceleration-time product, and any stimulation greater than 2.s.1 will be detected by the sees and communicated to higher cortical centres.[32.33] The rapid attitude changes and high roll rates inherent in SM flight are likely to far exceed Mulder's constant, and as such be of supra- threshold intensity.

The complicating factor is the requirement to move the head around whilst manoeuvring in order to maintain situational awareness and visual contact with other air- craft, particularly the target. Such head movement could well precipitate a cross- coupled or eoriolis illusion that could conceivably be quite severe.[32,33] Furthermore, the G-excess illusion could also be more prevalent and potentially more severe for the same reasons. Some individuals could also suffer from motion sickness due to the highly unusual nature of SM flight.

It is likely that the pilot will adapt to the potentially disorientating nature of SM flight, but certainly during initial conversion training or after a layoff period the potential for SD is much higher. It seems logical to argue that a not insignificant number of these aircraft will be lost as a consequence of SD during the first several years of their service life, due to the aircrew's inherent unfamiliarity with the dynamic nature of the SM flight environment.

Assisted escape systems

The modern ejection seat is an extremely capable escape system. SM fighter aircraft, however, create a new set of performance requirements for ejection seats. The performance envelope of the seat must have a greater volume than is currently available in order to reflect the enhanced manoeuvring capability of the airframe, and to ensure the safe escape of the pilot.

The ejection seat fitted to a SM fighter must be able to operate at low forward air- speeds, at high angular accelerations and at particularly unusual attitudes. Furthermore, it must be able to generate a safe escape trajectory despite the rapid gyrations that the aircraft might be undergoing as it manoeuvres. As has been seen already, SM flight is characterised by its highly dynamic nature, and the generation of a complex acceleration environment. The ejection seat must be able to cope with these forces, such as high lateral G loading, high AOA, high rates of rotation, or high sink rates, alone or a combination, at the moment that the ejection sequence is initiated. The seat must be capable of clearing the aircraft despite such adverse conditions, and of ensuring adequate altitude gain and time of flight for full parachute deployment. Unless the ejection seat is capable of meeting these objectives, the pilot has less chance of surviving an ejection during a SM phase of flight. At the very least, his chances of sustaining the well-known forms of ejection injury rise considerably. To prevent this, the SM fighter must have an ejection seat fitted that has been designed to meet SM specifications.

Conclusion

Life for the fighter pilot in the next millennium is likely to be far more complex than it is now with the introduction of SM aircraft into service. As has been discussed, there are significant biodynamic and physiological implications for the human occupant of the SM fighter. While the engineering development of these aircraft proceeds, a full appreciation of these implications remains pending.

There is little doubt that the spectacular increases in performance and capability afforded by SM fighter aircraft have a very real human cost. The aerospace medicine community must address the implications of human exposure to the SM flight environment, in order to protect the fighter pilot from the adverse consequences discussed in this paper. After all, it is these individuals who will be regularly exposed to what is essentially a complex, dangerous and poorly understood biodynamic environment.

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