Wright Brothers Lectureship in Aeronautics

Characteristics of Fighter Aircraft

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IT is challenging to have the opportunity to present views regarding fighter aircraft at this time, in the second half of the 1970's, since the western aviation world has just witnessed and is still witnessing, after a pause of some 15 years, a wave of new fighter designs being developed and launched into production and service. Some of these new airplanes will dominate the scene for the next 15 years or more, that is, well into the 1990's. Nevertheless, are we already entering the period where concepts for yet another generation of fighters are being developed?

The evolution of the fighter aircraft, and there have been a number of revolutionary steps, commenced with powered flight as pioneered by the Wright Brothers.

A brief review of this history may provide a better perspective for our views, even if the author of this paper is not a researcher of aircraft history and therefore may not be accurate in detail.

The initial generation of fighter aircraft (in W.W.I) had to solve the problem of developing an effective armament, the art of maneuvering flight having been provided by the Wright Brothers only a few years earlier. The unarmed early airplanes were nevertheless providing effective reconnaissance and were as such already "fighters." The Wright Brothers thus delivered the world's first actual fighter to the U.S. Army Signal Corps. The "armed fighter" was, in effect, only a reaction to an earlier airborne threat to the land and naval forces.

The initial fighter armament of handheld guns was soon overtaken by the aircraft-mounted machine gun, but it was difficult for the pilot to control the airplane with one hand and to point the gun with the other, especially if a propeller in the front was in the way of the natural line of sight.

The obvious solution of taking a weapons operator or "gunner" along was detrimental to the fighter's rate of climb and speed. The other solution of reverting to a "pusher installation" of the engine also resulted in a heavier airplane.

The truly ingenious solution was that of firing through the tractor-propeller with a rigidly mounted gun and accurately pointing and aiming by controlling the direction of flight and attitude of the aircraft. The propeller was protected first by local armor and later by a synchronizing system. This system was, I believe, invented by R. Garros of France in 1915, met instant success, and set a pattern which is still valid. I am recounting this well-known history because I believe that it really started the fighters as a special breed of airplane (see Fig. 1).

After its birth, the fighter aircraft during the next 20 years evolved apparently with the main aim of maximum 1-*g* SEP or rate of climb. This was done by increasing engine power in a number of steps from 80 hp by a factor of 10 while improving specific weights such that gross weight increased from 1100 lb by a factor of 3.5 only. (Power loading by 2.85.)

Airframe size changed little in this period; it was built around the pilot with a wingspan of 30 ft. Aerodynamics must have been subordinate to the structural designers who retained the light, simple, and well-proven externally braced and fabric-covered designs. Materials remained generally steel tube and wood, even though aluminum had already been used for the Zeppelin airships. This type of construction also had the advantage of being easy to repair.

By the early 1930's, however, the designers of airliners and bombers really started to apply aerodynamics, including retractable landing gears, and combined this with higher wing loadings and stress-skin aluminum structures. They were outspeeding the contemporary fighters, which did only about 230 mph with an engine of 600 hp. The fighter community had to react since it could not justify its existence for long by pointing out how excellent they remained in fighting their own

Gero Madelung was born in 1928 in Berlin, Germany, and was educated at Stuttgart Oberschule (Highschool) and Stuttgart Technische Hochschule. He then took his degree in mechanical engineering at the Clarkson Institute of Technology, Potsdam, N. Y., in 1950 and later his degree of Diplomingenieur at the Technische Hochschule München (Munich). From 1950 through 1952 he was employed by the General Electric Co., USA. He then joined the Messerschmitt Company and spent four years (1953-1957) in Spain – first as a project engineer and then as local representative of Professor Messerschmitt. During this period Messerschmitt developed and built, in conjunction with La Hispano Aviacion, the trainer aircraft HA 100 and the twinjet trainer HA 200. Project definition was also carried out on a lightweight supersonic fighter, the HA 300. In 1958 Prof. Madelung returned to Messerschmitt AG in the FRG and subsequently worked on behalf of Messerschmitt in the Entwicklungsring Süd – first as manager of the design department and then as director of design and Messerschmitt representative of the technical board of the group. During this period a large proportion of his work was devoted to vertical takeoff design of the VJ 101 experimental aircraft and variants. From 1965 to 1967 he was international program manager for the definition phase of the US/FRG advanced V/STOL weapon system program. He was then responsible at Messerschmitt-Bölkow-Blohm GmbH for the military aircraft division and the formation of the MRCA program. Prof. Madelung was appointed Managing Director of PANAVIA Aircraft GmbH upon foundation of this company in 1969. He is also a Professor of Aeronautics at the Technical University of Munich, and is a member of the Deutsche Gesellschaft für Luft- und Raumfahrt (DGLR) and of the AIAA.

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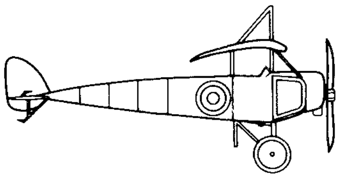

Fig. 1 Morane-Saulnier, 1914.

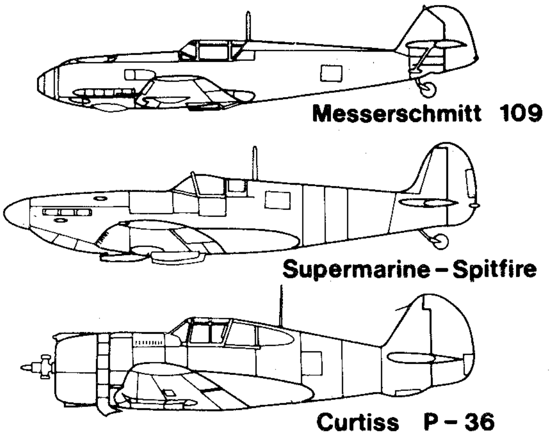

Fig. 2 Fighters 1935-1936.

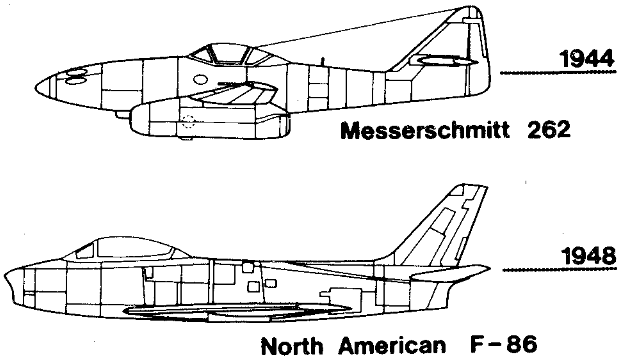

Fig. 3 Early jet fighters.

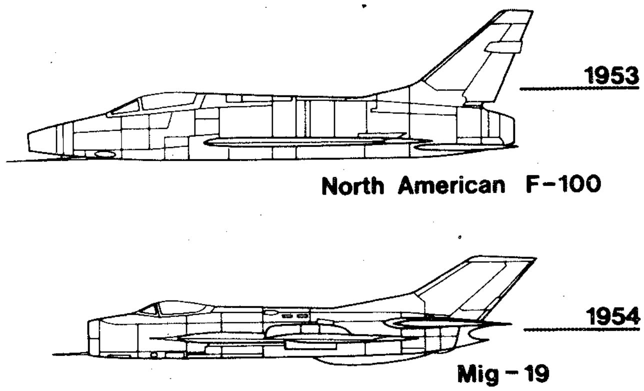

Fig. 4 First supersonic jet fighters.

kind. This started a revolution in fighter requirements, and for the next 25 years these were reoriented towards excelling in maximum speed. It also started the introduction of mechanical complexity with all sorts of variable-geometry features: retractable landing gear, hydraulic system, flaps and slats – soon used as maneuver devices, cooling system flaps, and variable-pitch propellers. The first fighter coming very close to this new concept in 1933 was, I believe, the Russian Polikarpov-"Rata," which only lacked the aluminum stress-skin and the closed canopy. In the following year appeared the ME-109 and the Curtiss P-36, followed shortly by the Spitfire (see Fig. 2), all of which had, initially without much increase in engine power, a speed advantage of some 30% over the previous fighters. Early combat encounters proved the superiority of the new design despite its higher wing loadings.

Once the philosophy of maximizing fighter speed had been accepted, it was soon recognized that propulsion by propellers (and reciprocating engines) would limit this to some 450 mph. Work on the first jet engines started at about the same time as the second-generation fighters emerged and took only 10 years, to the mid-1940's, to completely take over the propulsion of fighters. Jet propulsion was first applied to fighters! In this same period, reciprocating engines were developed with high performance (up to about 2800 hp) and with turbo-supercharging for altitude performance.

Yet in 1944 the first operational jet aircraft, the ME-262, immediately had a speed advantage of about 100 mph with two jet engines of only 2000 lb thrust each. Relative to the fastest bomber, the B-29, the advantage was almost 200 mph. The airframe and aerodynamics of these first jet fighters were not really much advanced over the contemporary propeller aircraft, apart from the thinner symmetric airfoil, tapered spar caps made of steel, and a nose landing gear with a braked wheel. I was an apprentice at Messerschmitt when production of the ME-262 started, and I recall that the advent of the jet engine was welcomed as a move towards mechanically simpler fighters. The reciprocating engines with their increasing number of cylinders (already 48-cylinder engines were under discussion), their supercharging, and their cooling system were getting increasingly more complicated. The jet engine had fewer moving parts and bearings, and the podded engine installation of the Messerschmitt twin-jet was mechanically very neat. (It was, however, not so from the pilot's point of view in terms of engine handling.) As you know, it did not take very long for complexity to catch up again.

As before, combat experience with the speed advantage was positive, despite another increase in wing loading. The associated disadvantage of requiring longer runways for these fighters was accepted by the various Air Forces.

It was evident that further development of the jet engine would soon push the aerodynamic design concept to its Mach number limit. The propulsion breakthrough was, however, followed by an aerodynamic breakthrough with discovery of the effect of wing sweep in the early 1940's. Again this technology reached the users first with fighter aircraft, that is with the F-86 and the Mig-15 in 1948. The speed was pushed right up to Mach 0.9, the limit of the thick swept wing, which was another step of about 160 mph (see Fig. 3).

The size and weight of those jet fighters was, despite this tremendous advance in performance, no greater than that of the most powerful propeller-driven fighter (N 15,000 lb). Many people thought that fighter speed performance would settle for a while at that, and this may have been better in the long run.

However, the aviation world, and in particular the fighter community, was in a speed craze; and daring experimental airplanes in the U.S. had demonstrated by 1947 that the sonic barrier could be overcome by brute force and skillful design in terms of thrust, reduced wing thickness, and powered control surfaces.

The increased thrust requirement could be met by the jet engine using reheat, which in turn required variable nozzles and resulted in additional complexity. Wing loading had to be further increased and so were the airfield requirements. Brake parachutes were required to shorten the landing run.

The fighter community, I believe, lost its innocence at this stage, and only the major military powers, the U.S. and Russia, entered this next round in the early 1950's with the introduction into service of the NA-F100 and, one and a half years later, of the Mig-19 (see Fig. 4). The thrust of these magnificent fighters was about 3 times that of their predecessors; their speed at Mach 1.3, about 40% higher. The single-engine single-seat F-100 had about twice the takeoff weight of its predecessors (30,000 lb) and was equal in weight to the twin-engine medium bomber "NA-62 Mitchell" with a crew of four, which saw service only 12 years earlier.

The aviation world of Britain, France, and Sweden, however, followed suit with prototypes capable of Mach 2 which were demonstrated in the mid-1950's. Introduction into service of these fighters started from 1958 to 1960. From the technology of the F-100 and the Mig-19, it was a matter of air intake development and further refinement of engine and airframe to reach the limit speed for aluminum airframes. The first fighter prototype to reach this limit was, I believe, the Lockheed F-104, with a thin unswept wing – a wing concept which was to gain prominence in future fighter designs, particularly in the U.S.

"Mach 2" was to be the limit of the fighter communities' speed craze; and only special purpose aircraft, such as the Lockheed YF-12 and SR-71 and the Mig-25, were developed for yet higher speeds. The fighters which were developed in the mid-1950's are, however, still dominant in the world's forces; and inflation makes these complex airplanes appear inexpensive relative to anything we do in the 1970's.

The question arises why, having reached the "ultimate performance" in terms of speed, new fighter designs were actually required. It is not surprising that the requirements picture was at first hazy for the follow-on generation, the development of which only started toward the end 1960's and early 1970's with one notable exception.

The following new requirement areas were, however, becoming apparent:

1) In the late 1950's concern was mounting relative to the vulnerability of fighter forces relying on 9000-ft runways. Much interest was shown in V/STOL concepts for fighters, including NATO level competitions; and a number of experimental engines and planes were funded and tested in various countries. I have been active myself in the development of a supersonic V/STOL concept, the VJ-101, with swivelling reheat jets and thrust/weight of course greater than one. Most of the concepts were, however, too complex, mainly due to safety considerations, and required three or more engines. However one of the earliest and most simple V/STOL schemes, the single-engine Hawker Harrier, was successfully introduced into service in the early 1970's.

The concern of airfield vulnerability is, however, still valid, and most of the latest generation fighters have improved field performance through increased thrust-to-weight and high-lift wings or reduced wing loading. Two designs, the Swedish Viggen and the European Tornado also employ thrust reversing. The latter also has less extreme tire pressures to allow emergency operation off the main runway and taxiways.

2) Another new requirement which became important to the fighters in their fighter-bomber role was that of low-level/high-speed penetration. In fact, most of the early Mach 2 fighters are usable in this role due to their high wing loading. The F-104 with appropriate navigation equipment and plenty of external fuel, is still widely in service for this task, a task which is of particular importance in Central Europe.

However, by the early 1960's new technologies became apparent which would allow a new style of low-level/high-speed penetration and weapons delivery. These were the fan-jet engines with greatly improved fuel consumption, and the terrain-following radar system. At the same time, a breakthrough in aerodynamics was achieved by John Stack at NASA with a practical scheme for the variable-sweep wing. The basic idea of variable sweep dates back to the mid-1940's when the problems associated with large angles of sweep became apparent; but it took 15 years to find a practical solution. For the fighter aircraft designer, variable sweep allowed the retention of optimum high-speed/low-level dash performance with a gain in cruise performance at all altitudes and greatly improved airfield performance. The additional complexity was not overwhelming, bearing in mind the multitude of powered control surfaces and landing gear or folding wings and blown flaps which were already in use.

It is unfortunate that the F-111, which pioneered these new technologies, had such a bad start on the part of engineering, mainly due to underestimating the difficulties of applying afterburning to a fan-jet. This is still not an easy task.

Of the fighter projects which were launched in the late 1960's or early 1970's, the majority used the afterburning fan-jet: in the U.S., F-14, F-15, and F-16; in Europe, the Jaguar and Tornado; in Sweden, the Viggen (actually launched earlier); and in Russia, probably the Mig-23 (Flogger) and SU-19 (Forcer). It is, however, significant that the latest of the U.S. fighter projects, the F-18, is reverting to a simpler afterburning jet, as has France with the M-53 which will be used in the Delta-2000.

Variable sweep is being widely applied with the F-14 in the U.S., the Tornado in Europe, and all three modern Russian tactical fighters. A terrain-following radar system is used on the Tornado and probably on the SU-19.

3) Yet another new requirement which emerged in the late 1960's called for a better balance of performance in air-to-air combat. The high-speed capability of the Mach 2 fighters of the mid-1950's turned out to be of little practical use as there were no bomber or attack aircraft flying at such speeds (apart from special purpose aircraft which could not be intercepted anyway by a tactical fighter), and air-to-air combat could actually be sustained only in the lower transonic regime with these airplanes. A better balance of performance could be achieved mainly by a decrease in wing loading, together with a capability of the airframe and the propulsion system to achieve increased angles of attack and, at the same time, increasing thrust-to-weight of the aircraft. These characteristics would provide for higher turn rates in the speed and altitude regime of dogfights, at the expense of increased wetted surface and of a heavier airframe, i.e. trading rate of climb and low-level dash performance. It is a tribute to aviation technology that the new generation of fighters actually improves the latter two performance regimes while making a big step forward both in turn rate and, as a fallout, reduced airfield requirements.

4) Finally, the new fighters would require a "look-down" capability of the radars in their air-to-air role in order to be able to fight the low-level intruders. The F-14 was probably the first fighter to have this important capability.

I will try to summarize the design response to the above stated requirements of the 1960's. These requirements yield the fighters which are no longer designed to the formula of maximum speed.

Most of the designs still do retain a specified Mach 2 capability – the F-14 and F-15, the Tornado and the Delta-2000, the SU-19 and the Mig 23. This is apparent from the air-intake configurations. However, the attack version of the Mig-23 is reported to have a fixed intake, and so have the F-16, F-18, and the Viggen. This is a significant new trend.

The four U.S. designs (the F-14, F-15, F-16, and F-18) and the Viggen have low wing loadings (50 to 70 lb/ft^2) to optimize turn rate. The latest three U.S. designs (the F-15, F-16, and F-18) have, at the same time, thrust-to-weight ratios in excess of one, resulting in a big step forward in dogfight capability. They employ advanced materials, including composites, and very advanced engines. The latter two designs are introducing a new aerodynamic feature, the "strake," to improve the lift of the thin unswept wings at high angles of attack. In the case of the F-15, this dogfight capability is combined with fairly long-range air-to-air missile intercept capability which results in a very big fighting machine, with a wing area of 650 ft^2, as big as the F-14 fleet defense fighter.

With these big fighters it makes sense to go for a "hi-lo-mix" with complementary lighter fighters like the F-16 and the F-18, in particular if it is possible to standardize on some of the components, notably the engine. This has been achieved between the twin-engine F-15 and the single-engine F-16, a practice which was quite normal in the older times. Lately, however, there is a strong preference in many services for twin-engine fighters, despite their high cost, due to better peace-time safety. In some countries the public media are using every fighter accident for adverse commentary, in particular in the critical launching phase of an expensive project. A new engine will therefore generally have to be introduced on a twin-engine aircraft, which unfortunately tends to compound the development cost of the aircraft.

In Europe most of the forces have emphasized requirements 1 and 2, that is low-level/high-speed penetration capability associated with excellent airfield performance. The defense environment of these countries requires instant and effective response, day and night and all weather in the land battle. The latest fighter engine technology, with the magnificent thrust-to-weight ratio of about 8.0, with variable sweep, and with considerable use of titanium, was applied in the Tornado to improve payload-range by a factor of about two for this mission and to cut runway requirements to 60%. This twin-engine fighter with plenty of avionics, a crew of two, and a wetted surface of only about 1850 ft^2 is smaller than an F-4 Phantom, about in between the big and new U.S. fighter with wetted surface of about 2800 ft^2 and the small fighter of about 1400 ft^2. At the same time this aircraft will provide first-class long-range air-to-air capability with an air defense avionics fit and long-range missiles.

Sweden has been, since the advent of the jet engine, in the forefront of advanced design and has developed with the Viggen a well-balanced single-engine single-seat fighter with two versions for air-to-ground and air-to-air missions.

France has launched the single-engine Delta-2000 fighter, which will apparently again emphasize high speed combined with high rate of climb. It has a comparatively small and simple "flying wing" airframe and also a fairly simple engine as noted above. One of the attractions of this airplane may be its cost. For comparison of the relative size of fighters discussed above refer to Fig. 5.

Russian military airplanes are difficult for this author to assess, largely due to the lack of data regarding the engines. The variable-sweep fighters, however, indicate design for longer ranges and higher maneuverability than the previous designs with large angles of sweep and small aspect ratio.

A general and very serious problem of this latest generation of fighters is that of high unit cost. A good fraction of the cost, perhaps one-third, is due to items and capabilities which were hardly present in the classic "fighters of the aces." This is due to avionics.

The introduction of avionics mounted in the early 1940's, when radar was fitted to the twin-engine two-seat escort fighters like the ME-110 or to light and fast bombers like the DH-Mosquito for night fighting of the bomber fleets. As a next major step the air-to-air guided missile was introduced in the 1950's with the F-102, permitting long-range interception; and this line of development was continued mainly in the U.S. with the massive twin-engine two-seat fighters, McDonnel F-4 and Grumman F-14. The size of missiles and the diameter of the long-range radar alone called for a big aircraft for this role. The requirement for the radar to "look down" and "track while scanning" added to the complexity of the equipment. In Europe somewhat smaller fighters were developed for this role, the latest one being the AD version of the Tornado. The electronic warfare versions of these fighters of course carry a considerable amount of other or additional avionics items. It would be idle to speculate as to whether the reliance on avionics to such an extent will be cost-effective. There is, however, no doubt that the right applications greatly enhance the capabilities of the air crew, a classic example being the lead-gunsight.

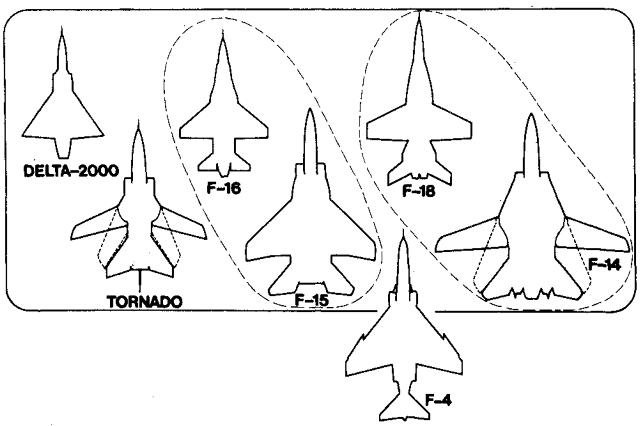

Fig. 5 Fighters of the 1980's (Western).

Now I should offer a personal outlook towards the future trends of fighter aircraft design:

This outlook appears fairly clear in those areas where the fighter shares and contributes/leads the mainstream of progress of jet transport technology – that is, in structures, propulsion, and basic avionics.

In the area of lightweight structures I expect an increased application of composites, depending upon the development of methods for really economic production. This is going to be a considerable challenge.

In propulsion I expect further refinement in components, including those for control, and hopefully also design features and methods which will reduce engine cost. I doubt that we will see a further dramatic increase in thrust-to-weight ratios in engines and aircraft due to the high cost of this feature. We will have to take increased account of the energy situation in our next generation of fighters.

In basic avionics I hope we will profit from the advances in microprocessors and will employ multiplexing on a large scale with attendant simplifications in aircraft wiring. We will "control configure" the next generation of fighters to a high degree and will thus improve performance at reduced cost. Also our other man-machine interfaces will be improved with a new generation of displays and controls with optimized modes for various operating conditions. A most promising development for the fighter appears to be the helmet-mounted display and sight.

The outlook into the more fighter-specific areas is difficult because of the attendant operational tradeoffs which depend upon projected structures of threat and friendly forces. The "haze" obscuring the real future requirements is still very thick, apart from the broad scope of ECM, the air-to-ground weapons area, and the requirement to reduce unit cost.

In any case it will be increasingly necessary to "distill" the essentials for future combat effectiveness, rather than relying on the simple formulas like maximizing rate of climb or speed or turn rate. We have already seen two breaks in such simple and general formulas. The trade of quality versus quantity will remain most difficult.

In fighter aerodynamics and control we will probably open up the poststall regime for another increase in dogfight maneuverability. As long as weapons remain installed in the classic fighter style requiring turning of the whole aircraft for pointing of the weapons, this poststall maneuverability may also be of interest to other than dogfight missions. Poststall maneuvering will require some form of auxiliary control such as used on VTOL aircraft or missiles, for example by thrust vectoring. It will also require an air intake and engine suitable for angles of attack of 90 deg. Both techniques are basically available.

Such a fighter would have tailsitter-VTOL capability almost as a complete fallout, if the simple takeoff and landing fixture like that of the Ryan X-13, which was tested in the late 1950's, was deployed at the air bases or aboard aircraft

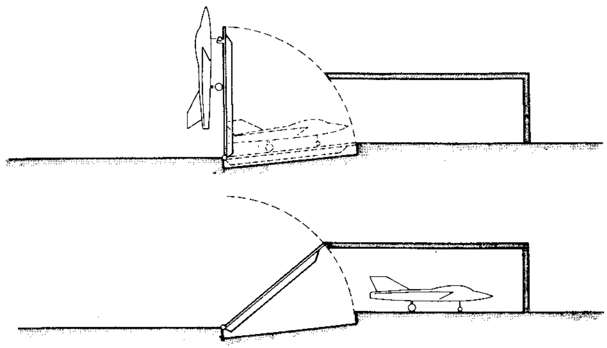

Fig. 6 V/STOL shelter.

carriers. At air bases where the fighters have to be sheltered it should not be too expensive to integrate the fixture with the shelter (see Fig. 6).

If the design were to retain a normal landing gear, it would be possible to do a rolling takeoff for overload missions and to operate in a conventional mode at airfields where the fixture is not available. Modern display and control technology should make safe tailsitter landing operations completely feasible.

Another next-generation fighter may be (the return of) some form of pointing the weapons other than by the pointing of the entire aircraft. I hesitate to put this forward since all earlier attempts involving some form of weapons-turret and a gunner have been failures when used on fighters. The fixed guns operated by the pilot have been a tremendous success due to their light weight and low volume and due to the accuracy of firing achieved with this installation. However the rate of pointing of the fixed weapons is slow; even a fighter with a turning rate of 18 deg/s will take some five seconds for a 90 deg change of direction. Modern weapons installations on ships and cars will do 90 deg in less than one second. One approach to overcome this problem is to program, with the aid of a helmet sight, the projectile or missile to execute a high-*g* turn after being fired from a convention fixed launcher. It may be rewarding to find a simple way of achieving this with a gun since this form or armament is still the most economic one.

Yet another design feature may be that of reduced signature for radar and ir-missiles. For a full-fledged fighter with all its other requirements these appear to me to be pretty difficult additional ones.

However one should bear in mind the advantages of small aircraft size in *this* context, as well as for reduced probability of visual detection, and last but not least, for a better chance of not being hit. The next generation of fighters should, and not only for these reasons, be of moderate size.

Finally, this outlook has to cover the prospects of unmanned fighter aircraft: adding up all the interface design features which are required to allow the pilot to control an aircraft, as well as the features to provide for the appropriate environment and safety, a lot of sensors and computing capacity could be provided instead, using microprocessor technology. The "cruise missiles" are paving the way in this direction and I expect that the fighter aircraft designers will have to take this development very seriously. The manned fighter will have to concentrate on the more difficult tasks which cannot be readily programmed. One can imagine combined systems of manned fighters and unmanned aircraft like a hunting party with hounds – the latter being "programmed" to track and harass under the command of the former.

The future of both the manned and unmanned fighter may however depend largely on the development of more effective weapons and methods for the air-to-ground battle in order to achieve a better balance of cost-effectiveness.

Some 75 years ago the Wright Brothers had the vision, skill, and persistence to develop *the* prototype of powered aircraft and gave birth to a new dimension of mobility and spirit of mankind. The fighter aircraft is one of the grim but magnificent outgrowths of this new dimension and will continue to participate in a lead role of aeronautics if the "fighter community" will maintain and develop *its* vision, skill, and persistence, offering new and cost-effective qualities and performance.