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Assessing the Sukhoi PAK-FA

Sukhoi/KnAAPO T-50/I-21/Article 701 PAK-FA
Перспективный Авиационный Комплекс Фронтовой Авиации

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by Dr Carlo Kopp, SMAIAA, MIEEE, PEng,
Peter Goon, BE (Mech), FTE (USNTPS)

First prototype of the PAK-FA during an early test flight, January 2010 (Sukhoi image).

Abstract

The public exposure of the Sukhoi/KnAAPO T-50/I-21/Article 701 PAK-FA or Перспективный Авиационный Комплекс Фронтовой Авиации following the 29th January, 2010, test flight has provided sufficient high resolution imagery, video camera footage, and incidental disclosures to perform an initial technical, techno-strategic, and strategic assessment of this new high performance low observable multirole fighter design.

The observed prototype design employs an interim supercruising and thrust vectoring engine, common to the production Su-35S Flanker. The configuration is intended to validate aerodynamic and systems performance, and is clearly not intended for full validation of low observables performance. A new 35 - 40 klbf class 3D TVC supercruising engine for the PAK-FA is currently being developed by NPO Saturn.

Analysis of PAK-FA prototype airframe shaping shows a design which has forward fuselage, inlet, upper fuselage, wing and tail surface airframe Very Low Observable (VLO/stealth) shaping which is highly competitive against the US F-22A Raptor and YF-23 ATF designs. Aft and centre lower fuselage, and aft fuselage and nozzle shaping is inferior to the F-22A Raptor and YF-23 ATF designs, sharing the same deficiencies as the F-35 Joint Strike Fighter. This may be an artefact of the use of the interim engines, and uncertainty about aft and beam sector observables performance will remain until later prototypes with the production engine and aft/lower fuselage shaping are available.

Analysis of PAK-FA prototype airframe aerodynamic features shows a design which is superior to all Western equivalents, providing 'extreme agility', superior to that of the Su-35S, through much of the flight envelope. This is accomplished by the combined use of 3D thrust vector control of the engine nozzles, all moving tail surfaces, and refined aerodynamic design with relaxed directional static stability and careful mass distribution to control inertial effects. The PAK-FA is fitted with unusually robust high sink rate undercarriage, intended for STOL operations.

Disclosures indicate that the avionic suite and systems fit will be derived from the Su-35S design, with the important difference in the use of an very high power-aperture product X-band multimode primary AESA radar. Five AESA apertures are intended for production PAK-FA aircraft. The highly integrated avionic suite is intended to provide similar data fusion and networking capabilities to the F-22A Raptor.

The available evidence demonstrates at this time that a mature production PAK-FA design has the potential to compete with the F-22A Raptor in VLO performance from key aspects, and will outperform the F-22A Raptor aerodynamically and kinematically. Therefore, from a technological strategy perspective, the PAK-FA renders all legacy US fighter aircraft, and the F-35 Lightning II Joint Strike Fighter, strategically irrelevant and non-viable after the PAK-FA achieves IOC in 2015.

Detailed strategic analysis indicates that the only viable strategic survival strategy now remaining for the United States is to terminate the Joint Strike Fighter program immediately, redirect freed funding to further develop the F-22 Raptor, and employ variants of the F-22 aircraft as the primary fighter aircraft for all United States and Allied TACAIR needs.

If the United States does not fundamentally change its planning for the future of tactical air power, the advantage held for decades will be soon lost and American air power will become an artefact of history.

Introduction

The emergence of the Russian Sukhoi PAK-FA marks the end of the United States' quarter century long monopoly on the design of Very Low Observable (VLO) or stealth aircraft[1].

The capabilities of the PAK-FA make a clear statement defining the Russian view of Within-Visual-Range (WVR) and Beyond-Visual-Range (BVR) air combat, which diverges fundamentally from contemporary Western thinking. The Russian paradigm is clearly centred on the idea that BVR and WVR combat are much alike, insofar as during the engagement endgame the fighter under attack is within tracking range of the weapon fire control system and where possible the weapon or fire control element should be defeated kinematically. The principal observed difference between WVR and BVR combat in the Russian model, is that the latter relies more heavily on long range sensors and their ability to defeat low observability measures, or active countermeasures.

Designed to compete against the F-22 in traditional Beyond Visual Range (BVR) and Within Visual Range (WVR) air combat, the PAK-FA shares all of the key fifth generation attributes until now unique to the F-22 - stealth, supersonic cruise, thrust vectoring, highly integrated avionics and a powerful suite of active and passive sensors. While the PAK-FA firmly qualifies as a fifth generation design, it has two further attributes absent in the extant F-22 design. The first is extreme agility, resulting from advanced aerodynamic design, exceptional thrust/weight ratio performance and three dimensional thrust vectoring integrated with an advanced digital flight control system. The second attribute is exceptional combat persistence, the result of a 25,000 lb internal fuel load. The internal and external weapon payload are likely to be somewhat larger, though comparable to those of the F-22A.

Russia intends to operate at least two hundred PAK-FAs, India two hundred and fifty of the Indian *Fifth Generation Fighter Aircraft (FGFA)* variant, with global PAK-FA exports likely to add at least 500 more tails to the production tally. The stated intent is to supply the PAK-FA as a replacement for existing T-10 Flanker series fighter aircraft.

Initial analysis of PAK-FA imagery and public disclosures by the Russian government and Sukhoi bureau indicate that a production PAK-FA will yield greater aerodynamic and kinematic performance to the current F-22A design, and similar low observables performance to the F-35A JSF[2].

While the basic shaping observed on this first prototype of the PAK-FA will deny it the critical all-aspect stealth performance of the F-22 in BVR air combat and deep penetration, its extreme manoeuvrability/controllability design features, which result in extreme agility, give it the potential to become the most lethal and survivable fighter ever built for air combat engagements[3].

It is important to consider that the publicly displayed PAK-FA prototype does not represent a production configuration of the aircraft, which is to employ a new engine design, and extensive VLO treatments which are not required on a prototype. A number of observers have attempted to draw conclusions about production PAK-FA VLO performance based on the absence of such treatments, the result of which have been a series of unrealistically optimistic commentaries.

PAK-FA Low Rate Initial Production is planned for 2013, and Full Rate Production for 2015, with initial deliveries of the Indian dual seat variant planned for 2017.

PAK-FA Development History

Early rendering of the PAK-FA design (NPO Saturn).

The evolution and development history of the PAK-FA, historically, has not been well documented in open sources, largely due to the high levels of secrecy surrounding this program since its inception. What is known from open sources largely amounts to a collation of various intentional and incidental Russian disclosures, and increasingly, disclosures by India, who have a 25% share in the development of the design.

Study of the aircraft's design features, and earlier Sukhoi demonstrators, indicate that much careful thought has been invested into this design and its progressive development over a period of two decades.

When the Soviets deployed the Su-27S Flanker B during the early 1980s, investment into a replacement was initiated. This resulted in the reasonably well known 1990s MiG I.44 MFI (Mnogo-Funktsionniy Istrebitel' or Multi-Role Fighter), which was a multirole fighter modelled on the aerodynamics of the three "Eurocanard" designs, but much larger and intended to be powered by the Al-41F supersonic cruise engine.

The MFI was built to supercruise, and to provide very high agility, but no investment was made into signature reduction, making it fundamentally uncompetitive against the early 1990s US Air Force Advanced Tactical Fighter (ATF) YF-22 and YF-23 demonstrators.

The lack of a future for an expensive high signature fighter, and the MiG organisations *de facto* bankruptcy due to the export market success of the larger Sukhoi Flanker, saw the MFI relegated to a demonstration program. The important product of the MFI program was the Al-41F supercruising engine, modelled on the United States' Pratt & Whitney F119 series, which powers the F-22A. The Al-41F is the basis of the high temperature core components used in the supercruise capable 117S series engine, which now powers the production Su-35S Flanker and PAK-FA prototypes.

During this period Sukhoi developed the unusual S.32/S.37 forward swept wing demonstrator, intended to combine supersonic performance with super-manoeuvrability. This design demonstrated the use of large LEX, over large quarter circular inlets. Like the MFI, this design was not stealthy and was used to prove basic technologies and design rules.

A more successful demonstrator built during this period was the Su-37 "Super Flanker", derived from the earlier Su-27M/Su-35 Flanker E. The Su-37 was intended to extend the T-10 Flanker design to the limit, especially in avionic systems and manoeuvre performance. It introduced the first axi-symmetric 3D (three dimensional) Thrust Vector Control (TVC) nozzles, manually controlled, and later integrated with the Digital Flight Control System (DFCS); the first quadruplex DFCS in a Russian fighter; composite structural components; a modern glass cockpit and force sensitive sidestick controller; digital core avionics; the N-011M BARS hybrid Electronically Steered Array (ESA) radar; and, a compact ESA tail warning radar.

The combination of aerodynamic design refined through progressive evolutionary development, DFCS, twin 3D vectoring thrust supercruising engines interoperating in and on an advanced kinematic design airframe, extended the Flanker design squarely into the category of "extreme agility" - which can be defined as the harmonised and complementary balance of extreme manoeuvrability and extreme controllability.

The Su-37 Super Flanker demonstration effort extended the viability of the basic T-10 Flanker design by almost two decades, and yielded basic technology used in the design of the Su-30MKI/MKM Flanker H and, as seen in the latter part of 2008, the Su-35S, often labelled the "4++ Generation Flanker". It also provided experience which was critical to the development of the replacement for the T-10 Flanker series.

The PAK-FA properly qualifies as a 21st century project, as formal tendering for the program was launched during the 2000 - 2001 period by the Russian MoD. Russian sources claim that Sukhoi, MiG and Yakovlev were invited to bid proposals. Initial thinking was to develop a fighter larger than the MiG-29 Fulcrum, but smaller than the Su-27 Flanker, with greater range/persistence to the Flanker, low observable capability, extreme agility, supersonic cruise capability, and near STOL short field capabilities. Sukhoi won the tender in 2002 with its T-50/I-21 proposal, with MiG and Yakovlev engaged as subcontractors in the development. Russian sources state that Sukhoi's ability to fund much of the development effort from company export revenue profits was a major factor in the decision.

The initial design of the PAK-FA was finished in 2004, amid public controversies about lower than intended maximum speed, and greater than intended empty weight. Full Russian MoD funding was not provided until 2005 - 2006[4].

The prototype flown on the 29th January, 2010, is intended to prove aircraft aerodynamics, structure, and compatibility of the VLO shaping with aerodynamic and structural constraints. It is claimed to be fitted with the 117S Al-31F engine variant, common to the Su-35S, as the intended new engine has yet to complete development and enter production. The latter is expected to be a variant or derivative of the Al-41F design. The existing prototype probably lacks a complete version of its final avionic suite, most likely employing large parts of the new and fully digital Su-35S avionic suite as a basis for evolving the design of the final avionics fit, as has been the case on the development of previous Flanker variants.

The first "public" flight lasted 47 minutes and was intended to test handling, engine behaviour, landing gear operation, and basic systems functions[2].

The PAK-FA was designed with a stated requirement of being able to operate from short, unprepared runways in support of expeditionary operations. With the exception of an observable deployed arrestor hook, the PAK-FA design incorporates all of the key design characteristics that are required in aircraft built to operate from Russian Navy ski-jump equipped aircraft carriers. It is not known whether the extant structural design includes the necessary provisions for arrestor hook loads.

Equipped with 3D TVC and large LEX control surfaces, power approach speeds in the order of 100 knots, sink rates somewhat less than 20 ft/sec and quite flat aircraft approach attitudes can be expected from this design, as can commensurately low arrestor hook and related carrier landing loads. Such performance, when combined with the extensive field of view provided by the fighter/strike/attack canopy configuration, and a functional arrestor hook system, likely integrated into the rear ventral internal weapon bay, would make the PAK-FA an eminently suitable aircraft for maritime operations.

India was engaged early in the PAK-FA development effort, but Russian sources suggest that negotiations on the work share between HAL and Sukhoi/KnAAPO were protracted. Open sources suggest that India is responsible for 25% of the development of the PAK-FA, primarily in software and systems integration, areas where India has recent experience via the Su-30MKI program. India is to also contribute in composite materials, with claims the PAK-FA structure is, by total aircraft weight, rather than just the airframe structural weight, some 25% titanium alloys, and 20% composites. Indian sources suggest that both single and dual seat variants will be built for India.

Tactical, Operational and Strategic Impact of the PAK-FA

The supersonic cruise capability, integrated sensor suite, respectable VLO performance, extreme agility and exceptional persistence of a mature production PAK-FA will produce a significant impact in the post 2015 period, at the tactical, operational and strategic levels. In turn, this will also produce a political impact.

The PAK-FA represents an excellent example of the kind of "*capability surprise*" studied in the late 2009 Defense Science Board report. While the failure to account for the imminent arrival of this design in United States TACAIR force structure planning qualifies the PAK-FA as a "*known capability surprise*", the important advances in PAK-FA aerodynamic, kinematic and low observables design also qualify it as a "*surprising capability surprise*".

Technical analysis of the PAK-FA, in the following sections of this paper, shows that its aerodynamic performance and agility will exceed that of all United States built combat aircraft currently in service or planned, with the exception of the yet to be defined "sixth generation fighter", which at best is 15 - 20 years away from Initial Operational Capability (IOC). Technical analysis of the PAK-FA also shows that the aircraft's VLO shaping permits the existing prototype configuration to achieve similar VLO performance to the F-35 Joint Strike Fighter, and with lower and aft fuselage VLO shaping design improvements, potentially competitive VLO performance against the F-22A Raptor.

At the tactical level this will produce a large impact in Beyond Visual Range and Within Visual Range air combat.

An important qualification is that most recent analyses of relative air combat capabilities performed in the United States assume that BVR combat will arise much more frequently than WVR combat. The basis of this assumption is that opposing air combat capabilities are easily detected and tracked by ISR systems, permitting United States fighter aircraft to choose the time, place and type of engagements to an advantage. This assumption collapses if the opposing fighter has significant VLO capability, as a mature PAK-FA will. The result is that attacking PAK-FAs will have to be engaged at much closer ranges than existing non-stealthy threats, as they enter predictable geometries, when attacking high value targets such as AWACS/AEW&C platforms, tankers, or defended surface assets.

Another important qualification is that the extreme agility of the PAK-FA design will significantly degrade the kill probability of all United States Air to Air Missiles, (AAM) especially though the AIM-120 AMRAAM, which will be challenged to sustain the necessary manoeuvres to defeat the PAK-FA. Like the F-22A Raptor, the PAK-FA will provide a significant capability for the kinematic defeat of inbound missile shots.

Parametric and tactical analysis performed by Air Power Australia in 2008 - 2009 on the likely impact of a mature production PAK-FA deployed against United States' fighter types has been completely validated, given the configuration of the PAK-FA prototype.

"*How stealthy does the PAK-FA need to be to defeat US legacy fighters? A radar cross section of only -20 dBSM would deny early Beyond Visual Range (BVR) missile shots using the AIM-120C/D AMRAAM to all current and planned US fighters. Doing any better, like -30 dBSM or -40 dBSM, simply increases the level of difficulty in prosecuting long range missile attacks.*"

"*The consequence of this is that missile combat will be compressed into shorter distances and shorter timelines, putting a premium on the stealth, supersonic persistence and close combat agility of US fighters. A larger portion of engagements will be at visual range, and most BVR engagements will end up taking place inside 30 nautical miles.*"[5]

In Beyond Visual Range combat, the combination of supersonic cruise and competitive VLO performance will allow the PAK-FA to emulate the tactics developed for the F-22A Raptor. The PAK-FA can thus be expected to produce greater lopsided air combat exchange rates to those achieved by the F-22A Raptor when flown against legacy "teen series" fighters in exercises since 2004. Even if the PAK-FA design were only to attain half of the effectiveness of the F-22A Raptor, it will still yield BVR exchange rates of the order of 50:1 against legacy fighters.

The arrival of the PAK-FA therefore irrevocably enforces the end of the operational usefulness of the teen series (F-15 / F-16 / F/A-18) generation of fighter aircraft, marked by the advent of the Su-35S, in the traditional fighter roles of air superiority, air defence and tactical strike in contested airspace. These aircraft will retain operational utility only in permissive environments, where neither the Su-35S nor the PAK-FA is deployed or is able to be deployed.

No less interesting is the impact at a tactical level when the PAK-FA is flown against the F-22A Raptor.

"Fights between the F-22A and the PAK-FA will be close, high, fast and lethal. The F-22A may get 'first look' with the APG-77, the Advanced Infra Red Search and Track (AIRST) sensor having been deleted to save money, but the PAK-FA may get 'first look' using its advanced infrared sensor. Then, the engagement becomes a supersonic equivalent of the Battle of Britain or air combat over North Korea. The outcome will be difficult to predict as it will depend a lot on the combat skills of the pilots and the capabilities of the missiles for end-game kills. There is no guarantee that the F-22 will prevail every time."[6]

The tactical impact of a mature production PAK-FA is therefore a loss of the overwhelming advantage provided until now by the F-22A Raptor. Flown against the PAK-FA, a decisive outcome can only be guaranteed by numerical superiority of the F-22A force in theatre.

The United States' Office of the Secretary for Defence (OSD) has since late 2008 promoted the use of the F-35 Joint Strike Fighter as a substitute for the F-22A Raptor, employing this rationale as a justification to Congress for the premature termination of F-22 production. Therefore, the survivability and lethality of the F-35 Joint Strike Fighter when pitted against a mature PAK-FA has become the critical measure of the operational and strategic value of planned United States TACAIR capabilities.

Parametric and tactical analysis performed by Air Power Australia in 2008 - 2009 on likely engagement outcomes between the PAK-FA and F-35 Joint Strike Fighter are also validated by technical analysis of the PAK-FA prototype design.

"The F-35 Joint Strike Fighter struggles to survive against the conventional Su-35BM Flanker, with only its -30 dBSM class front sector stealth keeping it alive in some BVR combat situations. Against even a -20 dBSM class PAK-FA, the F-35 falls within the survivability black hole, into which US legacy fighters such as the F-16C/E, F-15C/E and F/A-18A-F have already fallen."[5]

"The fate of the F-35 Lightning II would be far worse in an air combat environment challenged by the PAK-FA. If the Mach 1.5 PAK-FA is using its infrared sensor as the primary sensor and observes radio frequency emission control (EMCON), then the first detection by the F-35's APG-81 radar could be at ~20 nautical miles or less with a missile launched by the PAK-FA's infrared sensors already inbound from 60 to 70 nautical miles away. The PAK-FA could easily break to a direction outside the F-35's AIM-120 engagement zone."[6]

"The sustained turning performance of the F-35A Lightning II was recently disclosed as 4.95 G at Mach 0.8 and 15,000 ft. A 1969 F-4E Phantom II could sustain 5.5 Gs at 0.8 Mach with 40 percent internal fuel at 20,000 feet. The F-35 is also much slower than the 1960s F-4E or F-105D. So the F-35A's aerodynamic performance is 'retrograde' when compared with 1960s legacy fighters. The consequence of such inferior JSF performance is that its DAS might detect an incoming missile, but the aircraft lacks the turn-rate to out-fly it. As the F-35 also lacks the performance to engage or escape, repeated 'freebie' shots from the PAK-FA could inflict high losses. Expect the exchange rate to be of the order of 4:1 in favour of the PAK-FA, possibly much higher."[6]

The arrival of the PAK-FA therefore also irrevocably enforces the end of the operational usefulness of the F-35 Lightning II Joint Strike Fighter, defined around a 1990s technology threat spectrum, in the traditional fighter roles of air superiority, air defence and tactical strike in contested airspace. The F-35 will, not unlike legacy fighters, retain operational utility only in permissive environments, where neither the Su-35S nor the PAK-FA is deployed or is able to be deployed.

The operational impact of indecisive combat loss exchange rates between a mature production PAK-FA and the F-22A Raptor, and very high F-35 Joint Strike Fighter loss rates against a mature production PAK-FA have major implications at an operational level, and consequently, at a strategic and political level.

Once the PAK-FA is deployed within a theatre of operations, especially if it is supported robustly by counter-VLO capable ISR systems, the United States will no longer have the capability to rapidly impose air superiority, or possibly even achieve air superiority. This will not only deny the United States access to an opponent's defended airspace, it also presents the prospect of United States forces being unable to reliably defend in-theatre basing and lines of resupply. Should this occur, in-theatre basing and surface assets become exposed to air attack by aircraft armed with a wide range of accurate and highly lethal Precision Guided Munitions, with the potential for very high loss of life and equipment deployed in-theatre.

Conventional thinking in the planning of air campaigns, empirically observable from the Blitzkrieg campaigns of the 1940s through to the recent United States led air campaigns since 1991, places a heavy emphasis on the defeat of opposing airfields by aerial attack, to deny an opponent the opportunity to contest airspace. To achieve this effect, an attacker needs the capability to repeatedly penetrate defended airspace to shut down airfields, keep them shut down, and inflict attrition upon opposing aircraft on the ground.

The execution of this campaign strategy by United States forces, and Allies, is now becoming problematic due to the development and proliferation of advanced anti-access capabilities such as counter-VLO capable ISR systems, and advanced high mobility Surface Air Missile systems, such as the S-300PMU2 Favorit / SA-20B, S-400 Triumf / SA-21 and planned S-500 series. This strongly limits United States options, as only the B-2A Spirit and F-22A Raptor can penetrate such defences with acceptably low loss rates.

The deployment of a mature PAK-FA into such an environment very significantly increases risks to United States forces, as the aircraft can credibly challenge the F-22A Raptor in air combat. While the intended survivable strike/ISR aircraft defined in the most recent Quadrennial Defense Review document may, eventually, provide a credible capability to penetrate advanced anti-access capabilities, and thus attack opposing airfields, it will need to be defended against the PAK-FA, and airfields deploying this aircraft will also need to be defended against PAK-FA aircraft tasked with counter-air strike missions.

In terms of technological strategy, the PAK-FA thus effectively defeats the force structure model planned for United States TACAIR capabilities, as defined by OSD policy statements, and as reiterated in the recently released Quadrennial Defense Review document.

Should the United States continue along the force structure path for TACAIR mapped out by OSD policy definition of the last three years, it will be denied access to any operational theatre into which credible numbers of the PAK-FA are deployed by an opponent. In turn, the United States will be deterred from the use of conventional forces in such a scenario. The consequence of this, in turn, is that significant pressure will be placed upon a future President to threaten the use of, or operationally use, tactical nuclear weapons[7].

A not dissimilar situation would arise in the scenario where the Su-35S is deployed, in tactically significant numbers, or in concert with the PAK-FA. Jointly and severally, these scenarios have deeper geostrategic and political implications which are beyond the scope of this paper.

If the United States does not effect some fundamental changes to its force structure plan, it will lose the strategic option of employing non-nuclear military capabilities in theatres where the PAK-FA and/or significant numbers of the Su-35S are deployed.

The only practical low risk option available to the United States is to deploy over this decade large numbers of advanced fighter aircraft which are competitive against the PAK-FA in air combat, both BVR and WVR.

The proposed "sixth generation fighter" is not a viable contender in this time frame. The F-35 Lightning II Joint Strike Fighter is not competitive and cannot be made to be competitive due to basic design limitations in aerodynamic and VLO shaping performance. The only aircraft built by the United States which can survive in airspace contested by the PAK-FA is the F-22 Raptor, and given the time frame of interest, it is the only design which can be adapted to defeat the PAK-FA.

In basic grand strategy terms, the arrival of the PAK-FA leaves the United States with only one viable option if it intends to remain viable in the global air power game - build enough F-22 Raptors to replace most of the US legacy fighter fleet, and terminate the F-35 Joint Strike Fighter as soon as possible, as the F-35 will no longer be a usable combat aircraft for roles other than Counter Insurgency (COIN), though more cost effective and more appropriate solutions already exist for this role.

In strategic and techno-strategic terms, the PAK-FA is the most prominent "game changer" in the fighter domain since the T-10/Su-27S Flanker B entered operational service during the mid 1980s. If the United States does not fundamentally change its planning for the future of tactical air power, the advantage held for decades will be soon lost.

PAK-FA Design Philosophy

The first high quality in flight image of the prototype to be released by Sukhoi/KnAAPO. Closer inspection of the details in this image, particularly the absence of surface mounted INSTM on the fully articulated fin control surfaces suggests this image is from a different flight and might even be an in-flight image of another prototype airframe (Sukhoi).

The PAK-FA was quickly dubbed by Western observers as the "Raptor-ski" or "F-22-ski". This label is reasonable in terms of the niche the aircraft is intended to occupy, as it is intended to directly challenge the F-22A Raptor, but this label is quite inaccurate in terms of the configuration of the aircraft and its detailed design.

In the broadest of terms, the PAK-FA is a fusion of ideas and design features seen in late model Flanker variants and demonstrators, but incorporating specific stealth shaping features employed previously in the Northrop/MDC YF-23 ATF demonstrator, and the production LM F-22 Raptor. The PAK-FA is clearly a unique Russian design and is neither a copy of the F-22 or the YF-23.

No less importantly, the PAK-FA is by Western standards a low risk design, following the Russian philosophy of "evolutionary" design, rather than the "Big Bang" approach currently favoured in the West, of trying to start from scratch with most or every key portion of the design.

It is important to note that the Russian approach to development more than often differs from the Western approach, particularly that of the United States industry, with a much stronger Russian focus on risk management and risk minimisation. A powerful approach evident in the development of the Flanker family of aircraft has been, firstly, to plan long term, then to spread developmental risks across the series of planned new aircraft types and variants as well as parallel design/development activities. The benefits of such an approach are clearly obvious.

The best illustration of how much more effective Russian systems development philosophy is, is that the development of the PAK-FA, with a projected budget in the order of US$10 Billion, was launched officially in 2002, concurrently with the launch of the F-35 Joint Strike Fighter program, yet the latter has experienced repeated delays in schedule, repeated problems with basic technology, and remains heavily laden with accumulated design risks as well as inordinately high and growing costs.

If the objective is to produce a design on-time and on-cost without unpleasant surprises, there is much to be said for the Russian approach to systems development.

Russian sources indicate that the prototypes will be fitted with a derivative of the existing Su-35S avionic suite to reduce risk and cost. It is likely that this strategy of risk reduction by the use of existing production hardware will apply to other key internal components. The use of the 117S series engine common to the Su-35S in PAK-FA prototypes is a prime example.

Another example is the basic layout or configuration of the PAK-FA airframe design, which is demonstrably based on the T-10 Flanker series, with a large centre fuselage carapace, a pair of long serpentine engine inlet ducts, with inlets beneath a large LEX, the engines mounted in blast resistant tubes, which also provide the means for reacting empennage control surface and TVC loads, and a blended forward fuselage raised above the engine centrelines, not unlike the Flanker and F-14 series. The forward and centre fuselage design is therefore closer to the Flanker and YF-23 than the F-22A. The wing planform is closest to F-22, reflecting design aims in VLO shaping and supersonic cruise performance.

Where the PAK-FA departs most strongly from the earlier Flanker, the F-22 and the YF-23 is in the aft fuselage design, and the moving LEX or *Povorotnaya Chast' Naplyva* (PChN) design, intended to provide extreme manoeuvrability and controllability and, thus, extreme agility - an attribute absent in the F-22 and YF-23, but extant in some later Flanker variants, demonstrators and prototype programs.

To provide extreme agility, Sukhoi's design team employed all-moving stabilators and canted tail fins, a nodding movable LEX design, and 3D axi-symmetric engine nozzles. The wide spacing of the fully articulated fins and engine nozzles provides a much larger moment arm for both aerodynamic and TVC roll and yaw inputs, than observed with previous designs. While the tail surfaces do not impair observables, the use of axi-symmetric 3D nozzles does, no differently than the fixed axisymmetric nozzle of the F-35 Joint Strike Fighter.

The latter raises some very interesting questions about key design trade-offs, as yet not explained by Sukhoi. The existing design configuration suggests that extreme manoeuvrability was rated to be more important than all-aspect stealth was, suggesting in turn that the aircraft was not intended for use as a deep penetrator in the manner of the F-22 and YF-23. Given the low priority given in Western nations to the maintenance of deep overlapping SAM belt air defences, the susceptibility to aft quarter SAM shots inherent in limited all aspect stealth performance may not have been assessed as a risk worth serious investment in defeating.

Conversely, the current design may be an expedient development shortcut, with a more refined aft quarter VLO design to appear with the final production engine. The quality of the front quarter VLO design demonstrates that Sukhoi are capable of producing an aft quarter VLO shaping design no worse than the F-22A or YF-23 designs.

With the current PAK-FA configuration, which may well differ from a production configuration, stealth appears to be used primarily to deny an aerial opponent an early BVR firing opportunity, permitting the PAK-FA to close to a distance where its superior energy performance, extreme agility and large internal missile payload permit it to dominate the close combat engagement.

The combination of aerodynamic design features for extreme agility, high thrust/weight performance supersonic cruise engines to provide supersonic persistence, and the large combat persistence provided by a large internal fuel load and large weapons loads, make the PAK-FA the best fit to the Boyd "energy manoeuvrability" model yet to be developed.

The extreme agility of the PAK-FA design, when employed harmoniously with the other 5th generation design features, opens up a range of new tactical options, not feasible with established or currently planned Western fighter designs.

Consider a conventional BVR tail chase engagement geometry against an operational PAK-FA derivative air dominance fighter. A conventional fighter with legacy teen series class aerodynamic design and performance, an example being the F-35A Joint Strike Fighter, is positioned behind the PAK-FA, at a range of ~50 nm, with its X-band multimode radar locked and tracking, assuming that the PAK-FA aircraft retains the high signature aft fuselage and nozzle design.

The use of extreme agility design features would permit the PAK-FA derivative to perform reversal manoeuvres faster than conventional fighter designs, causing the pursuing fighter to lose radar lock as the PAK-FA presents its VLO class nose aspect to the pursuing fighter. Within seconds the PAK-FA can establish a weapons lock, as the weapon system will have established the position and identity of the pursuing fighter during the immediately preceding tailchase. The pilot of the initially pursuing fighter will then be presented with a salvo of mixed seeker equipped BVR missiles closing at high speed on a reciprocal heading.

The full tactical potential of extreme agility, especially in BVR engagements, remains to be explored at this time, as most studies to date have been strongly focussed on the close combat advantages arising from this flight regime.

Multiple Russian sources state that the PAK-FA will carry eight Air-to-Air Missiles in internal bays, with the option of another eight externally carried weapons in "permissive" threat environments. This emulates the strategy pursued by American designers in the F-22, and claimed but not properly implemented with the F-35 designs.

The PAK-FA has an unusually robust undercarriage design, more typical for carrier based naval fighters than land based fighters. This is consistent with the intended STOL capability to operate from short field FOBs, or MOBs with damaged runways, but also fulfils the intent to deploy a navalised carrier variant in the future. The latter was the subject of some discussion during the public debate in Russia, at the time the PAK-FA program was launched, but not a feature of the more recent debate. The configuration of the existing design would require that the tailhook be carried in the aft centreline weapons bay.

Based on analysis of the features and history of the PAK-FA design observed to date, an apt summary of this aircraft would be a High Speed/High Agility Interceptor/Air Dominance Fighter/Persistent Strike/ISR Platform, built for operation from short unprepared FOBs, and readily adapted for aircraft carrier operations.

What is abundantly clear from the basic design of the PAK-FA, is that this aircraft is the only design globally, which will be credibly capable of competing with the F-22 Raptor in air combat. It is also a much better fit to the stated, but very poorly implemented in the F-35, intent for a multi-service multirole fighter.

Preliminary PAK-FA Performance Specifications	
MTOW	81,600 lb
Max Speed	1,400 KTAS (Mach 2.44 ~36kft, ISA)[1]
Supercruise Envelope	700 KTAS to 920 KTAS (1.22M to 1.6M >36kft, ISA), though analysis suggests a likely higher top end point

	of ~1.9M.
Maximum Initial Climb Rate	69,000 fpm
Climb Ceiling	65,000 ft[2]

Sources: Sukhoi via Russian media, preliminary APA analysis
1 - supersonic flight duration not specified
2 - ceiling constraints not specified

Above PAK-FA prototype, below production F-22A Raptor. and Dem/Val YF-23A. These images expose both similarities and fundamental differences in the three designs (Sukhoi, US Air Force).

PAK-FA Low Observable Design

Detail of inlet and lower fuselage area (Sukhoi).

The low observable design shaping employed in the PAK-FA prototype shows an excellent grasp of the design rules employed by American designers in the development of the F-22A and YF-23 Advanced Tactical Fighter. This reflects an observation made to one the authors by a senior American design engineer some years ago "we always end up doing the really hard work learning how to build these things, making it easy for the Russians to follow with their designs".

The likely exploitation of F-22A and YF-23 Advanced Tactical Fighter low observable shaping design rules was predicted through analysis as most likely during the past decade, and subsequently published in March 2009. Sukhoi's prototype shaping validated that analytical prediction[5].

As observed previously, the Russian approach to development follows an "evolutionary" design philosophy, in which risks are retired early in the development phase of a new aircraft type or variant. Where possible, the retirement of risks is achieved in earlier programs, as demonstrated repeatedly in the development of the T-10 Flanker series of aircraft.

The PAK-FA prototypes displayed in January, 2010, are clearly intended to validate the compatibility of the overall observables shaping with the aerodynamic and structural design needs and clearly so, as the expensive detail RCS flare spot treatments we are accustomed to seeing on US prototypes are absent. The rationale for this is simple - why expend valuable but scarce development resources if aerodynamic / structural load testing shows that major changes are required to shaping of important design elements? For Western contractors, where the imperative is to extract the maximum of development funding from the customer, and make early cancellation of a program difficult, the highest risk approach will nearly always be sought by senior management. An excellent case study of the latter is the extremely high level of "concurrency risk", reported by the General Accounting Office, in the F-35 Joint Strike Fighter program.

The risk minimisation oriented development strategy explains the absence of serrations on the ventral inlet blow-in doors, and the absence of a serrated nozzle on the interim engine design. Design features which are intended to be permanent, such as the ventral weapon bay doors, aerial refuelling probe doors, and large access panels, all employ edge alignment or serrations no differently than the B-2A, F-22A and YF-23 demonstrator.

It is important to note that VLO shaping design is the single most critical aspect of VLO design with contemporary basic technology. This is because once the shaping is fixed in the design, the cost of implementing changes is prohibitive downstream, impacting structural design, aerodynamic behaviour and internal packaging of systems. If VLO shaping is done poorly, early in the development cycle, with the F-35 lower and aft fuselages being the representative case study, no reasonable downstream investment in additional absorbent materials and structures can overcome the resulting signature problems, and may introduce additional problems with weight, cost and strength/stiffness of skin panels.

By aiming for the best possible VLO shaping in the PAK-FA design from the very outset, Sukhoi's designers have demonstrated that they understand this aspect of VLO design very well. This strategy also opens up the prospect of progressive improvements in VLO performance as the design matures, and better VLO materials technology becomes available.

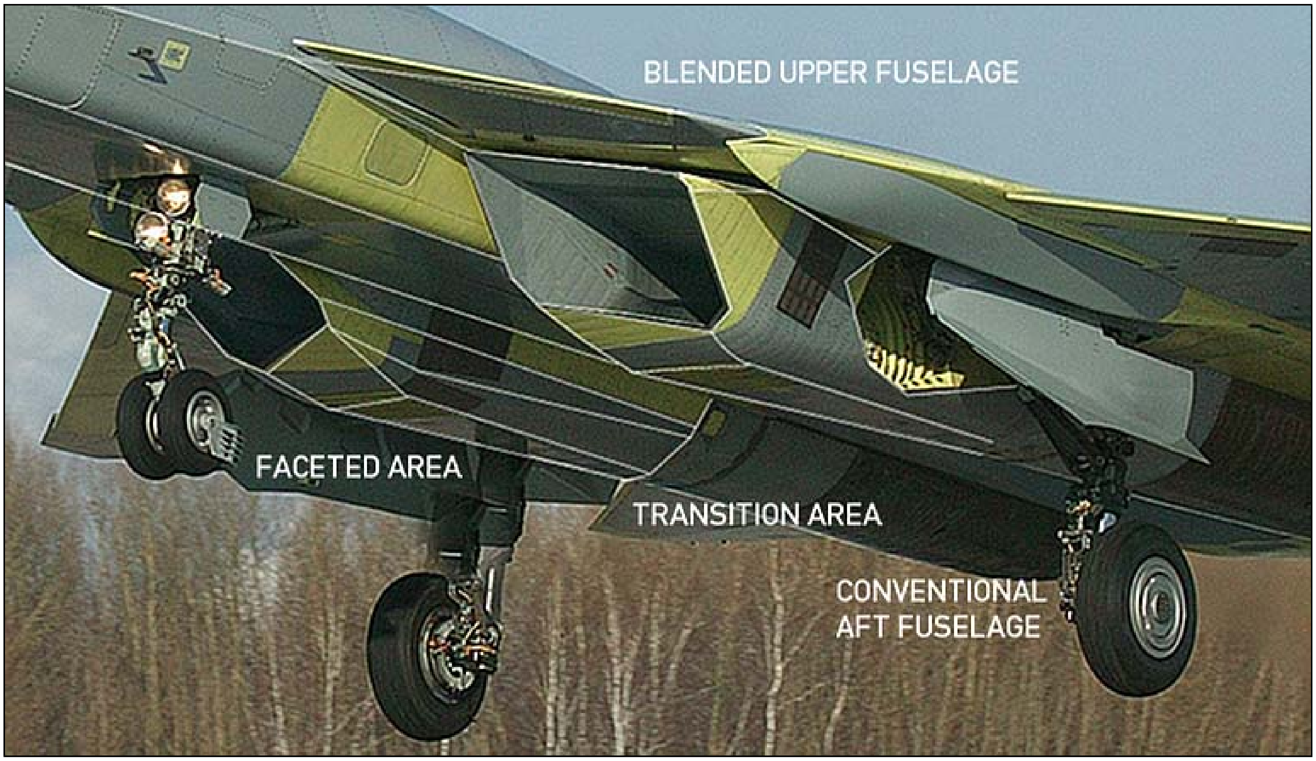
The prototypes show the extensive use of what appears to be conventional riveting, and conventional construction. If genuine VLO capability is intended, extensive robotic surface coating treatment or appliqué laminate technology will be required, with both techniques requiring a highly conductive substrate layer to suppress the surface impedance discontinuities resulting from the construction technique used. As observed in other areas of the Russian industrial base, coating and surface treatment technologies are well understood, and world class capabilities are available.

The forward fuselage is closest in general configuration to the YF-23, especially in the chining, cockpit placement, and hump aft of the cockpit canopy, although the blending of the upper forward fuselage into the upper carapace is more gradual. There are important differences from the YF-23. The chine curvature design rule is purely convex, like the chine design on the F-22A. The nose height is greater, to accommodate an AESA with a much larger aperture than that intended for the YF-23 or F-22A. If flare spots are properly controlled by the application of materials and serrated edge treatments around the canopy, and a good bandpass radome design using a frequency selective multilayer laminate is employed, the shaping related RCS contribution of the forward fuselage in the S/X/Ku-bands will be similar to that observed with the F-22A, YF-23 or F-35.

The Electro-Optical System (OLS) turret employed on the prototype is likely the Su-35S OLS, and is incompatible with a VLO design, as it is a broadband spherical reflector. We can expect to see a faceted VLO fairing similar to that designed for the cancelled F-22A AIRST (Advanced IRST [Image]) in a production PAK-FA configuration.

The conventional pitot-static probes currently mounted around and forward of the cockpit are like the OLS turret, incompatible with a VLO design, and we can also expect to see these replaced with VLO design ports in a production PAK-FA configuration.

The edge aligned movable LEX are readily treated with leading edge absorbers and will not present a major RCS flare spot. The treatment of the movable join will present the principal challenge in this portion of the design. The obtuse angle in the join between the LEX and forward fuselage is characteristic of good design and is very similar to the angles used in the F-22.



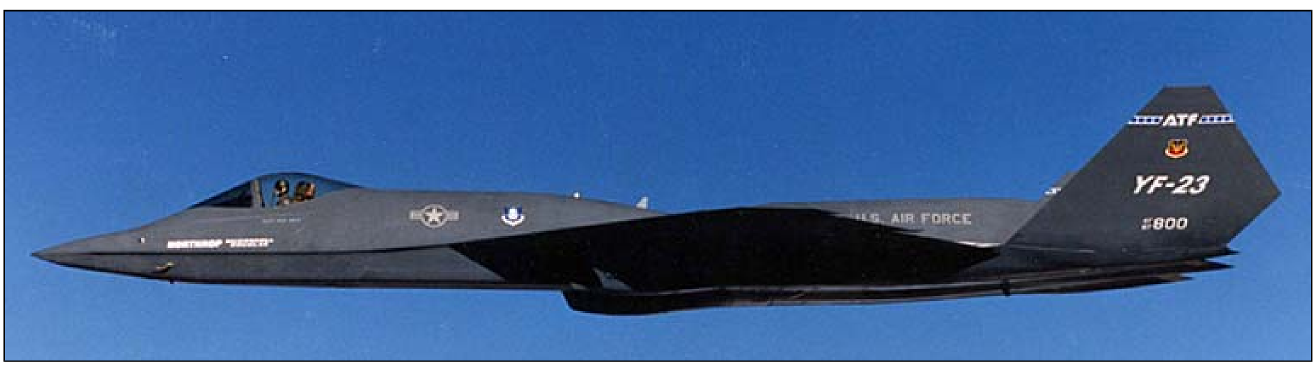
The lower fuselage of the prototype displays interesting incongruities. There is an abrupt transition between the carefully sculpted faceting of the inlet nacelles, and the smoothly curved aft engine nacelles and conventional aft fuselage. The faceting strategy is similar to the F-22 design rules, with singly or doubly curved transitions between planes (C. Kopp/Sukhoi image).

The edge aligned trapezoidal main engine inlets are similar in configuration to the F-22, but with important differences. The inlet aspect ratio is different, and the corners are truncated in a manner similar to the YF-23. If properly treated with leading edge inserts and inlet tunnel absorbent materials, the inlet design should yield similar RCS to its US counterparts.

The placement of the engine centrelines well above the inlet centroids, in the manner of the YF-23, results in an inlet tunnel S-bend in the vertical plane. Sukhoi have not disclosed whether an inlet blocker will be employed. Public disclosures on Su-35S inlet treatments claimed a ~15 dB reduction in X-band RCS compared to the untreated inlet tunnels on the Su-27SK. The use of an S-bend in the PAK-FA would permit an increase in the number of surface bounces further increasing attenuation and reducing RCS.

In the S/X/Ku-bands the basic shaping of the forward fuselage will permit the attainment of genuine VLO performance with the application of mature RAS and RAM, where the centre and aft fuselage do not introduce larger RCS contributions from the forward aspect.

Above: PAK-FA upper forward fuselage showing shaping details; below: YF-23A (Sukhoi, US Air Force).



Ventral view of prototype with undercarriage lowered (Alexander Baranov/Kommersant).

The wing design from a planform perspective is closest to the F-22A, and the upper fuselage similar to the YF-23, permitting the achievement of similar RCS performance to these US types, from respective aspects.

Where the PAK-FA falls well short of the F-22A and YF-23 is the shaping design of the lower fuselage and side fuselage, where the general configuration, wing/fuselage join angles, and inlet/engine nacelle join angles introduce similar intractable specular return problems as observed with the F-35 Joint Strike Fighter design. These are inherent in the current shaping design and cannot be significantly improved by materials application. Like the F-35 Joint Strike Fighter, the PAK-FA prototype design will produce a large specular return in any manoeuvre where the lower fuselage is exposed to a threat emitter, and this problem will be prominent from the Ku-band down to the L-band.

This problem is exacerbated by the inboard ventral wing root fairings, claimed by some Russian sources to be pods for the concealed carriage of folding fin close combat AAMs, such as the RVV-MD/R-74 series. While these fairings do not introduce large RCS contributions from fore or aft aspects, they will adversely contribute to beam aspect RCS, especially for threats well below the plane of flight of the aircraft.

The shaping remedy for the beam aspect signature problem lies in more obtuse join angles, which would require considerable effort in resculpting the fuselage/wing join from the main undercarriage bays to the tail, and narrowing the usable width of the lower fuselage tunnel between the nacelles. The latter is problematic. An alternative may be the use of thick RAM treatments, in effect replacing the skins of the sides of the inner forward lower fuselage tunnel with RAM panels, with some weight penalty as a result, which would not be significant relative to overall aircraft weight, given the small area to be treated.

The tailboom shaping is reminiscent of the F-22 and F-35 designs, and will not yield significant RCS contributions from the front or aft aspects. In the lower hemisphere, it will suffer penalties due to the insufficiently obtuse join angles between the wings and stabilators, and outer engine nacelles. The upper fuselage fairings which house the all moving vertical tail actuators are well shaped, and the join angles are well chosen. The outward cant of the empennage fins is similar to United States designs, and like the YF-23 tail surfaces, these are fully articulated with the VLO benefit of removing surface impedance discontinuities at the join of a conventional rudder control surface.

The axi-symmetric 3D TVC nozzles present the same RCS problems observed with the fixed axi-symmetric nozzles used in the F-35 JSF [analysis/imagery], and the application of serrated shroud treatments and tailpipe blockers as used with the F-35 JSF will not overcome the inherent limitations of this canonical shaping design. Observed from the aft hemisphere in the L-band through Ku-bands, the PAK-FA prototype configuration will produce to an order of magnitude an equally poor RCS as the F-35 Joint Strike Fighter[10].

The centre fuselage beavertail follows a similar chine design rule as the forward fuselage does, and will not present a significant RCS contribution from behind.

If production PAK-FA aircraft employ the same lower and aft fuselage design as the prototype does, they will be susceptible to aft hemisphere and beam aspect threats at depressed angles, operating from the L-band through to the Ku-band, in a manner no different to the F-35 Joint Strike Fighter.

It is worth observing that the unconventional flight control capabilities of the PAK-FA do open up some possibilities, in that they permit manoeuvres such as flat turns, or even turns where the bank angle is opposite to a conventional banking turn. Such manoeuvres permit the PAK-FA to execute, without difficulty or high energy bleed, turns away from beam aspect threats without significant exposure of the problematic lower fuselage, unlike the conventional F-35 JSF which becomes unavoidably susceptible to detection, tracking and missile shots in such geometries. As the PAK-FA will provide a similar supersonic cruise capability to the F-22, its window of vulnerability is very much shorter when attempting to evade a tail aspect threat, and it has a credible capability to defeat missile shots kinematically.

Whether the current aft fuselage design of the PAK-FA is an artefact of the use of off-the-shelf Su-35S engines, or a permanent long term feature of the design, is unclear.

The general configuration of the PAK-FA aft fuselage is as compatible with the style of 2D VLO shaped TVC nozzles used in the F-22A, and integrated with the F119-PW-100 engines, as it is compatible in principle with the superb non-thrust vector aft fuselage design used in the YF-23. The latter remains the benchmark for wideband aft sector VLO fuselage design.

Producing a 3D TVC nozzle design which has similar VLO shaping performance as the F-22A 2D TVC nozzle design is not a trivial task - there is no obvious simple solution to this problem. If the Russians have solved it, it would be a major advance in VLO nozzle design.

Until Sukhoi disclose their intentions in this area, such as deployable LO shrouds for cruising flight, or provide imagery of the production PAK-FA aft fuselage design, this will remain an unresolved issue.

From an RCS engineering perspective, the shaping design of the PAK-FA is an excellent first attempt by the Russians to produce a high quality VLO design. The forward fuselage and engine inlet area shaping design is highly competitive against more recent US designs, and with mature high quality RAS and RAM application, have genuine VLO potential. The upper fuselage, wing and tail surface shaping and planform alignment are also competitive against US designs.

The problematic lower and aft fuselage designs, if retained in production aircraft, will deny the PAK-FA the kind of deep penetration capability sought in the design of the F-22A and YF-23.

The only cited RCS performance data was a recent claim by Sukhoi that the PAK-AF will have 1/40 of the RCS of the Su-35S. Unfortunately this was not qualified by threat operating band, aspect, or whether the Su-35S was clean or laden with external stores. The RCS of the Su-35S, head-on in the X-band, has not been disclosed, but given the extensive RAM treatments applied could be as low as 0.5 - 2 m^2 for a clean aircraft with no stores. If the latter were true, then the PAK-FA X-band head-on RCS would be of the order of -13 to -19 dBSM. Such performance would be consistent with the shaping design, but not with the application of mature RAM and RAS to same.

Analysis of tactical options, as published in March 2009, assumed a PAK-FA forward sector X-band RCS of about -20 dBSM, which fits the outer envelope of the Sukhoi disclosure almost exactly[5,6].

The Russians have claimed that the design has engine infrared signature reduction measures, but these have not been detailed. The conventional axi-symmetric nozzle design is generally ineffective, from an infrared signature perspective, as the nozzle shrouds are exposed radiators, and the cylindrical exhaust aperture radiates into a conical volume behind the aircraft.

The use of 3D TVC nozzles with high angle rates, which are fully integrated in the DFCS, would present opportunities to minimise RCS contributions resulting from aerodynamic control surface movements, by employing where possible TVC controls for primary pitch, roll and yaw control when performing stealthy penetration. Given that this flight regime entails flight in cruise configuration, and gentle turning manoeuvres to minimise bank angles, observably large deflection control inputs would be unusual and thus very infrequent. As a result the pitch, roll and yaw rates produced by the TVC system alone would be sufficient for most control inputs in the stealthy penetration regime of flight.

Above: PAK-FA upper aft fuselage / tail showing shaping details; below: YF-23A, F-22A Raptor (Sukhoi, US Air Force).

PAK-FA Aerodynamic Design

Examination of the publicly displayed PAK-FA prototypes show that this design is a continuation of the highly evolved pedigree of Flanker aerodynamic design. However, as observed in and predicted from the most recent Flanker variant, the Su-35S, and the work done during the deep modernisation program that resulted in this design, Sukhoi have evidently taken the next step by providing the PAK-FA with relaxed static stability in the directional axis.

Open source materials such as high resolution imagery and video camera footage show there are a number of features about the aerodynamic design of the PAK-FA that are different to, but clearly enhancements on the tried and proven aerodynamics of the Flanker family of aircraft, including:

- Fully articulated, reduced aspect ratio dorsal fins that are canted outwards. These provide large control power and control authority while minimising drag and side area with the additional LO benefit of the latter.
- Articulated LEX sections/control surfaces above and immediately forward of the quite large intakes of the propulsion system.
- Main wing leading edge sweep angle of ~46.5° to which the leading edges of the LEX sections and the horizontal stabilisers are edge aligned, with the latter closely nested with the wing trailing edge flaperons.
- Large wing area, estimated to be ~840 square feet.
- Large leading edge flaps, around 90% span of each of the outboard sections of the main wing.

- Large trailing edge flaperons spanning about 60% of each of the outboard sections of the main wing, truncated and blended with the leading edges of the horizontal stabilators.
- Large aileron control surfaces of ~30% span of the outboard sections of the main wing.
- Prodigious wing/fuselage blending with primary area ruling achieved through shaping of the upper and lower portions of the engine nacelles.
- Classic later generation Flanker Boundary Layer Control (BLC) systems in and around the intakes, extending aft along the engine lower nacelles.
- The propulsion system intakes are quite large and clearly intended to accommodate thrust growth, possibly the use of 'ejector nozzle technology' for increased thrust augmentation (akin to the J58 engine of the SR-71 and more recent DARPA Vulcan program), and overall thermal management, as well as providing additional air for exhaust plume shrouding, the latter for infrared signature control.
- Alternate intakes for the propulsion system, as seen on earlier Flankers.
- Nominal engine thrust lines are canted outwards about 2° to 3° off the longitudinal centreline, with the engines spaced symmetrically around BL 00, at around 10 feet centre to centre spacing at the nozzle exit planes. This configuration reduces the risk of the rapid onset of large yaw rates at large thrust settings due to single engine in-flight shutdowns, while, when combined with the increased ~60°/sec angular TVC rates observed in the Su-35S design, enhancing the ability of the TVC system to augment/replace aerodynamic flight control inputs, while aiding in the provision of 'apparent static directional stability' through dynamic control to replace the normally 'natural inherent static directional stability' that has been relaxed.
- There has clearly been a concerted effort to establish harmony and complementarities between the inertial properties in each of the aircraft axes, as well as the physical sizing of the control surfaces for each axes. This work has its roots in earlier T-10 Flanker series designs, most recently, the Su-35S.
- As seen on the Su-35S, there is no separate, dedicated speed brake control surface, this function being subsumed by differential deployment of control surfaces.
- With the undercarriage fully deployed, the primary Nose Landing Gear (NLG) doors are closed with small ancillary doors providing the opening through which the NLG oleo and related dual wheel and steering assembly protrude, thus removing the directionally destabilising effect of the primary doors in the powered approach (PA) configuration.
- When deployed, the sizeable Main Landing Gear (MLG) doors are aligned to the longitudinal plane of the aircraft and likely contribute to the static directional stability of the aircraft in the PA configuration.

Observations from the video footage of the first "public" flight include:

- The relatively high speed taxi to the hold short line showed very little vertical motion or forward/aft interaction of the undercarriage oleos/tires spring/damper system which suggested the aircraft was likely at a relatively light, mid-fuel/mid centre of gravity (CoG) configuration.
- The aircraft flew away from the runway during the take off with no perceptible pitch control input, evidenced by no leading edge displacement of the horizontal stabilisers and no deflection of the TVC nozzles in pitch being observed. This is akin to the F-22A Raptor wherein take off trim and lift off speed are all that are required for the aircraft to unstick

off the runway. This contrasts strongly with the F-35 series of designs, where a conventional take off requires an elevator input in the order of 30° LE down to initiate the unstick /rotation process.

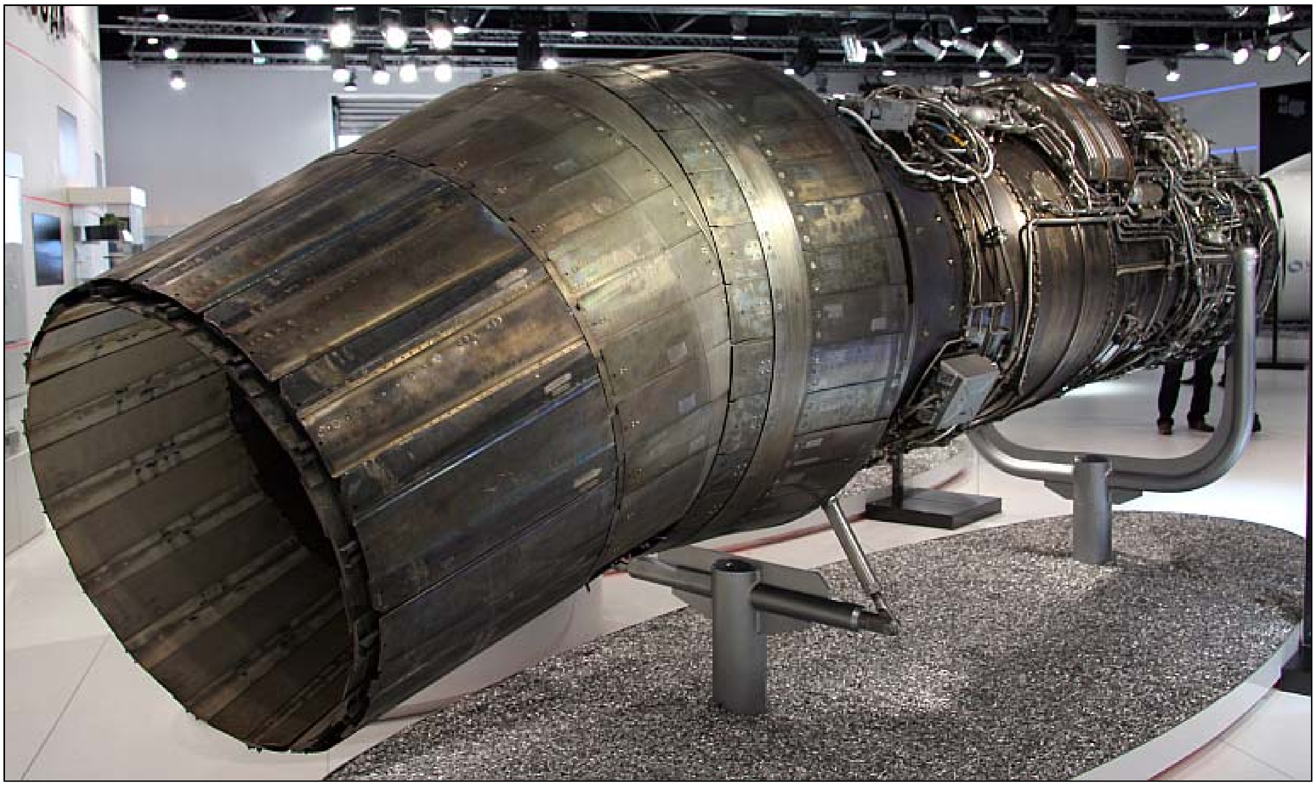
- Very little leading edge flap deployment, most likely employing the minimal take off trim setting, appeared to be required and no significant deployment of the trailing edge flaps was evident.
- During the ground roll, engine nozzles were in the trail position and no vectored input in either the longitudinal or lateral axes was evident.
- Take off roll to un-stick was estimated at somewhat less than 1,500 feet, taking some 12 seconds from brake release to rotation speed (V_r).
- Rotation and initial climb out appeared smooth, stable and well controlled with increasing rate of climb, with the causally increasing climb angle and climb attitude evident and monotonically climbing within 2 seconds after lift off.
- Little coverage of the up and away part of this flight was released into the public domain, though there are multiple reports that the undercarriage was cycled when airborne and some time was allocated for mild side slip and flat turn manoeuvres, along with lateral control excursions to around 45° from wings level flight.
- The landing was uneventful with what appeared to be minimum leading and trailing edge flap settings and little, if any, employment of TVC and/or the LEX control surfaces. The pilot held the nose wheel off the runway for approximately 4 seconds after the MLG contacted the runway, with the nose wheel run on to the tarmac coinciding with deployment of the two arrestor drag parachutes. These chutes were released some 10 seconds later, signalling the end of the 14 second ground roll portion of the landing iteration. Overall, the distance of this portion of the landing was estimated at somewhat less than 1,300 feet.

The results of detailed observations and analyses of the material now in the public domain combined with knowledge of the progressive ‘evolutionary and evolving’ development of aerodynamic techniques by Sukhoi over more than two decades, demonstrates that Sukhoi and its supporting team of engineers and scientists have achieved mastery of extreme agility throughout the whole air combat continuum. Since the Su-35S design is already accredited with the title of “extreme agility”, the aerodynamic and kinematic capabilities of the PAK-FA will likely require coining of the term “extreme plus agility” to do them justice.

The introduction of relaxed static directional stability in the PAK-FA design, alone, will ensure that the PAK-FA has the manoeuvrability and controllability capabilities and, thus, the agility that no Western fighter design can provide.

There is only one Western fighter design configuration that, with some upgrades and modification, will be able to approach the PAK-FA in manoeuvrability and controllability capabilities; specifically, the F-22A Raptor. The aerodynamic design of all other US air vehicles precludes such modifications, this including the F-35 Joint Strike Fighter.

PAK-FA Structural, Systems and Propulsion Design



The 117S powerplant used in the PAK-FA Prototype (© 2009 Vitaliy V. Kuzmin).

Examinations of the PAK-FA prototypes show clearly that the structural, airframe systems and propulsion aspects of the PAK-FA follow the now quite predictable, well managed and low risk developmental paths established by Sukhoi in the T-10 Flanker family of aircraft designs.

Over the last three decades, this approach has seen technological advancements, extensions and enhancements grounded solidly in those employed in previous designs, prototype programs and the resulting fighter/strike/attack/interceptor aircraft systems that were placed into operational service with Russian military forces as well as exported around the world.

The structural enhancements and advancements to be seen in the PAK-FA design include further use of light weight, high strength metal alloys, such as Ti, Al, and AlBe alloys, and the greater use of composite technologies and the associated materials, both of which provide a stiffer, stronger airframe with an even further reduction in the air vehicle's relative structural weight than that achieved in the Su-35S design revealed in the latter part of 2008.

There can be no doubt from the basic airframe shaping that the internal airframe structural details are derived from and were proven in the Su-35S and its preceding Su-35BM deep modernisation Program.

The same applies for the airframe systems, including the hydraulic, electrical, pneudraulic and fueldraulic power systems; fuel distribution and engine feed systems; environmental control systems (ECS), OBOGS, auxiliary power; and, all important thermal management systems.

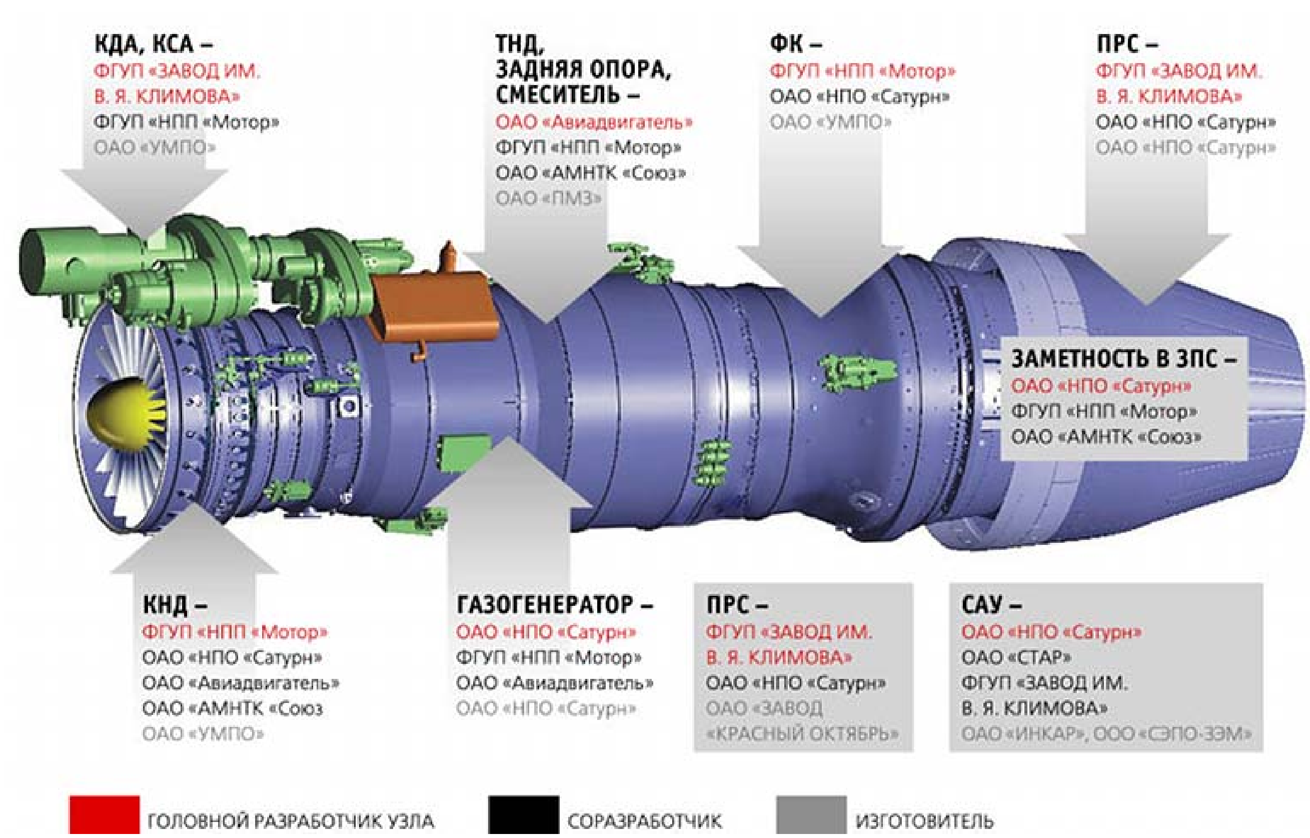
The large internal fuel capacity of ~25,000 lbs and the significant amount of high pressure air available from the oversize main engine inlets will ensure the PAK-FA will have none of the problems and challenges confronting earlier US fighter designs, and known to have become a critical and severely limiting design issue in the JSF Program.

The existing PAK-FA prototype effort is clearly focussed on minimising risk during the initial process of proving the aerodynamic, airframe and systems design. Russian open sources have stated that the prototypes are powered by the existing production Al-31F 117S, often labelled for marketing reasons as the Al-41F1A, variant 19,400/32,000 lbf (8,800/14,500 kp) engine, employed in the Su-35S. While this engine lacks the performance rating of the earlier developmental Al-41F series and its likely derivatives, it is capable of supercruise and thus permits significant flight test and flight control system development to be performed without the high risks characteristic of the concurrent use of a developmental engine and developmental airframe.

The cited TVC capability of the 117S engine is ±15° in the vertical plane, and ±8° in the horizontal plane, with deflection angle rates of now up to 60 °/sec, putting them in the same onset rate category as fighter-type aerodynamic flight control surfaces. The engine employs a larger diameter fan, at 932 mm vs. the 905 mm fan in the earlier Al-31FP TVC engine. Key hot end components in the core were redesigned to employ the cooling system technology developed in the 1990s Al-41F, permitting much higher TIT ratings and a commensurately reduced thrust lapse rate with altitude, in turn permitting supercruise operation.

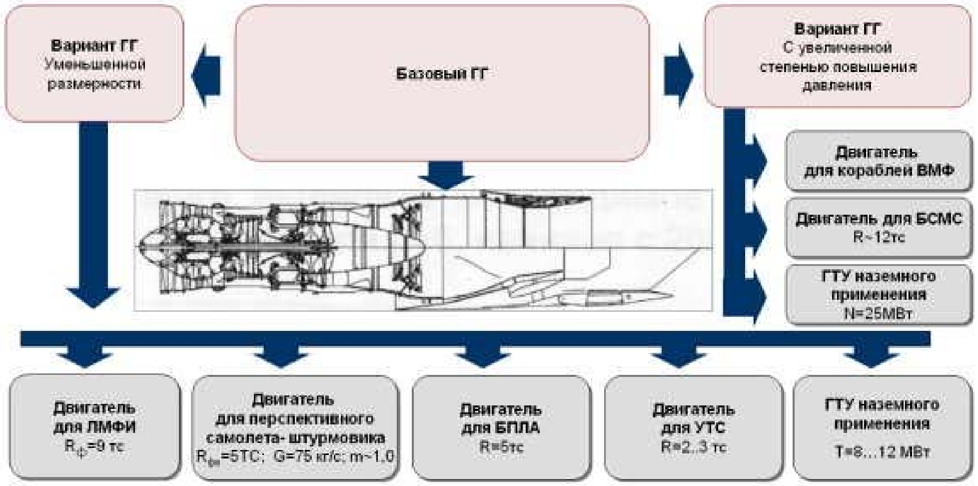
Harmonisation of the digital flight control laws with the precision 3D TVC nozzle system requires a robust and reliable 3D TVC nozzle equipped powerplant.

Uncertainties remain in terms of the capabilities and design of the intended powerplant for Full Rate Production aircraft. Saturn have been developing a new engine for the PAK-FA since 2006, labelled as the "Fifth Generation Fighter Engine". Clearly this will employ technology from the existing 39,600 lbf class Al-41F, developed initially for the MFI[8].



Above: workshare breakdown for the developmental fifth generation engine; below: intended applications for same. The Russian language legend shows a common core [Basic Gas

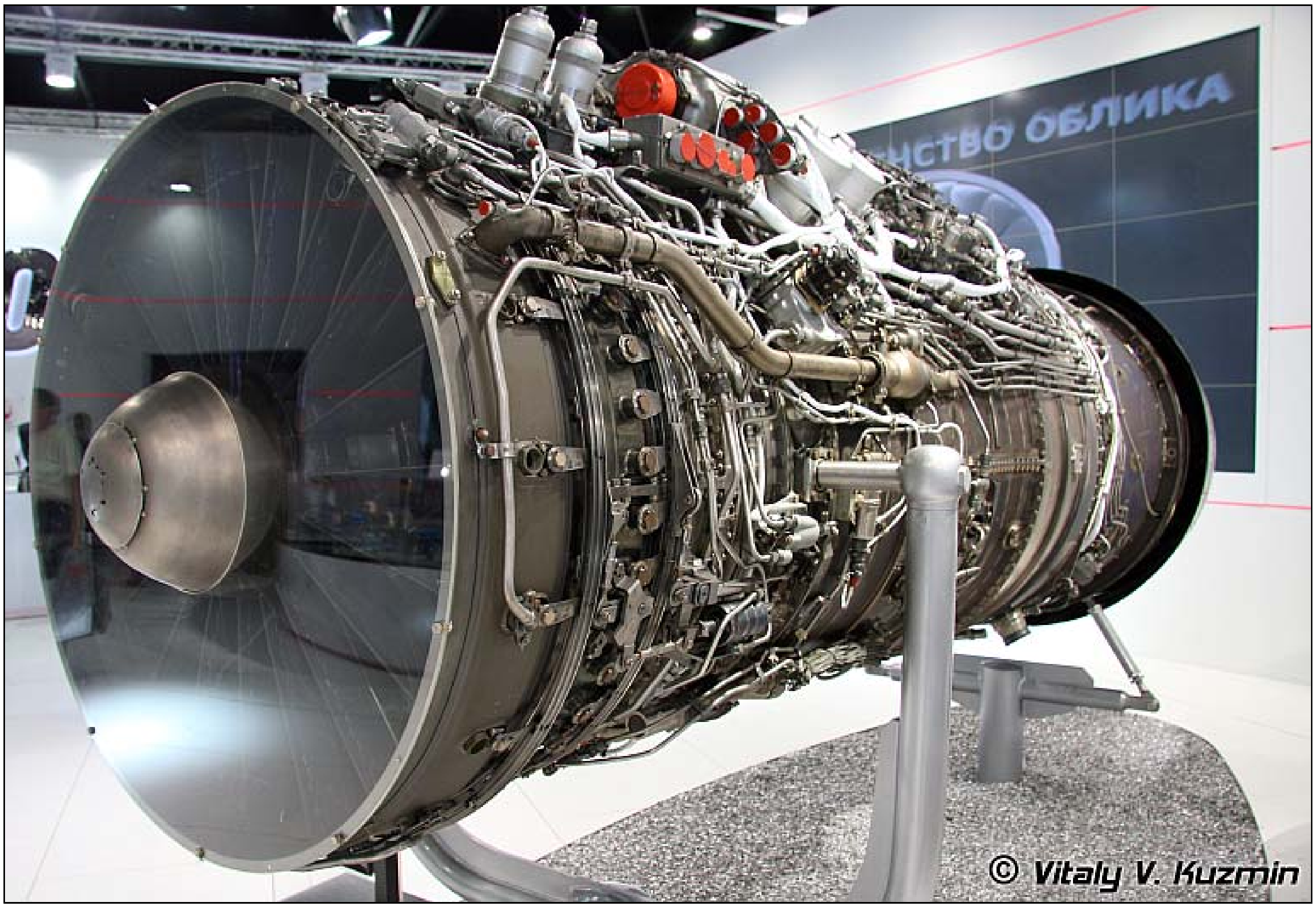
Generator] exploited for a range of other applications, including maritime surface combatant powerplants, and fixed power station or gasline pumping applications (NPO Saturn).



Public comments by Russian parliamentary scientific advisor Konstantin Makienko, in a recent media interview, indicate that the Russians envisage the PAK-FA project in terms of a 40 - 50 year operational life cycle, reflecting historical experience with the T-10, which entered development during the early 1970s[4].

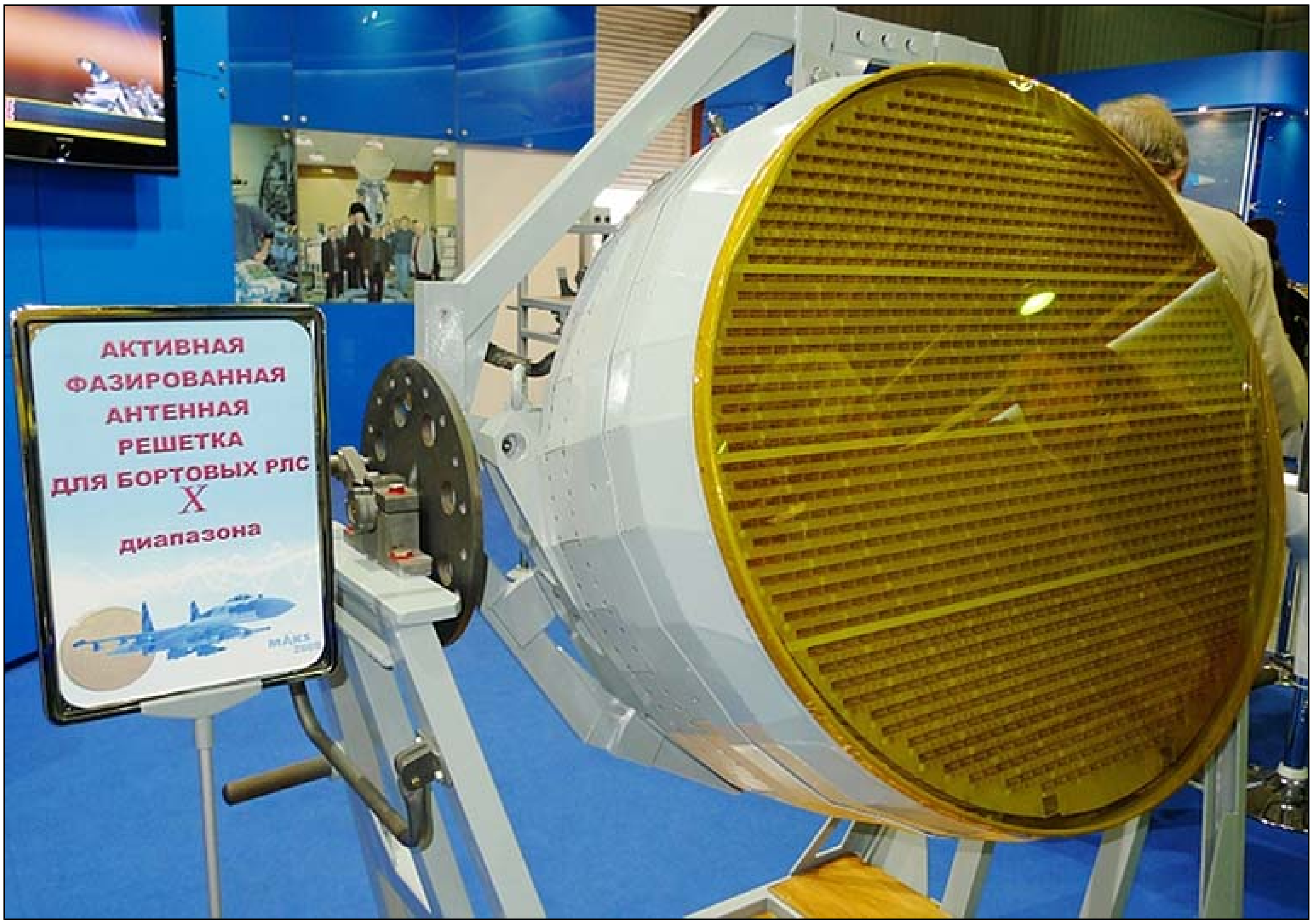
Against such timescales, it is a certainty that production PAK-FA aircraft will see two or three generations of powerplant fitted to the design, which further explains the employment of the large, seemingly oversize propulsion system intakes. Clearly, the Sukhoi penchant for alternate intakes in Flanker designs continues with the PAK-FA design.

Production PAK-FA aircraft will therefore at some stage acquire a high variable bypass supercruising engine with a variable cycle core and augmenter, as the diverse needs of long range/persistence and supercruise dictate this design approach. When the US dropped the variable cycle YF-120 from the ATF program during the early 1990s, it was for fear of development risks impacting deployment timelines, leaving the production F-22A Raptor with a much more basic F119-PW-100 engine design.



The 117S powerplant (© 2009 Vitaliy V. Kuzmin).

PAK-FA Cockpit, Avionics and Radar Design



Tikhomirov NIIP AESA on display at MAKS 2009 (© 2009, Miroslav Gyűrösi).

Russian statements on the core avionic suite intended for the PAK-FA have not been particularly revealing to date, but indicate the design will be in many parts an evolution of the Su-35S avionic design. Given that the avionic suite for the Su-35S is an entirely new and fully digital design, in basic technology terms it will differ little from the technology in current United States designs. The expectation that the PAK-FA might be combat ineffective if equipped with a derivative of the Su-35S Flanker avionic suite is illogical and clearly optimistic, as the Su-35S digital avionic system design is credible by any measure.

A minimal adaptation would retain all core components of the Su-35S avionic design, but replace all conventional apertures with VLO equivalents, and alter waveforms to provide LPI operating modes.

Sukhoi will face some interesting design challenges in developing the PAK-FA avionic suite. These will lie in the same areas which have bedevilled US designers in all recent VLO aircraft development projects, specifically in the provision of high capacity avionic cooling, which does not produce infrared hotspots, and in the design of wideband, yet very low RCS radio-frequency apertures for both passive and active sensors, and aircraft datalink/network terminal transceivers.

VLO aperture design has been a source of ongoing difficulties in design, as structural mode RCS and impedance mismatches against the aperture can result in prominent RCS flare spots, which can be disastrous in a VLO design. Even a small RCS contribution can be problematic, given the number of apertures required to support especially wideband all aspect ESM/RFS sensors.

An unknown at this point in time is the extent to which Russian designers will have exploited wreckage from the F-117A Nighthawk, lost in the 1999 OAF campaign over Serbia. The remains of this aircraft would be a valuable source of detail components, especially VLO rated antennas, VLO rated instrumentation ports and probes, and proven albeit older VLO materials technology.

Russian parliamentary scientific advisor Konstantin Makienko, in a recent media interview, noted that the PAK-FA avionic suite would be used as the basis for technology insertion upgrades on the Su-35S. He also observed that "Not just an active radar but an entire multifunctional integrated radio electronic system that contains five integrated arrays is being developed for PAK FA"[4].

The latter is interesting, as the beavertail has a radome compatible with an aft looking X-band AESA, an option available for a number of later Flanker variants. Statements have also emerged that cheek X-band AESA apertures, to supplement the forward AESA, were planned, analogous to the cheek AESAs planned for the F-22A. This however does not account for five AESA apertures.

If some RCS degradation in the L-band is tolerated, then L-band AESAs [analysis/imagery] could be installed in the leading edges of the LEX or wings, using a frequency selective bandpass radome. This however does not add up to five apertures, unless the paired L-band AESAs are counted as a single aperture, a possibility since both are operated as a single phase steered array[14].

As noted in the discussion of observables, the prototypes are likely to be equipped with a derivative of the Su-35S OLS.

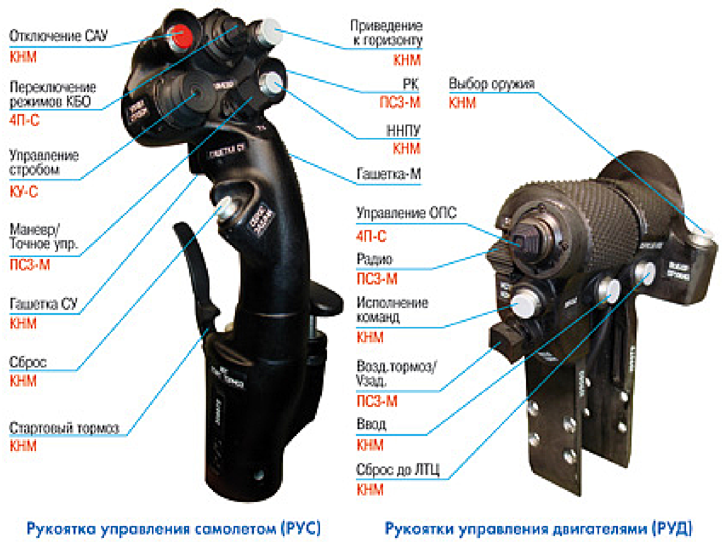
Su-30MKM aircraft supplied to Malaysia have been fitted with a multiple aperture optical MAWS. A similar MAWS design for a VLO airframe will confront analogous problems to radio-frequency apertures, likely resulting in similar flush window designs as used with the F-35 Distributed Aperture System (DAS).

Until representative late PAK-FA prototypes are seen, with the full avionic suite fitted, uncertainties will remain in properly assessing the capabilities of the active and passive sensor suites, threat warning systems, active countermeasures fit, and expendables options.

The lengthy intended service life of the PAK-FA and rapid evolution of avionics technology over coming decades indicates that this design is likely to see two or three generations of avionic suite installed over the aircraft's life cycle.

There have been no prominent disclosures on the PAK-FA cockpit design. It is likely that a derivative of the ergonomically well fashioned Su-35S glass cockpit would be used - this design employs a pair of large AMLCD panels to emulate the projector based arrangement in the F-35, but with more robust fault tolerance, greater simplicity in design, yet similar ease in operation.

Russian sources claim that the new OKB Aviaavtomatika HOTAS control set is likely to be used in the PAK-FA, but no formal disclosures by manufacturers have been made to date.



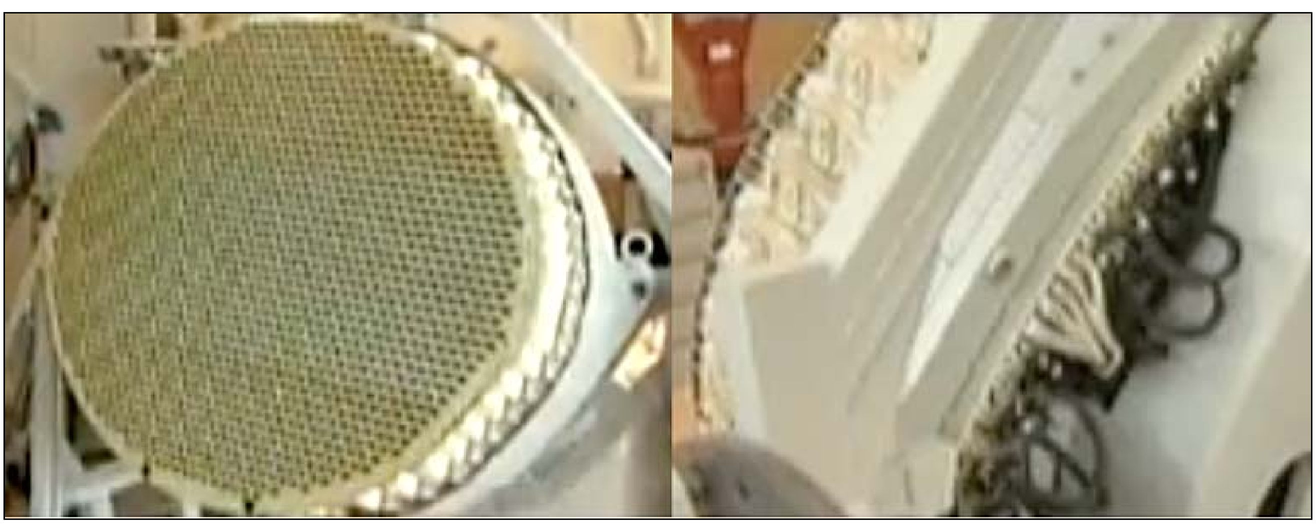
OKB Aviaavtomatika HOTAS controls which Russian sources claim to be the most likely design employed in the PAK-FA cockpit (Aviaavtomatika).

Like the Su-35S, the PAK-FA will employ a dual mode Glonass/GPS receiver and Kalman filter based inertial navigation suite, with an RLG.

As with the Su-35S, the PAK-FA will carry datalinks for bi-directional data transfers. There have been no disclosures at this time on the datalink terminals or waveforms intended.

In the integration of network terminals, Russian industry will confront much the same issues the US Air Force has had to resolve in defining and developing Low Probability of Intercept (LPI) datalink modulations compatible with stealthy operations. The Russians will be acutely aware of the design issues, given their previous effort in exploiting datalink terminal emissions for passive targeting of SAMs.

A number of Russian sources have commented on the use of "data fusion" in the PAK-FA avionic design, a technique which is used currently in the F-22A and intended for the F-35.



Enhanced stills from a Russian television broadcast reporting the Tikhomirov NIIP PAK-FA AESA design. Static display images of the antenna have a dielectric impedance matching screen installed, which obscures the actual TR module apertures (Vesti - Moskva via Youtube).

The Tikhomirov NIIP X-band AESA design for the PAK-FA is better understood than the core avionic suite, due to extensive disclosure by Tikhomirov NIIP at MAKS 2009. The antenna aperture is very similar in size, if not identical, to the aperture of the N-011M Irbis E used in the

Su-35S. The design is intended for fixed low signature tilted installation, rather than gimballed installation, and auxiliary cheek arrays are planned for. The design is also claimed to have been integrated with an existing BARS/Irbis radar for testing and design validation purposes.

Public statements made in Russia through 2009 claim 1,500 TR module elements. Counting exposed radiating elements on video stills of the antenna indicates an estimated 1,524 TR channels, with a tolerance of several percent. This is within 5% of the 2008 analytical model for a Flanker AESA[15].

NIIP have publicly cited detection range performance of 350 to 400 km (190 to 215 NMI), which assuming a Russian industry standard $2.5m^2$ target, is also consistent with the 2008 model for an AESA radar using ~10W rated TR modules, which in turn is the power rating for the modules used in the Zhuk AE prototypes. This puts the nett peak power at ~15 kiloWatts, slightly below the Irbis E, but even a very modest 25% increase in TR module output rating would overcome this.

There are distinct differences between the AESA displayed by NIIP for Vesti, which has less depth and uses circular radiators, and the examples displayed at MAKS 2009 and depicted on brochures, which are constructed using TR module sticks and are several inches deeper.

To drive down the cost of this AESA, the best strategy available to the Russians is the export of AESA upgrades to the global community of Flanker users over the coming decade, emulating the US approach with this technology, and driving up the volume of TR modules built. Tikhomirov NIIP brochures state that the existing AESA would be the basis of AESA upgrade designs for the Su-27/30/35 Flankers.

A design problem that Tikhomirov NIIP will have to grapple with is that of LPI waveforms for the AESA, as these are critical to covert stealthy combat operations. This will require that the AESA employ wideband feed networks, a wideband digital waveform generator, and generous provision of computing power for signal and data processing. LPI techniques have not been discussed to any extent in unclassified Russian literature, but are well covered in United States academic publications, and the technology is available to the Russian industry to develop and implement LPI equipment.

In conclusion, Sukhoi and its team of subcontractors will have to deal with a range of design challenges, mostly related to observables, no different to those which the United States industry has had to master during the B-2 and F-22 programs. This is well understood by the Sukhoi designers, as is evident from the careful thought invested into risk management across the whole PAK-FA design. The absence of public disclosures on the avionic suite does not indicate the absence of advanced avionic subsystems, for which Russian industry has all of the basic technology, but rather an intentional and demonstrated policy of non-disclosure until the greatest competitive advantage can be extracted in the market.

Su-35S Electro-Optical System turret fitted to PAK-FA prototype (© 2009 Vitaliy V. Kuzmin).

Su-35S cockpit (Sukhoi brochure).

PAK-FA Weapons Capabilities

The primary BVR weapon to be carried by early production variants of the PAK-FA is the KTRV RVV-SD, an extended range evolution of the R-77 / AA-12 Adder similar to the AIM-120D. Note the laser proximity fuse supplanting the radiofrequency fuse (© 2009 Vitaliy V. Kuzmin).

Very little has been disclosed to date on the intended weapons suite for the PAK-FA. The internal bays are claimed to fit eight AAMs. The limited width of the centre fuselage bays indicates that most likely these would each fit three staggered RVV-SD rounds, this being the latest variant of the R-77 / AA-12 Adder and a direct equivalent to the US AIM-120 AMRAAM series. To date only the active radar seeker equipped RVV-SD variant has been displayed, the intended heatseeking and anti-radiation variants have yet to be seen in mockup form or marketing literature.

While a new WVR AAM has been planned, it is likely that a derivative of the RVV-MD / R-74 Archer series will be used with early PAK-FA variants.

For very close air combat, a 30 mm gun mounted in the starboard forward fuselage will be employed - the type has not been disclosed to date but it is likely to be a variant of the GSh-30 series carried by the Su-35S Flanker.

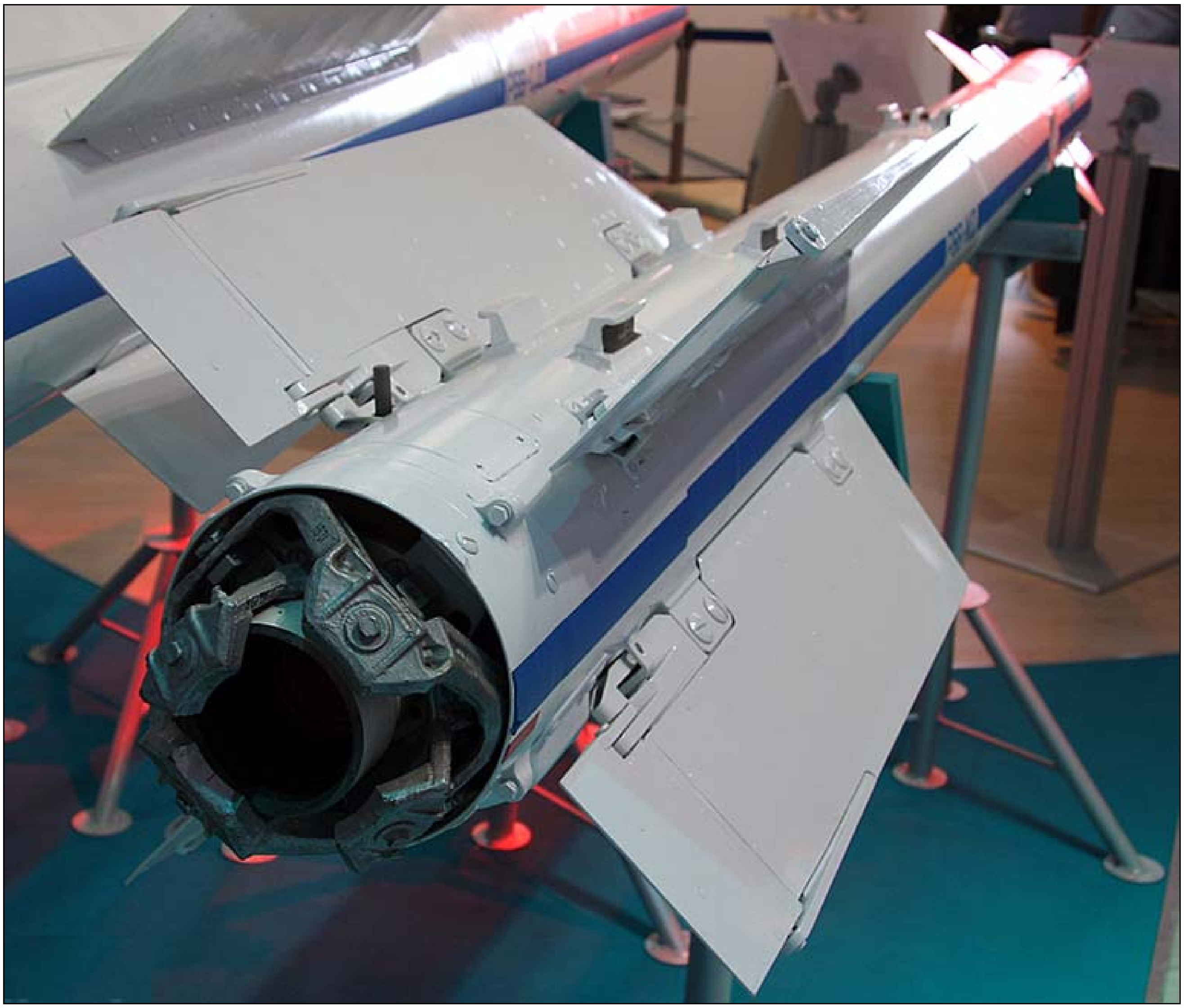
With eight stations cited for external stores, and the diversity of guided bombs, ASMs and cruise missiles available for the Su-30MK/Su-35S Flanker series, there is no shortage of alternatives for external carriage by the PAK-FA[7].

Internal weapons for strike roles are a much more interesting consideration, due to the limited volume of the internal bays. Recent designs known to have folding surfaces for internal carriage include the new KTRV Kh-38 and Kh-58UShKE Kilter.

It is likely, but yet to be confirmed, that KTRV are developing an analogue to the GBU-39/B Small Diameter Bomb.

Given the well established and managed aerodynamics of this area of the Flanker designs, weapon clearances from the internal bays across the whole of the PAK-FA's operational envelope should be achieved with little, if any, difficulties, and without the need for employment of exotic and heavy techniques such as aero-acoustic local flow control and shaping or similar.

The primary close combat weapon to be carried by early production variants of the PAK-FA is the KTRV RVV-MD, an extended range evolution of the R-73/74 / AA-11 Archer with a jam resistant two colour scanning seeker and a laser proximity fuse. Note the wideband ZnS or ZnSe IR window replacing the narrowband MgF_2 *design used in earlier variants (© 2009 Vitaliy V. Kuzmin).*



Kh-38 mockup on display. Note the folding fins for internal carriage (© 2009 Vitaliy V. Kuzmin).

KTRV Kh-58UShKE Kilter anti-radiation missile. Note the significantly revised radome and cruciform reduced span folding wing design of this recent variant (© 2009 Vitaliy V. Kuzmin).

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(Images Sukhoi, KnAAPO, Rosoboronexport, RuMoD, Tikhomirov NIIP, KnAAPO, Other, Author)

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Carlo Kopp	*Air Power Australia*	May 2007	Supercruising Flankers?
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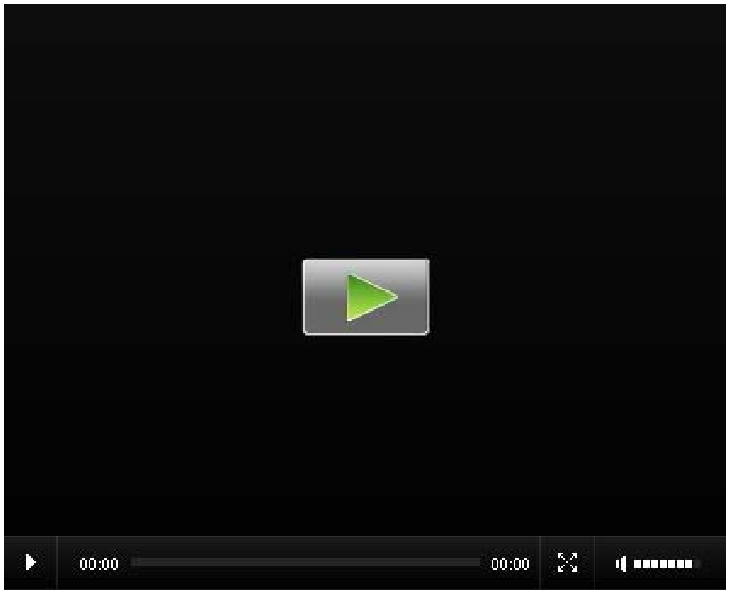
Annex A PAK-FA Prototypes

First prototype of the PAK-FA during an early test flight, January 2010 (Sukhoi images).

Left: PAK-FA with Su-30MK chase plane, showing relative sizes; above plan view (via Russian Internet).

Annex B PAK-FA Multimedia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Pak Fa (T-50) First Flight Full Video
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PAK FA today
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YouTube
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Three revolutionary designs - Sukhoi T-50 PAK F...
YouTube
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NIIP's radars from MAKS 2009 including PAK FA's...
Юрий Белый
Генеральный директор НИИП им. В. В. Тихомирова
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