HIGHSPEED ROTORCRAFT OF THE MI-450 FAMILY – A NEW GENERATION OF CROSS ARRANGEMENT ROTARY – WING AIRCRAFT

Mikhail Korotkevich, Stanislav Midzyanovskiy, Valery Ivchin

JSC Moscow Mil Helicopter Plant,
140070, 26/1 Garshina str., Tomilino, Moscow region,
Russia

Key words: helicopter, helicopter with wing, helicopter with auxiliary propulsion, compound helicopter, tiltrotor.

Abstract

The paper presents the results of the studies carried out to validate the concept of a new generation compound helicopter of cross arrangement (side-by-side rotor) configuration with the estimated cruise speed of 450 kmh, dubbed the Mi-450.

The key features determining the Mi-450 rotorcraft family configuration are as follows:

- a new type rotor system which consists of two slowed during cruise mode rigid rotors accommodated overlapped on a short wing;
- a thrust propeller located above the fuselage on the fin;
- modular split torque rotor gearboxes having large-diameter shafts which house blade pitch fly-by-wire actuation devices;
- rotor blades with embedded in the roots hinges;
- a transport module which is a fixed wing aircraft type fuselage equipped with a high energy absorbing landing gear and new generation on-board systems.

The Mi-450 design and technology characteristics of rotor and transmission systems make it possible to eliminate the design limitations of the Ka-22 side-by-side compound helicopter which caused the helicopter crash and led to subsequent program closing; it is also possible to avoid significant weight increase inherent to single and coaxial rotor helicopters.

The study shows that the Mi-450 compound helicopters require significantly less power to fly at 100 to 400 kmh as compared to conventional helicopters and tiltrotors. On the other hand the Mi-450 compound helicopters require more power for hovering and low-speed level flight than conventional helicopters and tiltrotors due to wing download and rotors interference. However, unlike tiltrotors the required power increase for these flight modes and decreasing autorotation performances are not that dramatic for the Mi-450 rotorcraft.

The Mi-450 compound helicopters family transport efficiency is considerably higher than that of conventional helicopters and is close to tiltrotors by this criterion.

The following are the main competitive advantages of the Mi-450 compound helicopters family as compared to tiltrotors: development, production, certification and operation cost reduction due to lighter and less complex construction. Also it provides a much safer flight because in case of engine failure it is possible to land safely on autorotation due to much lower disk loading, higher rotor inertia and lower rotor blade twist.

1. Introduction

One of the main trends in modern helicopter engineering is enhancing investigations aimed at development of new rotary-wing aircraft concepts capable of filling a nearly two-fold gap between conventional helicopters and tiltrotors in terms of speed and range, but at the same time that will provide a higher level of safety and a more economically viable life-cycle cost of an aircraft.

Current helicopters, most of which are conventional, have reached the maximum of their cruise speed of 285-300 kmh. Production helicopters service experience, engineering estimates and experimental studies show that increasing level flight speed results in drastic increase of loads, vibration and much higher power is required. Up to now these reasons stood in the way of development of an economically viable (a cost-effective) civil single rotor helicopter, the cruise speed of which would exceed 300 kmh.

Tiltrotors are capable of reaching twice the speed of conventional helicopters, but they are exceedingly difficult to design, produce, test and certify and as a result they have a very narrow market share of special purpose military rotorcraft.

However the demand for vertical takeoff and landing aircraft (VTOLs) flying at much higher speeds and over greater range, capable of carrying out transport support of commercial exploitation in Arctic and hard-to-reach areas of Siberia, Far East and Russia's polar sector (Fig. 1, 2), regional passenger transportation in areas without aerodromes, search and rescue (SAR) operations; emergency medical operations and humanitarian missions, as well as supporting special services and rapid deployment forces in guarding of borders and anti-terrorist operations in local conflicts, is becoming increasingly urgent (Fig 3).

An X3-based single rotor compound helicopter called LifeCraft with an estimated cruise speed of 220 knots (407 kmh) (Fig.4) has been unveiled in Europe alongside with the AW-609 (Fig.5) and ERICA (Enhanced Rotorcraft Innovative Achievement) development programs.

Bell Helicopter and Karem Aircraft are developing new generation tiltrotors (Fig 6, 7); AVX Aircraft and Sikorsky-Boeing team are developing coaxial rotor compound helicopters (Fig.8, 9) for the US Army JMR program which are to reach maximum cruise speeds of 426 kmh (230kts) and range not less than 424 km (the cruise speeds of the UH-60 Black Hawk and the AH-64 Apache are 274 and 285 kmh respectively, and their combat radius is about 200 km).

In Russia the program of new generation high-speed rotary-wing aircraft includes simultaneous development of several designs (Fig. 10, 11, 12, 13). JSC Moscow Mil Helicopter Plant's Innovation Center has initiated and is carrying out one of the research and development efforts, namely, "Concept Definition Study of the Advanced High Speed Compound Cross Arrangement Helicopter and Critical Technology Development using small-sized and full-scale Technology Demonstrators" (Fig 13).

The penalty for the unique capabilities of vertical take-off and landing of current helicopters is significant reduction of cruise speed and range as compared to fixed-wing aircraft. Helicopters cruise speed and range are the most important for the customers.These are the performances that are determining at present and will determine in future the role of rotary–wing aircraft as an effective way of transporting passengers and cargoes and as combat systems of the 21st century.

2. Key Definitions, Facts and Conclusions

There are five classes of modern rotary-wing aircraft:

1. Conventional helicopters are vertical take-off/landing aircraft having one or more rotors (single rotor helicopters, coaxial rotor helicopters, tandem rotor helicopters, side-by side rotor helicopters, synchropters).
2. Helicopters with wing are helicopters having one or more rotors and a wing.
3. Helicopters with auxiliary propulsion are helicopters having one or more rotors and a means of providing propulsive force (a propeller or a turbojet engine), the fraction of the propulsive force can be carried by the main rotor.
4. Compound helicopters are helicopters having one or more rotors, a wing and a means of providing propulsive force, a fraction of which can be carried by the main rotor.
5. Tiltrotors or tiltwings are aircraft having a fixed or a tilt wing which provides lift in forward flight and tilting rotors which provide lift in hover and low-speed flights and propulsive force in level flight.

Record speeds (Fig. 14) have been achieved by "clean-sheet" proof-of-concept rotorcraft or modernized production helicopters. Cruise speed of in-production helicopters is generally much lower. Thus Westland Lynx proof-of-concept rotorcraft set a speed record of 400 kmh. The current in-production helicopter has a maximum cruise speed of 230kmh.

The "**1940 – 2010: Brief history of hybrid helicopters around the world**"[1] survey published at eurocopter.com shows that 21 out of 25 helicopters built in the last 70 years are single-rotor helicopters, 3 are coaxial helicopters and 1 (the Ka-22) is a cross arrangement (side-by-side rotor) helicopter. 23 of them were proof of concept aircraft built for research in single quantities. The USA single-rotor Lockheed AH 56-A Cheyenne (Fig. 15) and the USSR Kamov Ka-22 (Fig. 16) side-by-side rotor compound helicopters were developed for practical use and built in limited numbers. However, the programs were cancelled as each helicopter suffered fatal crashes caused by technical problems. In his interview to *Aerospace Knowledge* magazine a former Mil Helicopter plant General designer (1970-1991) academician M.N. Tishchenko mentions a combat cross arrangement configuration helicopter project (Fig. 17, 18) which was considered to be the Mi-28 candidate configuration.

It is common knowledge that the correlation curve of helicopter fuel burn per unit of distance has a rather flat minimum. So when cruise speed differs only slightly from best-range airspeed fuel burn increases insignificantly. On this basis let's consider that cruise speed is the speed which an aircraft may develop in level flight at maximum continuous power.

Comparing the helicopters of the above mentioned classes such terms as rotor efficiency, overall aircraft lift-to-drag ratio as well as aircraft propulsive coefficient as described by M.N. Tishchenko[2,3,4] are used in this paper.

Rotor efficiency is rotor lift-to-drag ratio in autorotation, that is at zero rotor shaft power when rotor can be compared to a wing.

Overall aircraft lift-to-drag is wing, rotor and non-lifting components (fuselage, stabilizer and others) **lift ratio to overall drag force** equal to the sum of

rotor drag in autorotation, wing and non–lifting components drag.
With respect to the above mentioned definitions of lift-to-drag ratio and propulsive coefficient the level flight speed of a rotary wing aircraft can be calculated by the following equation:

$$V = \frac{3600 \cdot N \cdot K_{AIRCR} \cdot \eta_{PR} \cdot \xi}{m_{TO} \cdot g}$$

where:
- N - engine power, kW;
- K_{AIRCR} - aircraft lift/drag ratio;
- η_{PR} - propulsive coefficient;
- ξ - main rotor power coefficient;
- m_{TO} - take-off weight, kg;
- g - gravity acceleration, m/sec^2.

The equation shows that helicopter level speed with given take-off weight is directly proportional to the engines power, aircraft lift-to-drag ratio and rotor propulsive coefficient.

3. Helicopter Maximum Speed and Alternative Ways of Helicopters Speed Increase

3.1. The Factors that Limit the Maximum Speed of Helicopters

The maximum speed of conventional helicopters is limited by advancing blade compressibility and by one of the several phenomena lumped together under the term “blade stall” on the retreating blade. To obtain the highest maximum speed a rotor speed must be selected that allows the retreating blade to experience blade stall at the same time that advancing blade experiences compressibility.

3.1.1 Main Rotor Retreating Blade Stall

One of the predicted characteristics of the main rotor retreating blade stall is a retreating tip angle of attack. A diagram in “Engineering Design Handbook. Helicopter engineering”[5] shows (Fig. 20) the retreating tip angle of attack as a function of horizontal speed for a conventional helicopter, a helicopter with wing, a helicopter with auxiliary propulsion and for a compound helicopter.
The diagram shows that if the angle of attack of the retreating blade is 12 degrees conventional helicopter and helicopter with the wing can reach a speed of 350 kmh, helicopter with auxiliary propulsion can fly at 435 kmh and **a compound helicopter (a helicopter with wing and propulsion) doesn’t have any speed limitations caused by main rotor retreating blade stall**.

3.1.2 Main Rotor Advancing Blade Compressibility

There are three components of required power that are usually taken into account during trade-off analyses of aircraft of different types. They are induced power, profile power and the parasite power (power required for overcoming parasite drag). For a first-order approximation we may assume that induced power of the wing and the main rotor are equal if rotor diameter and wing span coincide. Parasite powers are also equal at equal CxS of the aircraft. But profile power for helicopters is much higher than for fixed wing aircraft.
A. Braverman, the former head of Aerodynamics Department at the Mil Development Design Office, in his report “Strategy of Helicopter Main Rotor Profile Loss Enhancement” [6] stated: “The required for high-speed aircraft power calculations show that with the increase of speed the profile losses of the main rotor grow significantly. At 380 kmh they are twice as much as at 300 kmh and five times as much as in hover. At 350-400 kmh profile losses are about 50% of the helicopter required power”.
The cause of sharp increase of profile power with the growth of level speed is that profile power is proportional to the cube of air flow rate. Ambient velocity at the advancing blade of powered main rotor is much higher than at the fixed wing. That is why the L/D ratio of main rotor is many times less than the L/D ratio of the wing.

3.2. Alternative Ways of Increasing Helicopters Speed

3.2.1. Conventional Helicopters

The only way to expand the speed envelope of conventional helicopters is to increase helicopter lift-to-drag ratio, propulsive coefficient and coefficient of the power used by the rotor. This can be achieved by improving main rotor blade aerofoil sections and planform, higher harmonic blade control, reducing parasite drag through boundary layer control. However, it is rather difficult to get essential speed increase through such improvements [7-9]. The fact that conventional helicopters are not among JMR TD contenders, which are to be the 21st century aircraft, indirectly proves it.

3.2.2. Helicopters with Wing

Adding a wing without auxiliary propulsion devices on a single-rotor helicopter is known to result in increasing the power required for flight and with keeping initial power-to-weight ratio will lead to speed decrease. The main advantage of adding a wing on a single-rotor helicopter is rotor offload and lower rotor and rotor control systems loading.

Moreover with the wing added the power necessary for hovering increases due to wing download. The ambiguous benefits of adding a wing can be illustrated by the fact that 500 out of 900 Mi-6 helicopters with wing were operated by civil aviation with the wing detached.

3.2.3. Helicopters with Auxiliary Propulsion

The two candidate configurations for a high-speed helicopter are the tandem rotor Kamov Ka-102 with two rigid rotors and two propellers and the coaxial Sikorsky S -97 Raider with two rigid rotors and a pusher propeller. Using rigid rotors with each canceling out the other's roll moment allows to avoid stall onset. A significant difference in forward and rear rotors and their gearboxes loading is known to be one of the main disadvantages of tandem rotor helicopters. It makes rotor unification impossible and results in helicopter weight growth and life-cycle cost increase. The main disadvantage of coaxial helicopters is that they are prone to the "whipping" of blades and blade hitting each other in case of their damage and subsequent out-of-balance condition.

3.2.4. Compound Helicopters – Helicopters with Wing and Auxiliary Propulsion

As have been mentioned earlier there were numerous attempts to achieve higher helicopter speeds by **adding** a wing and propulsion devices to their construction. Proof-of-concept demonstrators developed speeds significantly higher than those of existing helicopters. However, construction complexity and empty weight growth resulted in unacceptable transport efficiency and weight coefficient reduction and stood in the way of developing a cost-effective rotary-wing aircraft for practical use.
Investigations of compound helicopters have been resumed because of the urgent need for new generation high-speed rotary-wing aircraft. Among a number of proof-of-concept compounds only the Kamov Ka-22 experimental cross arrangement compound helicopter had hinged rotors.

4. The Mi-450 Compound Cross Arrangement (side-by-side rotor) Helicopters Concept Validation

4.1. The Mi-450 Compound Helicopters Key Features

The key features determining the Mi-450 compound helicopter family concept[10-18] (Fig. 21) are as follows:

- a new type rotor system which consists of two slowed during cruise mode rigid rotors accommodated overlapped on a short wing;
- a thrust propeller located above the fuselage on the fin;
- modular split torque rotor gearboxes having large-diameter shafts which house blade pitch fly-by-wire actuation devices (Fig. 22);
- rotor blades with embedded in the roots hinges;
- a transport module which is a fuselage of a fixed wing aircraft type equipped with a high energy absorbing landing gear and new generation on-board systems.

Built in the 70s of the last century the Sikorsky S-69 was the first proof-of concept compound helicopter to implement ABC concept (the Advancing Blade Concept) which uses torsionally stiff main rotor blades to provide higher lift on advancing blade. The retreating blades are offloaded, as most of the load is supported by the advancing blades of rotors so the stall of the retreating blades and its effects take place at much higher speeds. However, to make the concept viable the blades should have high torsion stiffness and be cantilever-mounted on the rotor hub. In its turn this results in significant rolling moments, which are to be compensated for helicopter balance. Using cyclic pitch for this purpose eliminates the advantages of the ABC concept.
The Mi-450 compound cross arrangement helicopter is a modified ABC concept in “cross arrangement (side-by–side)” configuration. Using high rotor overlapping suited for rigid rotors it is possible to develop quite a compact and light construction. The wing between the rotors allows for essential rotor blade loading reduction as wing can carry some lift.

4.2. The Mi-450 Initial Dimensions Setting and Construction Weight Calculation Approach

When carrying out studies on the Mi-450 high-speed compound helicopters of cross arrangement concept validation the performance data of single-rotor helicopters, coaxial rotor helicopters, compound helicopters and tiltrotors were compared in a wide size range.
The paper presents the results of comparison of medium weight category helicopters (Fig. 23, 24, 25) designed for airlifting a 2,000 kg cargo to the distance of 800 km.
Cargo compartment dimensions were assumed to be the same.
Rotor system and transmission components design weights for a single–rotor helicopter were assumed to be equal to those of existing helicopters in the similar weight category.
To determine the Mi-450 rotor system and transmission weights in medium weight category detailed design and engineering studies have been conducted.

4.3 The Results of the Mi-450 Compound Helicopters Family and Aircraft of Alternative Configurations Contrastive Performance Analysis

For the trade-off performance evaluation the required power for level flight at H=1,000 m was calculated. The calculations for tiltrotors were made for fixed-wing and helicopter configurations. The results of the calculations are shown in Fig.26.

The diagram (Fig.26) shows that at a target tip speed value of 210 mps the Mi-450 has the maximum flight speed 55 kmh less than a tiltrotor in a fixed-wing configuration. At the same time this very configuration shows 35 kmh higher speed than a coaxial ABC helicopter. As compared to conventional single-rotor helicopters the Mi-450 will provide about 70 kmh speed increase, and it is 90 kmh faster than helicopters with the wing.

The diagram (Fig.27) shows that reduction of tip speed from 210 mpc to 180 mpc allows to increase the speed by approximately 60 kmh with the same engine power.

To estimate flight envelope of the aircraft types under consideration the calculations for maximum speed depending on pressure altitude in ISA were made. Performance data of the aircraft under consideration are summarized in Table 2.

Summary

1. Two slowed during cruise mode rigid rotors accommodated overlapped on a short wing of the Mi-450 allow to implement ABC concept, gain significant advantage in lift-induced drag of main rotors as compared to tandem, coaxial and conventional helicopters, achieve higher lift-to-drag ratio and increase flight speed.
2. A thrust propeller located above the fuselage on the fin of the Mi-450 allows to improve safety as compared to compound side-by-side helicopters, reduce cockpit and environmental noise level and improve performance characteristics.
3. The Mi-450 design and technology characteristics of rotor and transmission systems make it possible to avoid significant weight increase inherent to single and coaxial rotor helicopters.
4. The Mi-450 compound helicopters family transport efficiency is considerably higher than that of conventional helicopters and is behind only tiltrotors.

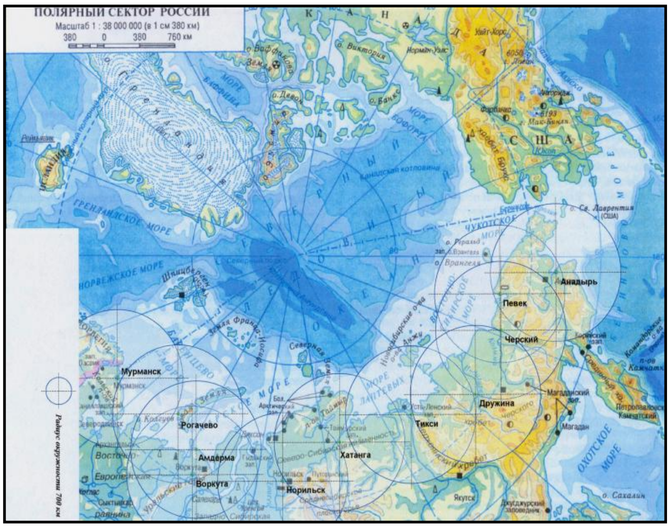

Fig.1 Helicopter transport support of commercial exploitation in hard-to-reach areas

Fig.2 Helicopter transport support of off-shore operations

Fig.3 Helicopter transport support of SAR operations

Fig. 4 An X3-based single rotor compound helicopter LifeCraft

Fig.5 The AW-609

Fig.6 Bell Helicopter new generation tiltrotor

Fig.7 Karem Aircraft new generation tiltrotor

Fig .8 AVX coaxial rotor compound helicopter

Fig.9 Sikorsky-Boeing coaxial rotor compound helicopter

Fig.10 Russian new generation Kamov Ka-92 high-speed rotary-wing aircraft concept

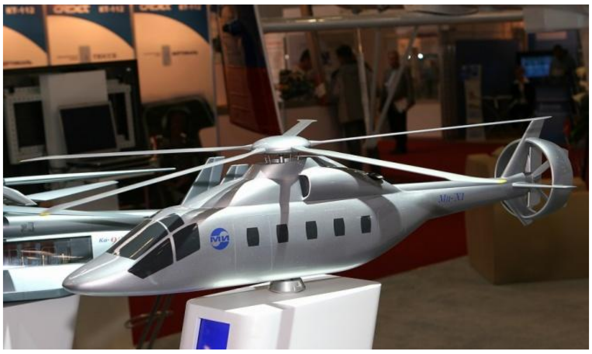

Fig.11 Russian new generation Mi-X1 high-speed rotary-wing aircraft concept

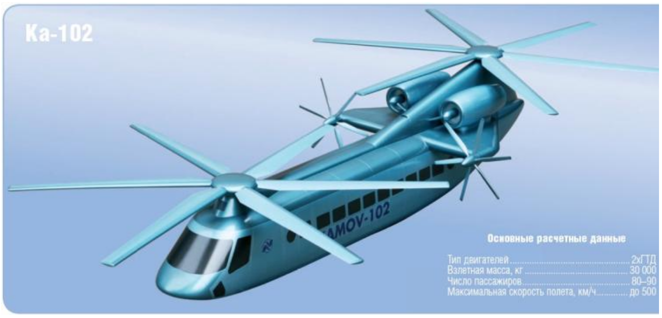

Fig.12 Russian new generation Ka-102 high-speed rotary-wing aircraft concept

Fig.13 Russian new generation Mi-450 high-speed rotary-wing aircraft concept

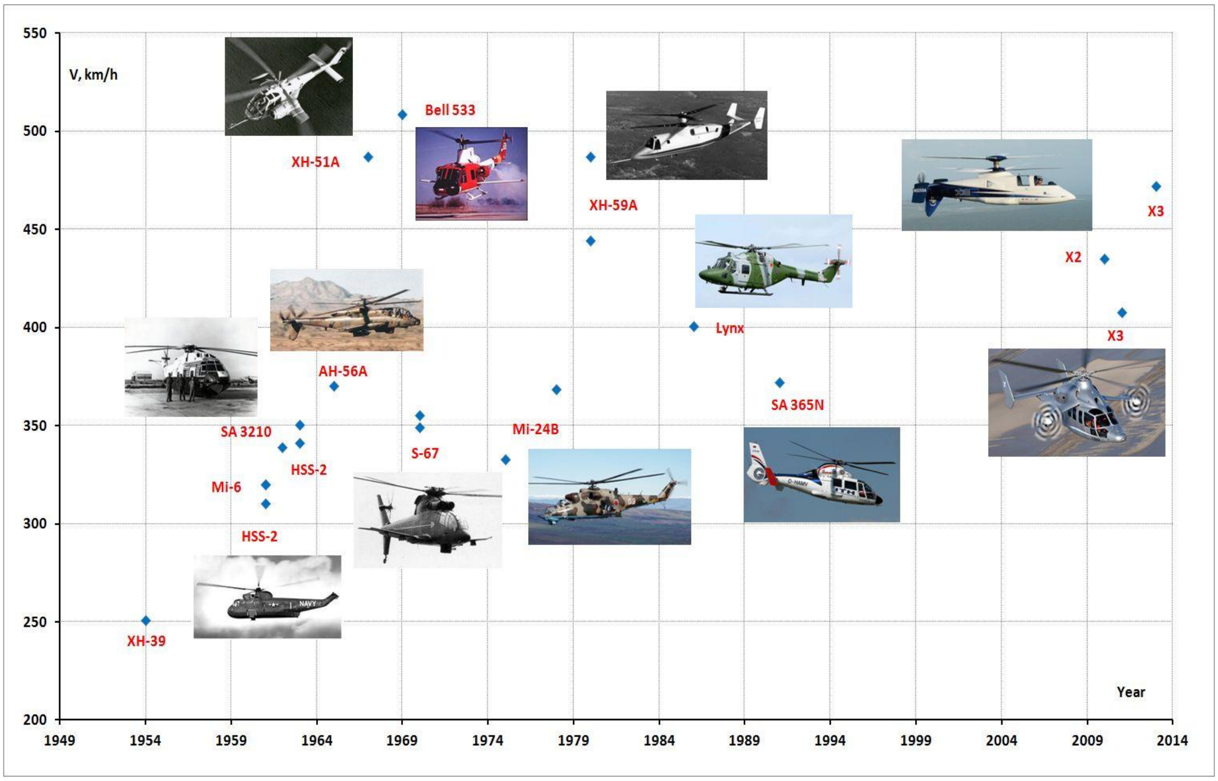

Fig. 14. Speed records of helicopters and compound helicopters

Fig.15. The Lockheed AH 56-A Cheyenne

Fig.16. The Ka-22

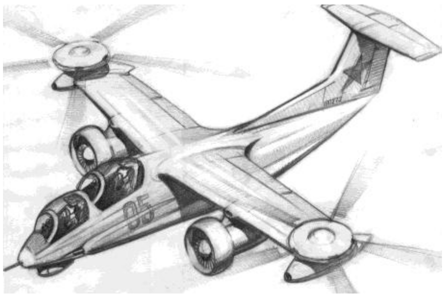

Fig.17. The Mi-28 candidate configuration for a combat cross arrangement configuration helicopter project

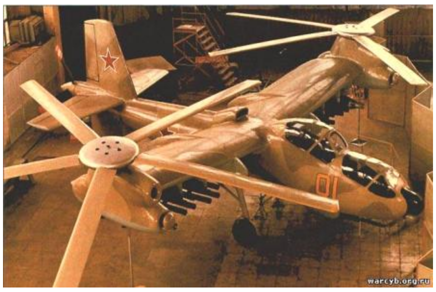

Fig.18 The Mi-28 candidate configuration for a combat cross arrangement configuration helicopter project

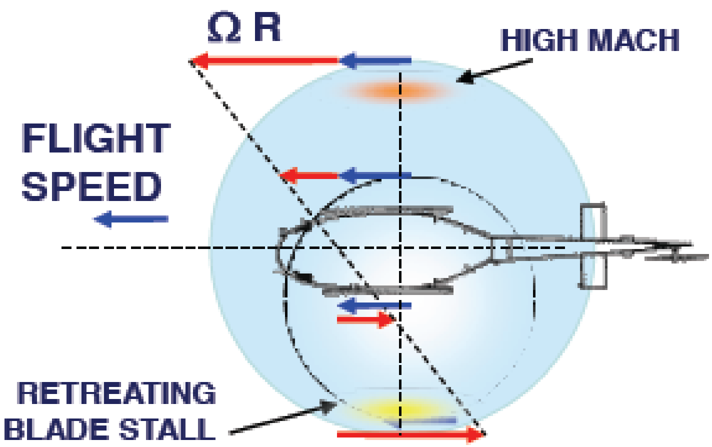

Fig.19 Main Rotor Retreating Blade Stall

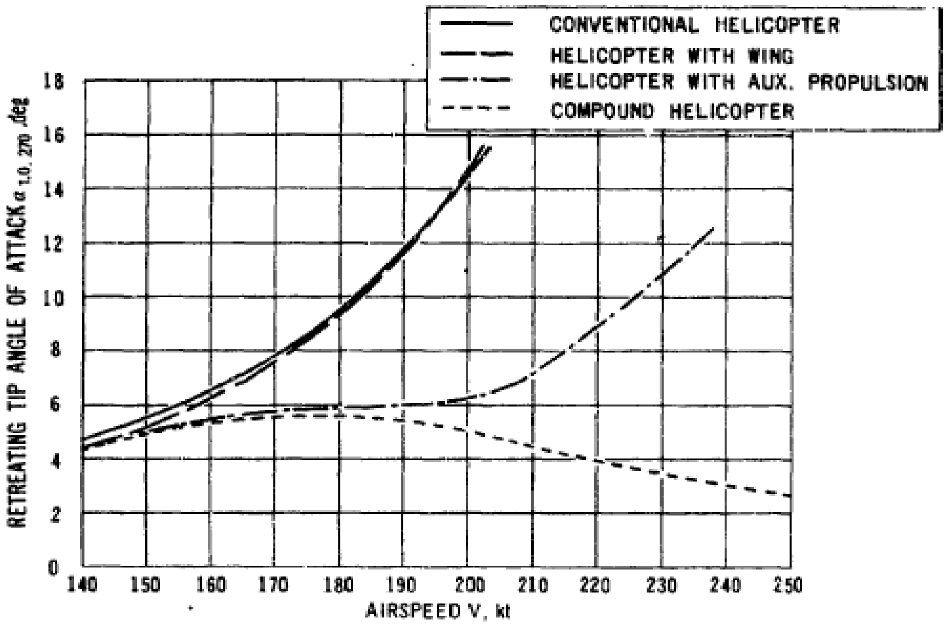

Fig.20 Retreating tip angle of attack as a function of horizontal speed

Fig. 21 The Mi-450 compound helicopter family concept

Fig. 22 A modular split torque rotor gearbox

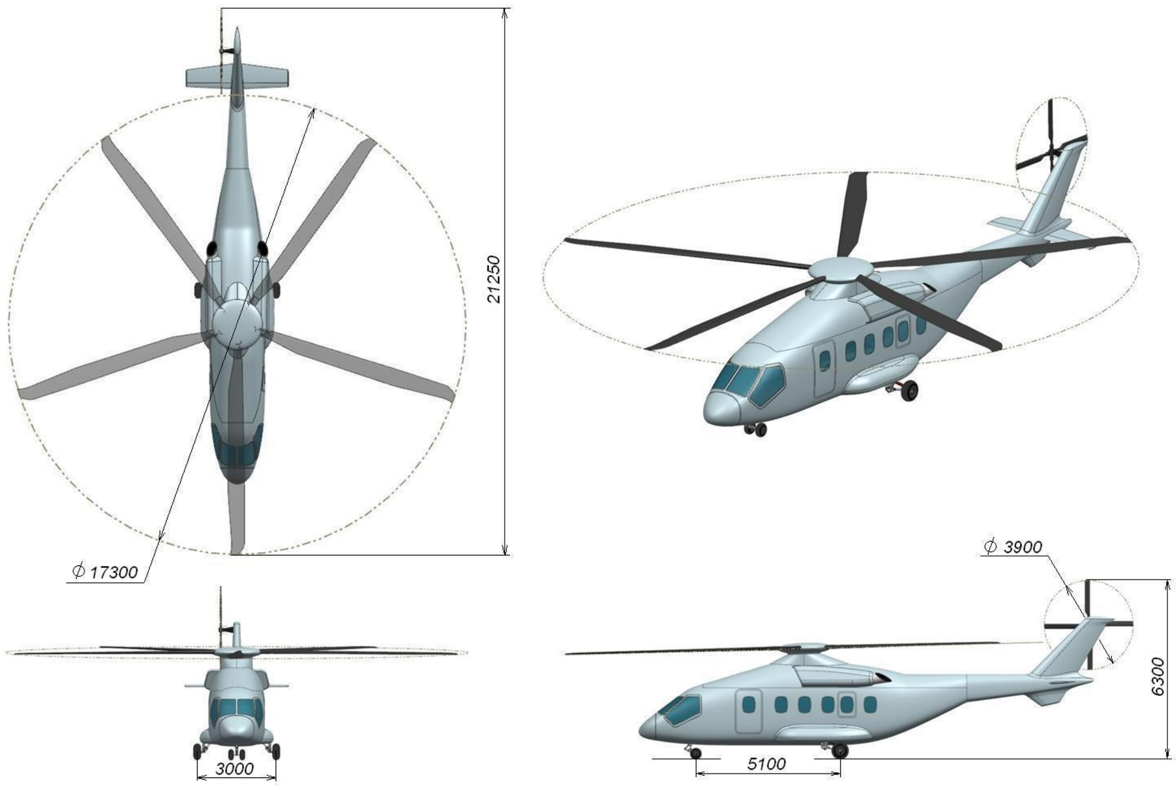

Fig.23 Conventional single-rotor helicopter

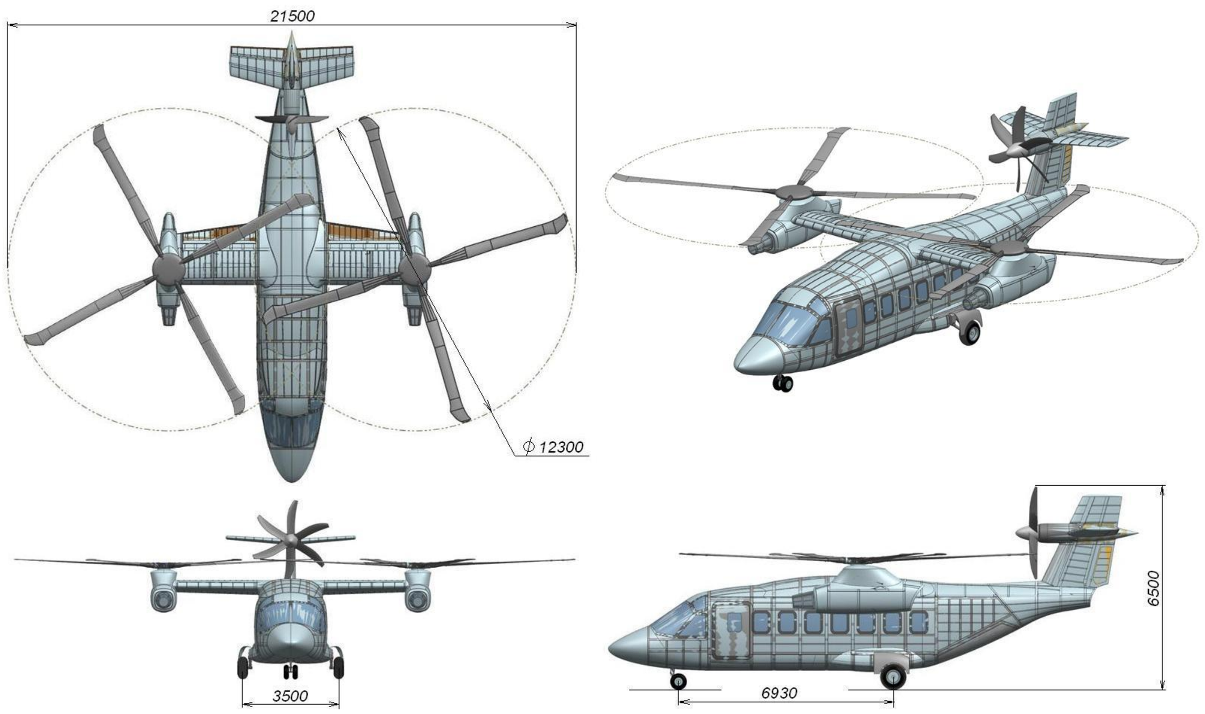

Fig.24 The Mi-450 cross arrangement compound helicopter

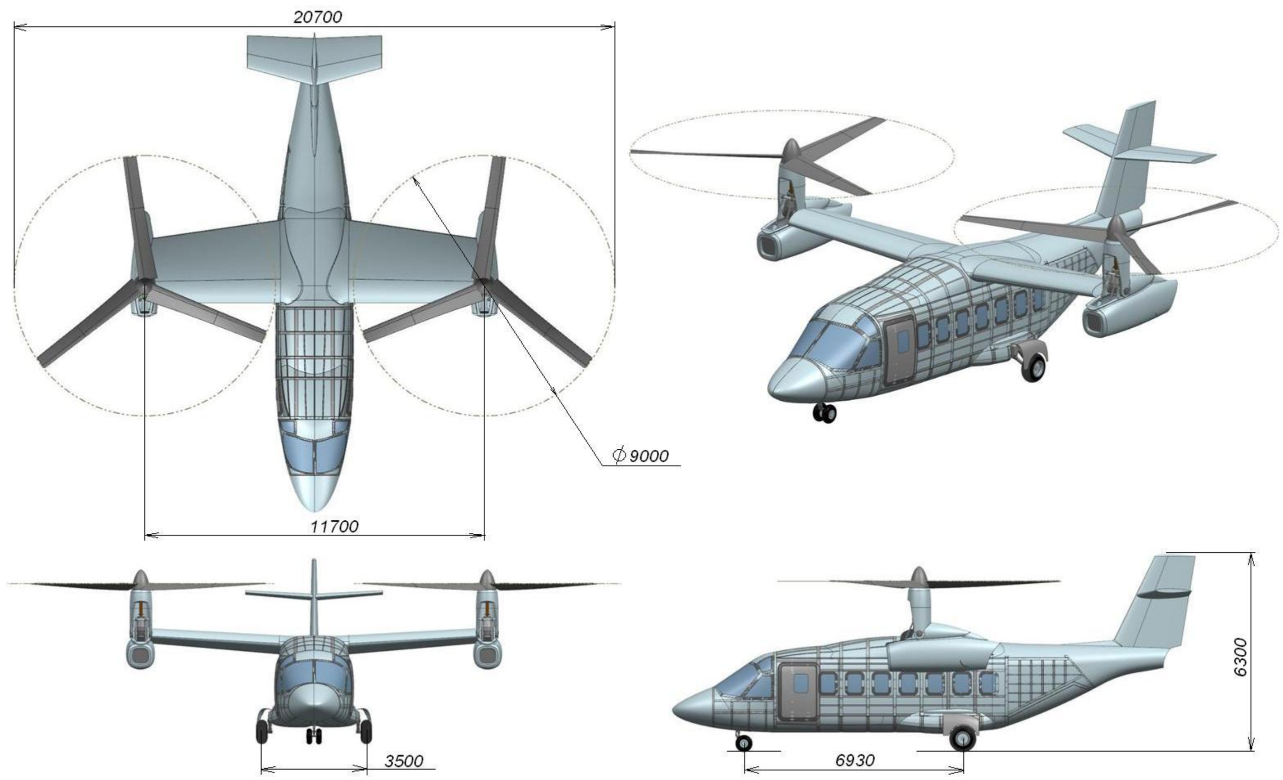

Fig.25 Tiltrotor

Table 1. Initial data summary for performances estimation

	Conventional helicopter	Mi-450 (Mi-X3)	Tiltrotor		Coaxial ABC
			helicopter	airplane	
$Weight_{cargo}$, kg	2000	2000	2000	2000	2000
$Weight_{gross}$, kg	11500	12000	12500	12500	12000
Cockpit size L*H*B	6.0*1.6*1.8	6.0*1.6*1.8	6.0*1.6*1.8	6.0*1.6*1.8	6.0*1.6*1.8
CxS, m^2	2.2	1.9	2.7	1.8	2.8
D_{MR}, m	17,3	2*12,3	2*9	2*9	2*14
Blade number	5	4	3	3	3
b, m	0,62	0.46	0,65	0,65	0,48
wR, mps	210	210	230	210	210
L_{wing}, m	-	7,6	12,5	12,5	-
b_{wing}, m	-	2,4	1,5	1,5	-
S_{wing}, m^2	-	18.24	18.75	18.75	-

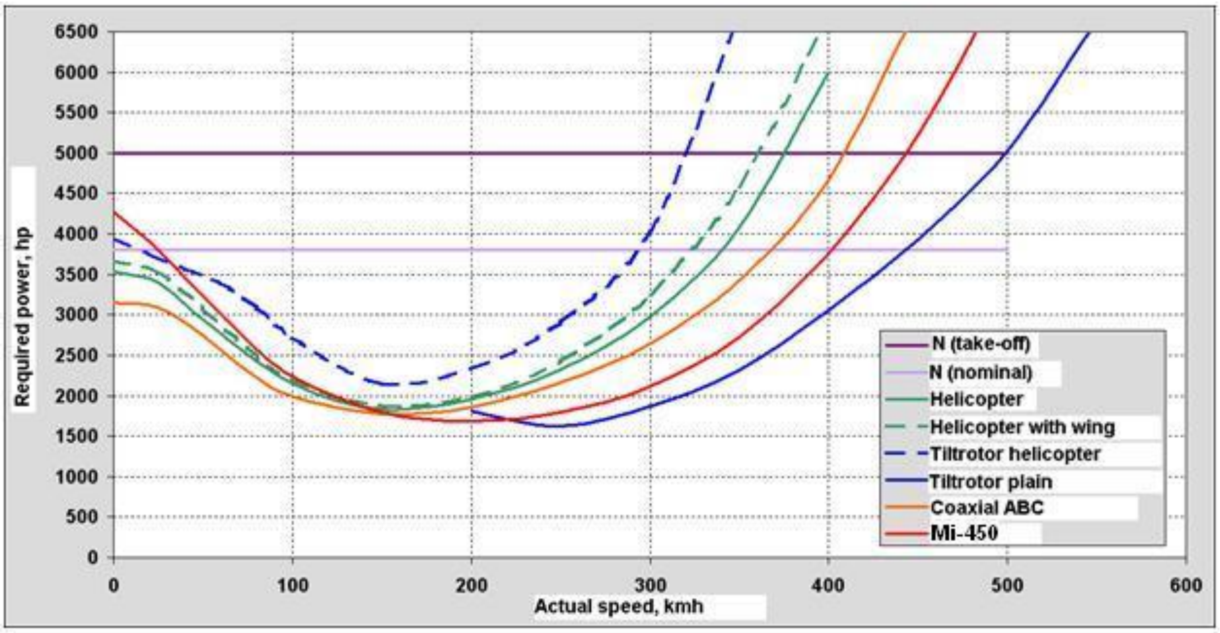

Fig.26 The Mi-450 maximum flight speed

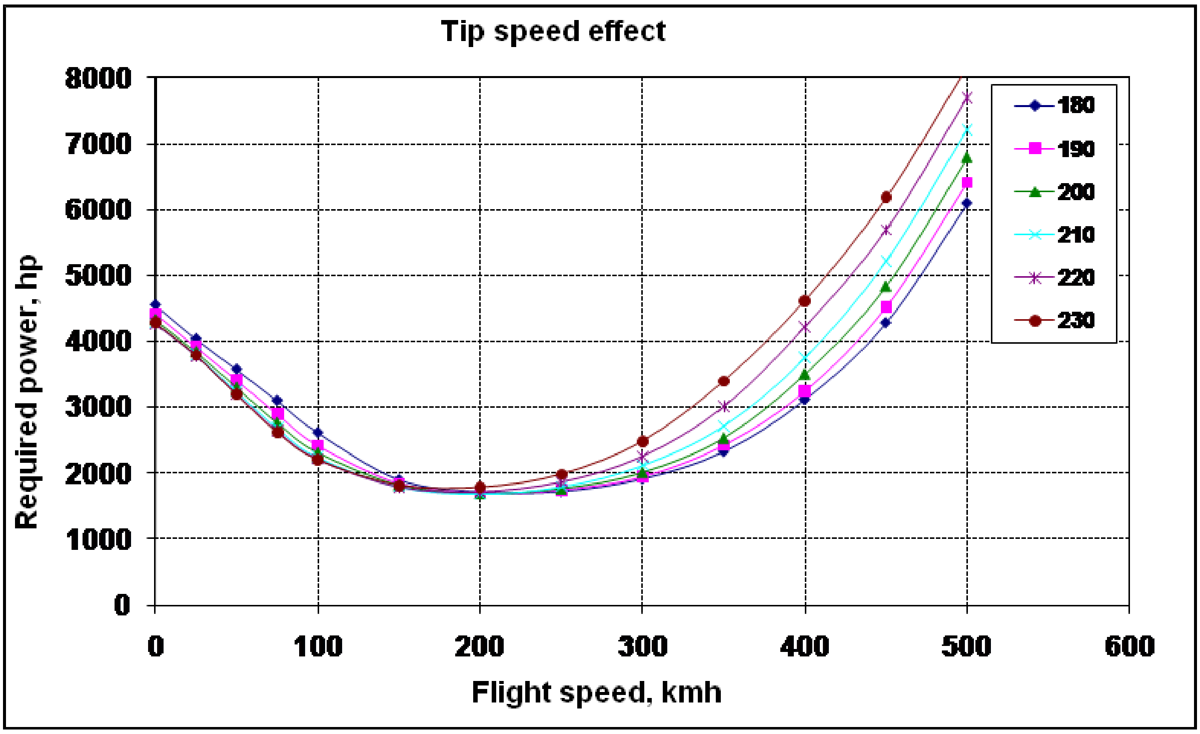

Fig. 27 The Mi-450 maximum flight speed

Table 2 Performance data summary of the competitive aircraft configurations

	Conventional helicopter	Mi-X3	Tiltrotor		Coaxial ABC
			Helicopter	Fixed-wing	
Take-off rate power, hp	2×2500	2×250 0	2×2500	2×2500	2×2500
Maximum speed V_{max}, H=1000 , kmh	360	465	320	590	415
Hover ceiling $H_{ст}$, m	3600	3000	3700	-	3500
Rate of climb Vy at take-off rate power, H=1000, mps	14.0	14.0	13.5	14.5	17.7

References

1. 1940 – 2010: Brief history of hybrid helicopters around the world. http://www.eurocopter.com/w1/PAS11/History_EN.pdf
2. Marat N. Tishchenko, "Mil design Bureau Heavy-Lift Helicopters" (as presented at local chapters of AHS in June 1996), p. 142
3. M. N. Tishchenko, A. V. Nekrasov, A.S. Radin, Helicopters, Parameter Choice in the Design, Mashinostroeinie Publishers, Moscow, 1976
4. M.N. Tishchenko. Helicopter Parametrization in Preliminary Design Stage, Moscow Aviation Institute, Moscow, 2011
5. Engineering Design Handbook. Helicopter engineering, Part one, Preliminary design; AMC PAMPHLET No. 706-201, Army Materiel Command: Alexandria, Virginia, 1974
6. A.S. Braverman, "Strategy of Helicopter Main Rotor Profile Loss Enhancement", Proceedings of the 9th Russian Helicopter Society Meeting, Moscow: Moscow Aviation Institute Press, 2010
7. J. Gordon Leishman, Principles of Helicopter Aerodynamics, Cambridge University Press, 2000
8. William W. Chung, Dan Salvano, David Rinehart, Ray Yuong, Victor Cheng, Jim Lindsey, An Assessment of Civil Tiltrotor Concept of Operations in the Next Generation Air Transportation System

9. Carl Russel, Wayne Jonson, Conceptual Design and Performance Analysis for a Large Civil Compound Helicopter, Presented at the AHS Future Vertical Lift Aircraft Design Conference, San Francisco, 2012
10. S.P. Midsyanovskiy, M.Z. Korotckevitch and others, High-speed compound helicopter, Patent № RU2507121, 2012 (patent holder JSC Moscow Mil Helicopter Plant)
11. S.P. Midsyanovskiy, M.Z. Korotckevitch, High-speed compound helicopter, Application for an invention № RU2013151276, 2013 (patent applicant JSC Moscow Mil Helicopter Plant).
12. D.O Zhdanov, Controlled transmission for rotary wing aircraft. Patent № RU2525353, 2013 (patent holder JSC Moscow Mil Helicopter Plant)
13. S.P. Midsyanovskiy, M.Z. Korotckevitch, Propeller, Application for an invention № RU2014101639, 2014 (patent applicant JSC Moscow Mil Helicopter Plant).
14. S.P. Midsyanovskiy, M.Z. Korotckevitch, High speed compound helicopter, Patent № RU110715, 2010 (patent applicant JSC Moscow Mil Helicopter Plant)
15. S.P. Midsyanovskiy, Modular aircraft, Application for an utility model № RU2014101639 (issue of a patent dated 17.06.14), 2014 (patent applicant JSC Moscow Mil Helicopter Plant)
16. S.P. Midsyanovskiy, R.R Yemeleyev, Compound helicopter, Application for industrial design № RU2013502443 (issue of a patent dated 10.06.14), 2013 (patent applicant JSC Moscow Mil Helicopter Plant)
17. S.P. Midsyanovskiy, Compound helicopter, Application for an invention № RU2014117931 (issue of a patent dated 17.06.14), 2014 (patent holder JSC Moscow Mil Helicopter Plant)
18. S.L Chernyshev, V.V Vozhdayev, A.I. Dunayevskiy and others, Commuter aircraft, Patent № RU2482013, 2011 (patent holder Ministry of Industry and Trade of the Russian Federation)
19. S.V. Mikheyev, S.V. Nosov, S.I. Pyzhov, High speed compound helicopter, Patent № RU127364, 2012 (patent holder S.V. Mikheyev)
20. Ray Prouty. Another Look at the Advancing Blade Concept. Vertiflite, Summer 2006
21. V. Palgino, Forward Flight Performance of a Coaxial Rigid Rotor. Proceedings of 17th Forum of American Helicopter Society, 1971
22. E.I. Ruzhitsky. World Records of Helicopters. Vertolet Publishing House, 2005
23. Raymond L. Robb. Hybrid Helicopters: Compounding the Quest for Speed. Vertiflite magazine, Summer 2006
24. A.V. Nekrasov. Dynamics, Strength and Aerodynamics of the “Rigid” Main Rotor. Moscow Helicopter Plant Technical Report, M., 1968
25. V.M. Pchelkin, N.S Pavlenko, Helicopter main rotor head, RF Patent № 1658538, 1991
26. N.S. Pavlenko, A New Concept of the Main Rotor for a High-Speed Single-rotor Helicopter, Proceedings 33th European rotorcraft forum, Kazan, Russia, 2007
27. M. L. Mil, How to create a helicopter needful for people, Mashinostroeinie Publishers, Moscow, 1999
28. M. L. Mil, A. V. Nekrasov and others, Helicopters, Volume 2, Mashinostroeinie Publishers, Moscow, 1967
29. N.S Pavlenko, 400 km/h is not the limit, High-Speed Single-rotor Helicopter Concept. Helicopter Industry, Moscow 2007
30. R. A. Mikheyev, Helicopter robustness, Mashinostroeinie Publishers, Moscow 1984
31. S.V. Mikheyev, Ways of Development of Rotary-wing Aircraft, Moscow Aviation Institute Publishing house, 2006

COPYRIGHT STATEMENT

The authors confirm that they, and their company, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission for the publication and distribution of this paper as part of the ERF2014 proceedings or as individual offprints from the proceedings and for inclusion in a freely accessible web-based repository.