Comprehensive approach to comparative efficiency evaluation of HPS for helicopters

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Abstract
Purpose – The purpose of the work is to carry out analysis of the possibilities and estimation of electric drive efficiency for rotors of helicopter propulsion systems (PS).
Design/methodology/approach – Methodology and comprehensive multidisciplinary technology for efficiency estimation of conventional and unconventional architectures PS on rotorcraft system level at preliminary design phase were developed.
Findings – Application of the approach allow to carry out analysis of hybrid (based on gas turbine and piston engines) and full electrical PS for superlight-, light- and medium-size helicopters.
Practical implications – It was shown what level of electrical technologies improvement may provide positive effect of the using of hybrid and full electrical helicopter PS of different architectures.
Originality/value – Close matching of helicopter and engine design and calculation aspects, as well as possibilities to use the external (experimental) performances of engine components, whole PS and helicopter aerodynamic performance, are the distinctive features of proposed technology and methodology.

Keywords Helicopter, Hybrid PS, Electric PS, Comprehensive multidisciplinary technology, Mathematical model, Optimization, Mission performance

Paper type Conceptual paper

Nomenclature

APU = auxiliary power unit
CAD = computer-aided design system
CIAM = Central Institute of Aviation Motors
ED = electric drive
EG = electrogenerator
IG = intermediate gearbox
MG = main gearbox
MM = mathematical model
MR = main rotor
OG = on-board gearbox
PE = piston engine
PS = propulsion system
RCS = rotorcraft system
SB = storage battery
TG = tail gearbox
TGTE = turboshaft gas turbine engine
TR = tail rotor
$W_{T/O}$ = takeoff weight

Introduction

Nowadays, electrification of air vehicles including helicopters is an one of most advance directions of aviation improvement. Development of helicopter with hybrid or electric propulsion systems (PS) is an urgent problem.

To answer the question about feasibility of such vehicles development methodology and comprehensive multidisciplinary technology for efficiency estimation of conventional and unconventional architectures, PS on rotorcraft system (RCS) (including helicopter) level were developed in Central Institute of Aviation Motors (CIAM). Software of the technology is based on upgraded comprehensive mathematical models (MM) of industrial computer-aided design system (CAD) system developed by the Central Aerohydrodynamic Institute and CIAM earlier (Shkadov, 1983).

Structure of MM

Structure of improved comprehensive multidisciplinary technology for efficiency estimation of PS on RCS level at the preliminary design phase are presented in Figure 1.

As it is seen in Figure 1, developed multidisciplinary software package includes common block for preparation of input data of the "RPS–PS" system and widespread (several dozens) particular engineering methods and algorithms related to different stage of design of RCS and PS and containing following sequential calculations:

- geometry and aerodynamic performances of RCS;
- climate-altitude, throttling, speed, weight and dimension performances of PS;
- weight balance and volumetric packaging of RCS;
- RCS mission performance; and
- design criteria of the "RCS–PS" system.

Subsystem of results visualization and analysis is also a part of the developed software package.

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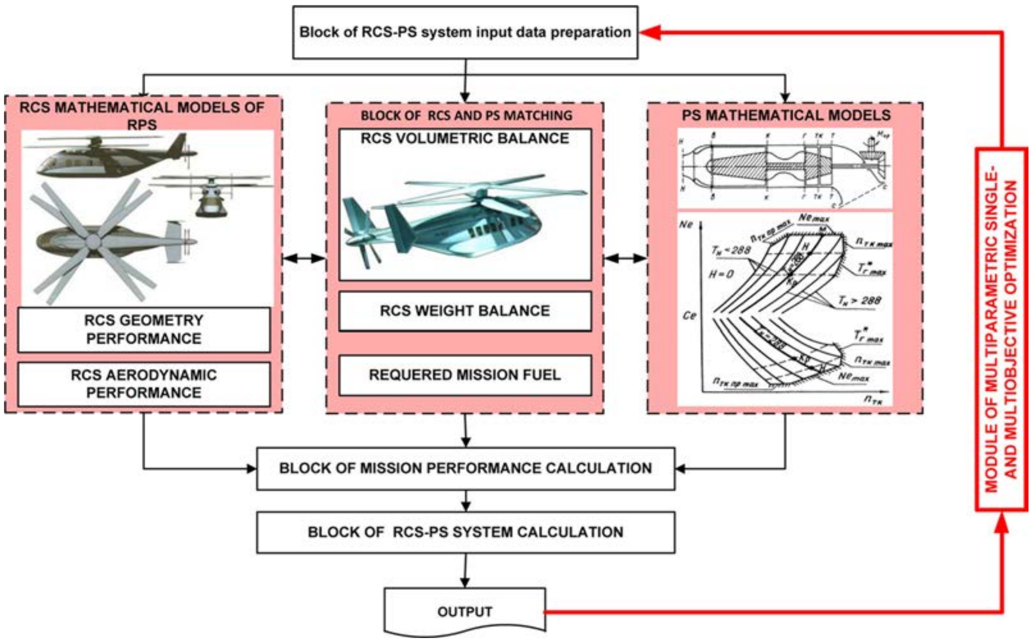
Figure 1 Structure of technology for multidisciplinary analysis of the "RCS–PS" system



All particular methods and calculation blocks conditionally distribute between MM of RCS and PS, matching block and block of mission performance and design criteria calculation.

Close matching of helicopter and engine design and calculation aspects, the possibilities to use the external (experimental) performances of engine components, whole PS and helicopter aerodynamic performance and finally organic interaction of considered software package with packages of multiparametric single- and multiobjective optimization are the distinctive features of proposed technology and methodology.

Technology structure presented on Figure 1, do not directly disclose the algorithm of the RCS–PS design process on the computer. That is why we consider more in detail the algorithmic implementation of the RCS–PS design process and PS efficiency estimation on the RCS level using helicopter as an example.

In general, two problem statement options can possible solve the engineering tasks of air vehicle design: direct and inverse problem statement, each of which may include a number of subtasks depending on specification and input data quality.

Calculation of helicopter mission performance and efficiency criteria at the partly or fully given helicopter and PS performances is required in case of direct problem statement. In general, aerodynamic performances of helicopter rotors (main and tail, and pusher propeller if it is there) and individual helicopter parts (such as fuselage, wing and landing gear), helicopter geometry and weight performance (takeoff weight and/or weight breakdown with indication of structural and equipment weights, weight of crew, payload and fuel weight), engine performance (altitude-climate and throttling), engine weight and dimension performances (including gear and transmission systems with their efficiencies) and required flight modes (typical flying mission), for which helicopter mission and efficiency criteria calculations are necessary, are given (are known). Naturally, in the case of a direct problem statement, helicopter main design parameters are not generated (they are fully given or updated if are given only partly), but calculations of helicopter mission performance and efficiency criteria are only performed at "fixed" geometry.

In the case of an inverse problem statement, helicopter and its PS design are performed by sequentially (iteratively) under given specifications of helicopter. Such specification may include given range at fixed payload mass, given maximal flight speed at required flight altitude, required hovering and dynamic ceiling altitudes, etc. Most of these specification are contradictory and that is why inverse problem solution supposes application of procedure for selection and optimization design variable to have extreme of single or several considered efficiency criteria of the whole "RCS–PS" system. Most often helicopter takeoff mass (as it is directly or indirectly links to helicopter tactical, technical, operational, and cost factors) are selected as such minimizing criterion.

Inverse problem statements are more various than direct problem statements and may be characterized by scope of input data formalization, as well as modeling level of helicopter and its main parts, including PS. In general, criterion dependences of aerodynamic performance of helicopter parts (first of all, helicopter flight structure and fuselage), weight improvement coefficients for helicopter parts and systems and generalized dependences of specific engine performances, specific power, SFC and specific mass on ambient conditions (ambient air temperature and pressure, flight altitude and engine modes) and transmission elements (gear boxes, shafts, etc.). Such type of input data assignment is typical for zero-level helicopter and PS MM (Ju *et al.*, 2008; Butov, 1993).

At more detail mathematical modeling of helicopter and its PS performances based, for example, on solution of set of equations for power and airflow balances between PS components, all characteristics required for helicopter mission

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calculation are directly defined by MM of rotorcraft vehicle and MM of PS. Here, PS MM of first and second level (Ju *et al.*, 2008; Butov, 1993), describing in more detail the components operation, are usually used.

Then, the structure of helicopter and PS MM are considered in detail.

Flowchart of comprehensive helicopter MM used for solution of direct problem (definition of helicopter performance), of inverse problem (helicopter design start from scratch) and of combine problem (from inverse to direct problems) are presented on Figure 2.

The calculation of integral aerodynamic characteristics of helicopter rotors are implemented during solving of direct problem, in particular, dependences of values of torque moment factors on the values of helicopter flight altitude and speed, as well as the values of torque moment and power required to rotate the rotors are defined. Then, calculation of helicopter weight balance (definition of fuel availability if it is not given) and mission performance is carried out. Relationships between available PS power and one required to rotate rotors define main mission parameters of helicopter, which in particular may be refined by iteration with simultaneous recalculation of helicopter weight balance.

Solving inverse problem generation of helicopter and PS design are realized by sequential execution of following procedures (Figure 2):

- calculation of first approximation of helicopter mass based on given design parameters and statistical relationships;
- calculation of main parameters of rotorcraft flight structure;
- calculation of required helicopter power and definition of PS size (engine design power) taking into account losses in transmission components during power transfer from engine to main and tail rotors;
- calculation of helicopter weight balance, which results provide the definition of mass of airframe parts and helicopter systems, as well as fuel mass, which may be located in on-board fuel tanks; and
- calculation helicopter mission performance.

During the generation of helicopter design, procedure of "inner" optimization of rotor loading may be carried out or it

Figure 2 Flowchart of comprehensive MM of helicopter

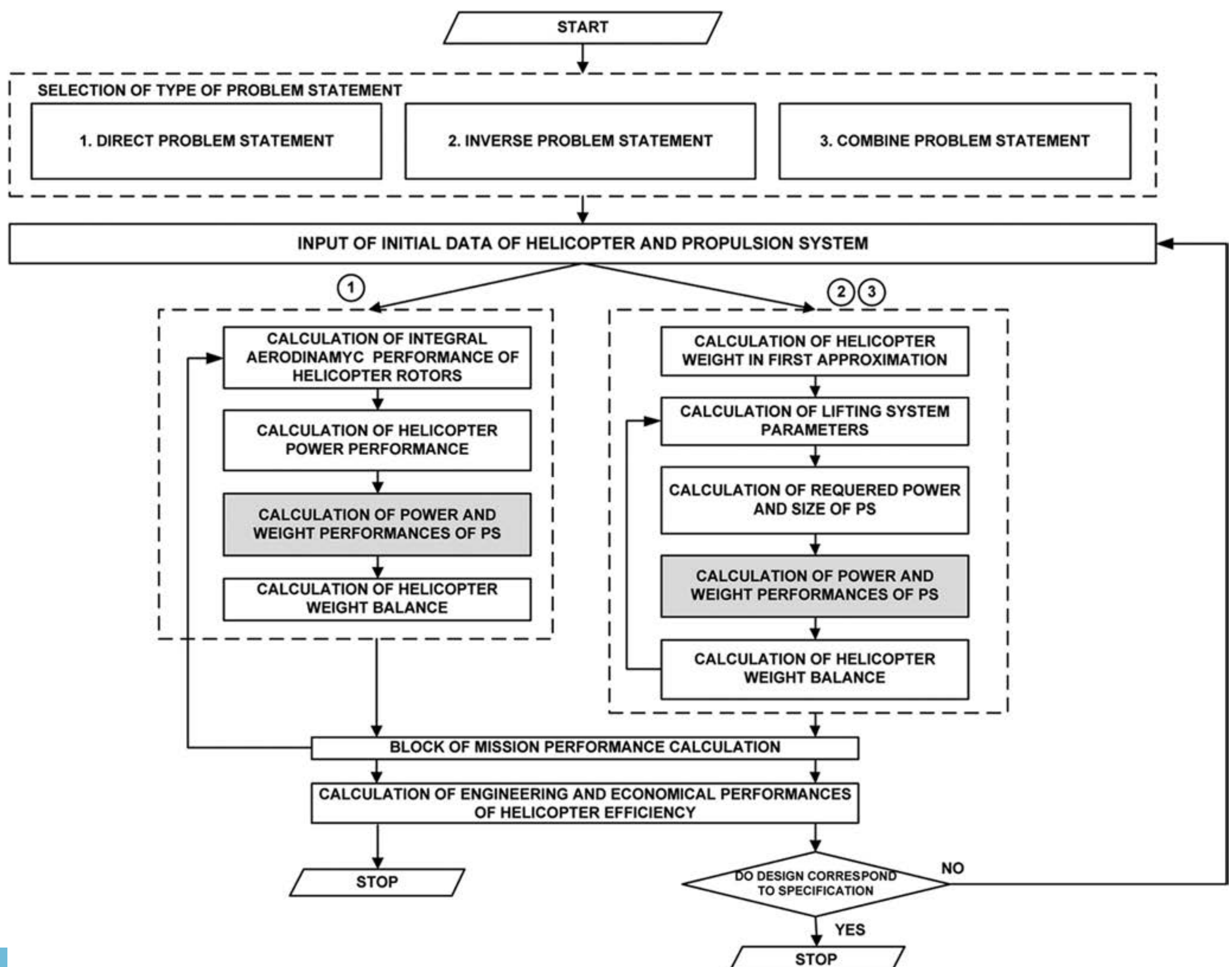


Figure 3 Flowchart of helicopter PS MM (direct problem statement)

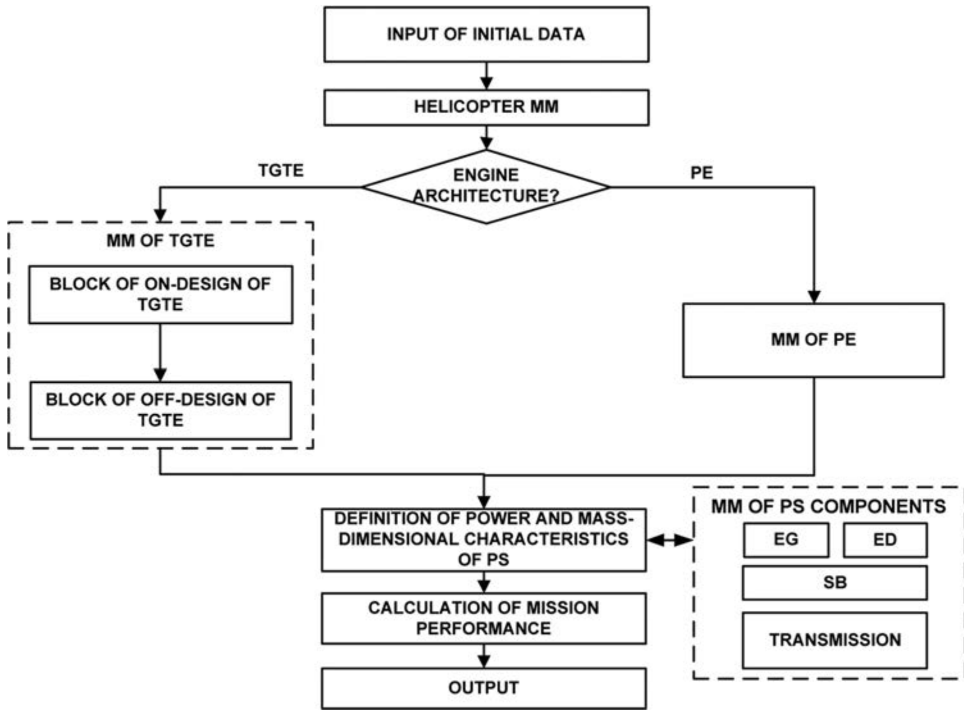
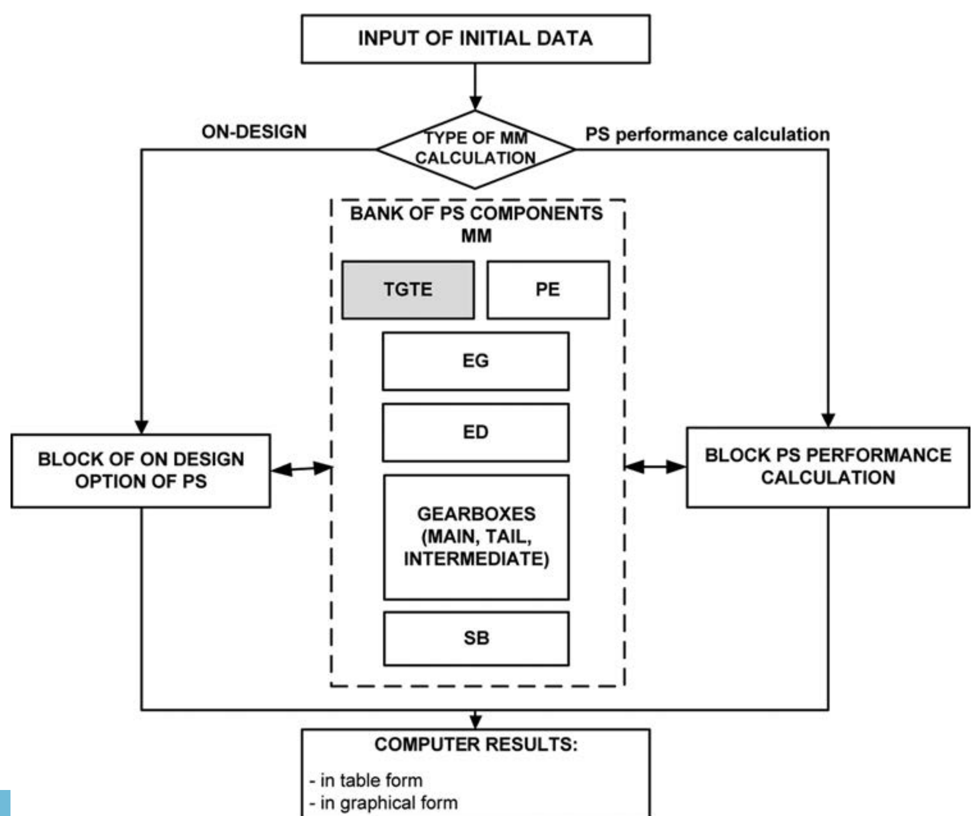


Figure 4 Flowchart of helicopter PS MM (inverse problem statement)



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may be implemented by external module of multiparametric optimization (Figure 1).

The value of helicopter takeoff mass defined by solving of weight balance equation at given specifications and level of technology improvements of helicopter and PS along with other helicopter (or in general rotorcraft) parameters may be used as efficiency criterion for evaluation of alternative versions and optimization of performances of helicopter and PS (Brusov, 1989):

$$(P_{\mathrm{var}})_{opt} = \underset{\mathrm{P_{var}}}{\mathrm{argmin}}\, W_{\mathrm{T/O}}\,(P_{\mathrm{var}},\ P_{fix}) \rightarrow RCS_{opt},$$

where $\mathrm{P_{var}}$, P_{fix} – design variable and fixed design parameters of rotorcraft.

At preliminary design phases, the specifications for system "rotorcraft-PS" are not always reasonable because of they reflect the natural wish of customer to get helicopter with fully or partly improved performance in comparison with similar helicopters of previous generation or helicopter prototype of nearest term. Validation of the specification is separate sufficiently complicate scientific and technical problem, and that is why they may be changed further.

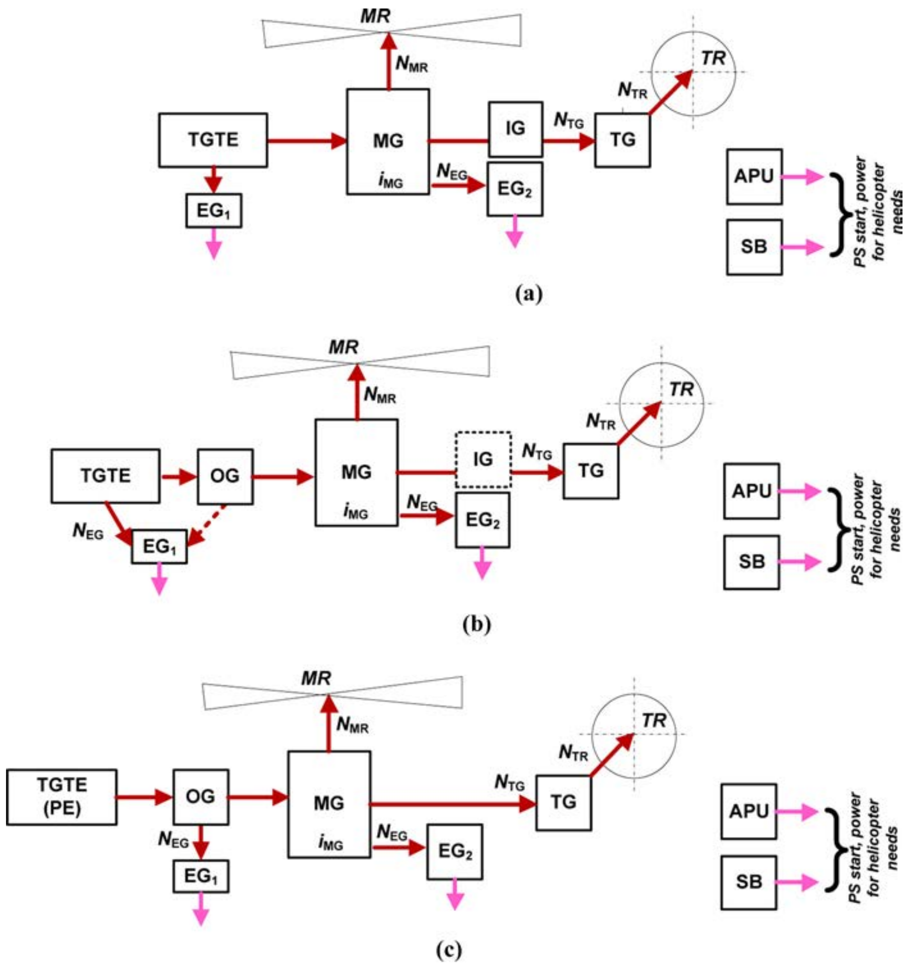
If helicopter design obtained by calculation does not meet given specifications, execution of iterative procedures may be necessary to achieve required helicopter parameters.

Taking into account the influence of a lot of helicopter and engine factors (from few dozen up to few hundreds depending on complexity of used MM) on system "rotorcraft-PS" parameters practically impossible to generate the simple analytical dependences of helicopter takeoff weight, flight range and other characteristics on considered (variable) design parameters. The approach of calculation of helicopter mission performance and range along given (design) flight profiles using a takeoff mass, defined as some approximation accounting the solution of weight balance equation and matching of volumes, and then iterative determination of takeoff mass, providing given specification, e.g. maximal flight range. Direct problem with definition of mission under given helicopter is solved more simple because of it does not require multiple iteration which significantly reduce the computer.

Then the algorithm features of PS MM, which is element of comprehensive helicopter MM of the "rotorcraft-PR" system, are considered in detail.

There are features of the PS MM functioning at the solving direct problem with calculation of helicopter using given input

Figure 5 Options of conventional architectures of helicopter PS without electro-driven helicopter rotors (version 1)



Notes: (a) option 1.1; (b) option 1.2; (c) option 1.3

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data. As it is seen on the Figure 3, in the case depending on engine architectures, i.e. turboshaft gas turbine engine (TGTE) or piston engine (PE), after running of corresponding MM and definition of its power and mass-dimensional characteristics, it is accessed to bank of MM of remaining PS components: transmission and electrodevices, electrogenerator (EG), electric drives (ED), storage battery (SB), etc. As a result correction of reference (conventional), PS option is realized to account one or another version of electrification and further calculation of mission performance for considered helicopter version.

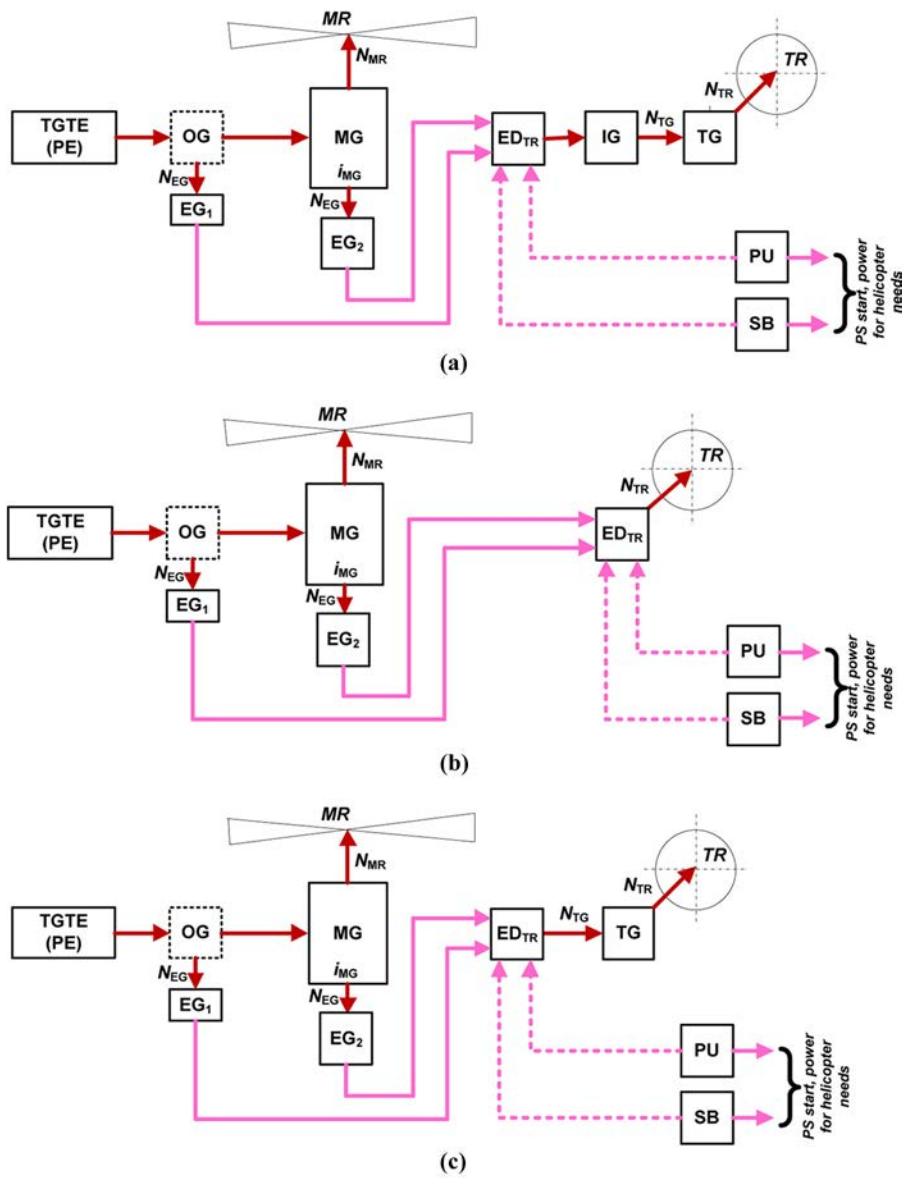
The flowchart of helicopter PS MM for inverse problem statement is presented in Figure 4.

As seen in Figure 4, after input of initial data (or obtaining them from helicopter MM), PS MM may function in one of the two possible options: on design option (for helicopter/PS matching) and off-design option (for PS performance calculation).

At least one call of block of PS MM on design option during a work session of helicopter MM is mandatory condition for PS performance calculation. It is connected with necessity to match all engine components (for TGTE they include compressors and turbine spools, combustor, intake and nozzle) and transmissions on design point to provide required (design) power.

As seen in Figure 4, both block of PS MM (on- and off-design modes) may automatically (according to the PS architectures given by researcher) access to bank of MM of TGTE, PE, EG, ED, SB and gearboxes (main, tail and intermediate). These MM allow calculation of both power parameters (for TGTE, PE, EG, ED and SB) and losses of transmission (gearboxes) of PS components, and their

Figure 6 Options of modeling PS architectures for helicopter with ED TR (version 2)



Notes: (a) option 2.1 (b); option 2.2; (c) option 2.3

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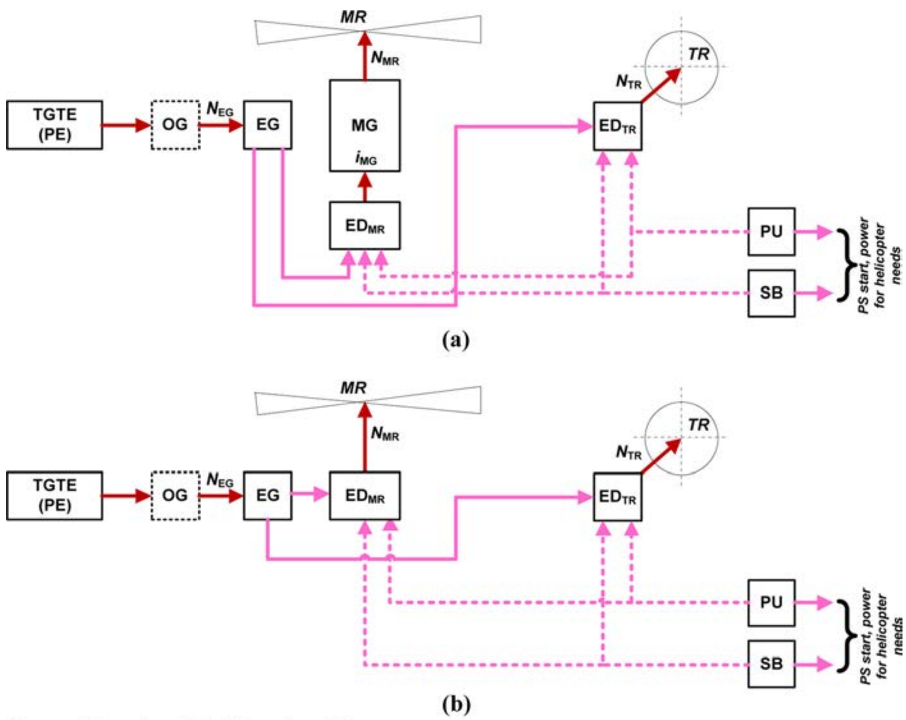
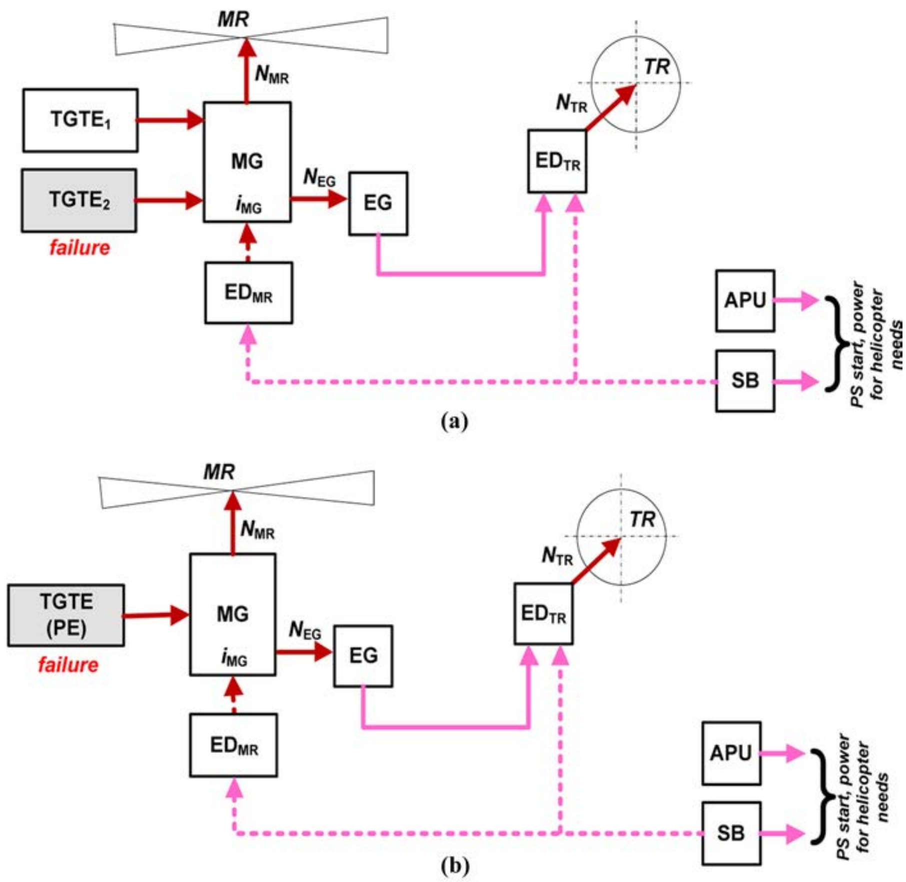
Figure 7 Options of modeling PS architectures for helicopter with ED TR and ED MR ("generative" versions 3)



Notes: (a) option 3.1; (b) option 3.2

Figure 8 Options of modeling PS architectures for helicopter with ED TR and ED MR in case of engine emergency



Notes: Failure one of TGTE or PE: (a) option 4.1; (b) option 4.2

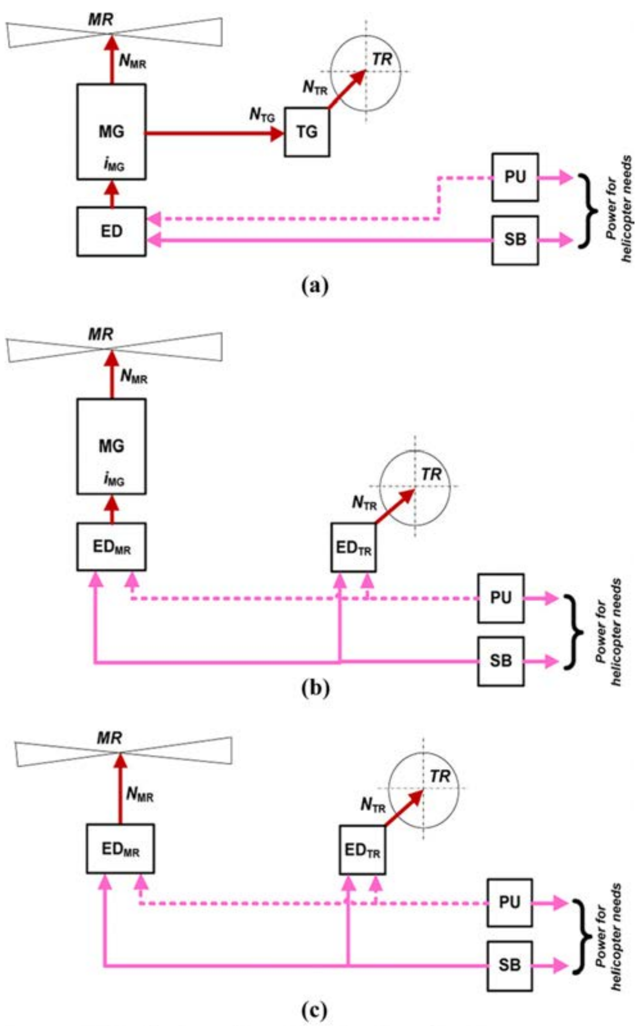
mass-dimensional performances, required for inverse problem solution (generation of helicopter design under given specifications).

Mathematical models of PS components used in considered PS MM have various level of the complexity. For example, MM of TGTE may be presented by various level of complexity (working procedure detailing): from 0 to 2, and MM of remaining helicopter PS components (PE, EG, ED, transmission and SB) have only first level of complexity, i.e. they are described in PS MM as approximation functions (as "black box").

Possible HPS architectures

PS MM, developed by authors, allow modeling (helicopter/PS matching and performance calculation) more than 15 different versions of helicopter PS. The basic circuits of some of versions are shown on the Figures 5-9. Here, short descriptions of some of the presented PS versions are further cited.

Figure 9 Options of modeling PS architectures for helicopter with all-electrical helicopter PS



Notes: (a) Option 5.1; (b) option 5.2; (c) option 5.3

Versions 1 are conventional architecture helicopter PS based on one or two TGTE and one PE (recently portion of helicopters with two PE are insignificant). Power are accordingly transferred by main gearbox (MG) and tail gearbox (TG) to main rotor (MR) and tail rotor (TR). Intermediate gearbox (IG) may be installed in several PS architectures at transfer of power for MR. Basic difference between three introduced options of version 1 (Figure 5(a-c)) is a presence or an absence of on-board gearbox (OG).

Also, as a rule, variation of rotation speed at power transfer from output shaft to main rotor in high-power TGTE is realized through main helicopter gearbox ($i_{MG} > 30$) (Figure 5(a)) because of an absence of OG. As a rule, TGTE with power up to ~1,500 hp has OG (Figure 5(b)) with low reduction ratio ($i_{OG} = 4$ [. . .] 7). In case of using of helicopter PE, the engine always has OG, performing also as a rule for other function (oil crankcase section, valve cover, etc.).

Additionally, SB of the PS available on-board of helicopter is used for engine start, and to power supply helicopter it needs to provide operation of different helicopter systems. After starting and reaching minimal steady operation mode SB supplies EG, installed directly on engine and/or on MG (Figure 5 EG_1 and EG_2) and served to feed helicopter systems and PS.

Version 2 is partly electrical architectures of PS with electro-driven tail rotor (for single main rotor helicopter). Power transfer from main gearbox to tail rotor is absent on the architectures (Figure 6(a-c)), and driving of tail rotor is realized from electro drive of TR (ED TR), electricity for which is supplied by EG_1 and/or EG_2.

Basic difference between three PS architectures presented on Figure 6 is the way of decreasing the rotation speed of ED TR output shaft at transfer of torque moment on TR. So in option 2.1 (Figure 6(a)), intermediate reducing gearbox (as a rule as planetary gear) is installed close to electro drive, and then a conventional TG is located behind it. Here, transmission is turned by 90° angle. In option 2.2 (Figure 6(b)), TR is directly installed on output shaft of ED TR (due to absence of intermediate and tail gearboxes). Option 2.3 (Figure 6(c)) differs from option 2.1 by absence of intermediate gearbox.

Version 3 is partly electrified PS architecture with electro-driven helicopter main and tail rotors. In the PS version, TGTE and PE are used for driving of main EG, providing electroenergy for ED MR and ED TR. In the case transmission is absent.

Structural difference between the two options of PS version 3 is presence (for option 3.1 – see Figure 7(a)) or absence (for option 3.2 – see Figure 7(b)) of main gearbox at power transfer from ED MR to MR.

Like previous version 2, on-board SB and power unit (PU) may be partly used to supply ED MR and ED TR.

Versions 4 represent also partly electrical PS architectures with ED of MR and TR of helicopter (Figure 8). As distinct from versions 2 and 4 TGTE and PE are used in the version 4 at all flight modes to drive MR, and TR is driven by its own ED TR. ED is installed on main gearbox of helicopter. It additionally turns MR in case of one TGTE is inoperative (for a twin-engine helicopter) or TGTE (PE) (for a single-engine helicopter). The energy source of ED MR is SB. Capacity of

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SB is defined using given flight mode (takeoff, cruise and landing) and its duration.

Such variety of structural architectures of transmissions with ED MR and ED TR is explained by searching of compromise between mass-dimensional and power performances of ED and gearboxes at strong restrictions on centering of gravity of the whole helicopter. On one hand, installation of relatively heavy components in tail boom of helicopter complicates balancing of helicopter, and on the other hand, increase of rotation speed of output shaft of ED leads to decrease in mass and dimensions, but at the same time mass–dimensional performance of gearboxes is worsened due to limitations of rotation speeds of MR and TR.

Versions 5 represent full electrical PS architectures of helicopter. The architectures (Figure 9) do not use TGTE or PE, and electrical energy for electrical driving of MR and TR is extracted either from SB or from full flight time functioning power plant (e.g. based on fuel cells or combination auxiliary PE + EG of power plant), or concurrently from SB and power plant. Constructive difference between the three PS options of version 5 consists in existence or absence MG and TG (option 5.1 has common ED, options 5.2 and 5.3 have two individual ED MR and ED TR).

Different variants of application of electric devices are considered for versions 2, 3, 4 and 5 at the preliminary design phase. In particular, following devices are under consideration:

- electric engine with liquid and air cooling of stator and rotor or with liquid cooling of stator and air cooling of rotor;
- EG with air or liquid cooling of stator and rotor; and
- electric energy transducer with air or liquid cooling.

Conclusion

Application of the approach allows to carry out analysis of hybrid (based on gas turbine and piston engines) and full electrical PS for superlight-, light- and medium-size helicopters.

In particular, analysis of possibilities to use hybrid and all-electric PS was conducted for ultralight- (takeoff weight $W_{T/O}$ up to 1,500 kg), light- ($W_{T/O}$ up to 6,000 kg) and medium-weight ($W_{T/O}$ up to 25,000 kg) helicopters. It was shown at what development level of electric technologies (specific parameters of SB, ED, EG, etc.) may provide positive effects of using hybrid and all-electric PS of different architectures.

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