Simulation Driven Development Of Aviation Composite Structures And Technologies Of Its Manufacturing

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Abstract. *Applying to helicopter composite tail rotor blade manufacturing some examples of the SDPD – Simulation Driven Product Development – concept is demonstrated. We consider an investigation of dynamics behavior of the helicopter tail-rotor blade at the stage of its CAD design, and also a heat transfer and phase transition at forming of composite spar into mould. All computer CAE simulations were performed in finite element soft package Comsol Multiphysics integrated with CAD system Solid Works. For conversion of the workpiece mathematical models from CAD to CAE system and correct substitution of the spline geometry representation the optimized technique of splines building by genetic algorithm was used. As a program tool for such optimized conversion we used the Genetic Algorithm Toolbox MATLAB.*

Key words: *Computer Aided Engineering (CAE), Helicopter Rotor Blade Manufacturing, Dynamic Analysis, Composite Workpiece Forming, B-spline, Bezier curve, Genetic Algorithm.*

Introduction

There has been a growing tendency of integration CAD and CAM systems in the last decade or so. This integration allows accelerating process of structure development from the conceptual design to it efficiency. However design of important composite workpieces (in particular, aircraft structures manufactured from composite materials) and technologies of their manufacture requires simulation of mechanical, thermal processes at all stages of project development. This tendency is emphasize of the concept SDPD – Simulation Driven Product Development. Thereof the developers try to supply a compatibility of CAD/CAM/CAE program or maximum to integrate them.

A common problem at conversion of geometry representation from CAD to CAE – system is the correct substitution of spline describing workpieces geometry. In CAD systems all curves and surfaces decribed by Non-Uniform Rational B-Splines (NURBS by short), whereas CAE systems utilize B-splines or rational Bezier-curves. For elimination of exactitude losses at NURBS to rational Bezier curves transition a minimization problem stated and solved with the help of genetic algorithm.

In the presented paper on an example of the helicopter tail-rotor blade the adjustment of composite spar CAD model (created in SolidWorks) for CAE finite-element (FE) dynamic analysis and for simulation of a temperature schedule at curing of spar (in Comsol Multiphysics environment) is demonstrated. The results of this simulation will be used further for rotor blade design enhancing and manufacturing technology optimization.

Composite spar of the helicopter tail rotor blade. Spline description and its optimization

The considered tail rotor blade displayed on Fig.1. Its spar is manufactured by winding of unidirectional fibre glass tape at 60 degree angle with respect to spar axes and by curing of epoxy resin in special mould. A quality of the tail rotor blade determines the basic working parameters and reliability of flight vehicle. At rotation on given frequency the spar undergoes the intensive longitudinal, bend and twist deformations [1]. A careful dynamic analysis is necessary for supply it required dynamical properties and reliability. Therefore a design process must be supported by simulation of rotor blade dynamic behaviour.

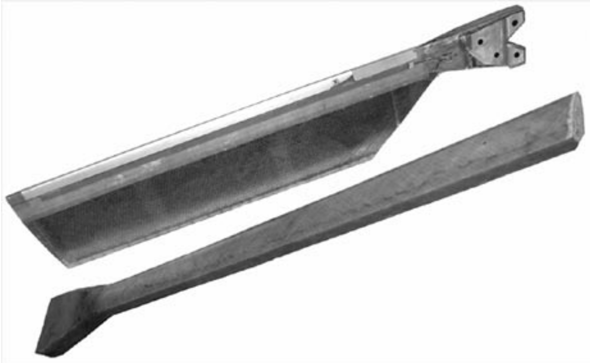


Fig. 1. Tail rotor blade and composite spar

Technology of manufacturing of a fiberglass reinforcement with epoxy resin matrix composite spar include the following phases: winding of a preimpregnated unidirectional glass-fiber tape on a steel mandrel; polymerization of a prepreg in a mould during approximately 16 hours; extraction of a baked spar from a mould and removal it from mandrel. For achieve of high strength and fatigue characteristics of spar material it is necessary to maintain a given temperature schedule of polymerization both lengthways, and across the section of the item. Accuracy of the geometrical shape and walls thickness also depend on temperature schedule. The deviations from the given temperature should not be more than 5^o C.

A presented spar has very complicated shape that designed by construction of each cross-section's connected splines (see Fig. 2, a, b), and conjunction of all sections by generatrix curves (Fig. 2, c). Obtained surfaces have formed a solid body (Fig. 2, d). In order to perform FE mechanical or thermomechanical analysis embedded in CAE converters perform a transit from NURBS to simpler spline kind. There is, for instance, B-spline for ANSYS and rational Bezier curve for Comsol Multiphysics.

Both Bézier curves and B-splines are polynomial parametric curves. But polynomial parametric forms cannot represent some simple curves such as circles. As a result, Bézier curves and B-splines can only represent what polynomial parametric forms can. By introducing homogeneous coordinates making them rational, Bézier curves and B-splines are generalized to rational Bézier curves and Non-Uniform Rational B-splines. Obviously, rational Bézier curves are more powerful than Bézier curves since the former now can represent circles and ellipses. Similarly, NURBS are more powerful than B-splines. The relationship among these types of curve representations is given by mathematical relationships below.

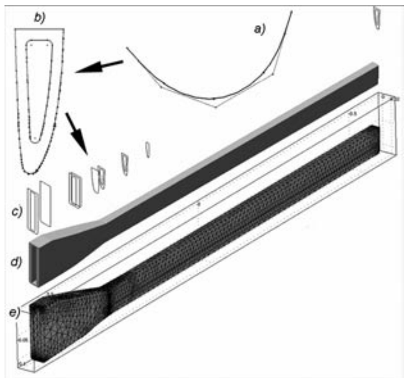


Fig. 2. A sequential design: from splines to CAD and FE models

As it is known a parametric curve given by NURBS defined by expression [2]

$$C(u)=\sum_{i=0}^{n} N_{i,p}(u)\cdot w_i\cdot P_i \Bigg/ \sum_{i=0}^{n} N_{i,p}(u)\cdot w_i \quad , \qquad (1)$$

where: P_i – radius-vector of i-th point of control polygon; $u \in [0;1]$ a current parameters value; p – the degree of a curve; $U = \{u_0, u_1 \dots u_m\}$- knots vector that have the not decreased elements; $W = \{w_0, w_1 \dots w_m\}$ – weigth vector, and functions $N_{i,p}(u)$are referred to as basis functions defined by recursive relationship

$$N_{i,0}(u)=\begin{cases}1; & u_i \le u \le u_{i+1}\\ 0; & u \notin [u_i;u_{i+1}]\end{cases}$$

$$N_{i,p}(u)=\frac{u-u_i}{u_{i+p}-u_i}N_{i,p-1}(u)+\frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}}N_{i+1,p-1}(u) \qquad (2)$$

Since each control point needs a basis function and the number of basis functions satisgies to equality

$m = n + p + 1$ (3)

NURBS is most powerfull means for curves and surfaces design, but it require to define the rather many numbers: *(m + 1)* – knots, *n* – weigths, *2 (n+1)* – coordinate of control points (for 2D geometry), 1 – degree, [*m + 3n + 3*] – numbers in all. Thus full determination of relative simple patch of 2D curve defined by 5 control points require not less then 25 numbers.

The rational Bezier curve (also a parametric curve) defined by expression

$$C(u) = \sum_{i=0}^{n} B_{n,i}(u) \cdot w_i \cdot P_i \Bigg/ \sum_{i=0}^{n} B_{n,i}(u) \cdot w_i \quad (4)$$

where the basis functions are the Bernstein polynomials

$$B_{n,i}(u) = \frac{n!}{i!(n-i)!} u^i (1-u)^{n-i}, \quad (5)$$

and remainders designations were explained early. In the case of Bezier curve determination of considered 2D – patch require *n* – weigths, *2 (n + 1)* – coordinate of control points – [*3n + 1*] *= 16* numbers only. Therefore such way of curve dscribing is more practises for FE modelling.

The NURBS curves have exclusive flexibility and controllability, but for its use for FE – simulation these qualities are excessive since open-work modelled structure requires an extreme refinement of a FE mesh and consequently an immense laborious calculations. Therefore geometry of a structure for fulfilment of simulation is usually simplified, e.g. by use of rougher describing by Bezier curves. At converting NURBS to Bezier curves it is necessary to guarantee two major requirements. At first, minimum to distort geometry of modelled area, and the arised distortions should not affect considerable on a modelled phenomenon, in particular, on a stress-strain state or on temperature field. In second, the guiding profiles should be described probably by smaller number of Bezier curves, since in points of their connection and along generatrix the algorithm of triangulation will be refine the finite elements. Result of this refinement will be formidable increase of FE-model's number of degree of freedoms, and, hence, major computational complexity. The embedded in FE- programs conversion modules have no enough settings to well performe this conversion. Therefore such conversion should be executed controlled for further successful use of modelled geometry.

In cases when it is necessary to convert a surface NURBS having shape close to cylindrical (cross-section of the cylinder can be of the arbitrary shape, it should not sharply vary along generatrix line) the surface csross-sections can be submitted with arbitrary exactitude by discrete set of points (coordinates). This array of coordinates is saved in the text file by 2 or 3 column matrixes, the number of which rows is equal to number of points of cross-section. The further procedure we shall illustrate on an example of a spar of the helicopter tail-rotor blade.

The coordinates of section points formed in SolidWorks were saved in the text file and then are read out in MathCAD (Fig. 3). The upper and lower surfaces of an aerofoil section we suppose to describe by two 3rd order rational Bezier curves – first the upper and second lower contour. To supply a smoothness of curves seaming it was required to dispose points of a control polygon (4 from above and 4 from below) on tangent to initial and final points of contours. The passing such tangent through 2 outside points of a contour was undesirable because of major influence of errors. Therefore in the beginning we created approximating parabolas, and tangent equations built by a taking of derivative of parabolas equations in starting points (see Fig. 4).

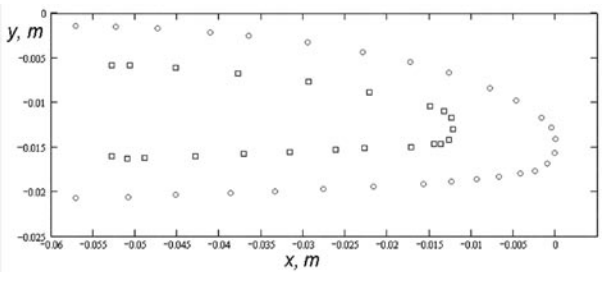


Fig. 3. Cross section points liable to fitting by rational Bezier curves

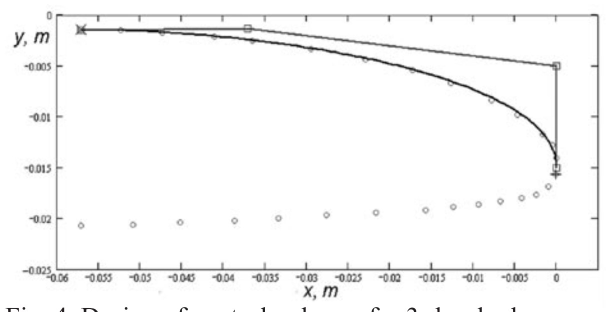


Fig. 4. Design of control polygon for 3rd order by rational Bezier curve

The equations of a constructed tangent line used in the parametric form that give convenience of the points of control polygon variation. As upper and lower Bezier curves had the identical order – third, the condition of continuity on a leading edge was satisfy at equality of lengths of vertical legs. Thus, two linked with C1 continuity Bezier curves were characterized by the following parameters:

- position of control points on a leading edge – 1 parameter;
- position of control points for trailing wall – 2 parameters;
- weight of points (3 on the upper surface and 3 on the lower surface) – 6 parameters.

Thus, the entire curve depends on 9 parameters. By variation of these parameters it was possible to change the shape of curves in particular limits. For obtaining a the Bezier curve closest to points of NURBS was necessary to minimized a functional

$$\Delta = \frac{1}{n}\sum_i \left| R_i^{NURBS} - C_i^{BZ} \right|, \qquad (6)$$

where R_i^{NURBS} – coordinates of NURBS – points, C_i^{BZ} – nearest to them, points of Bezier curve. Its minimization was performed with the help of genetic algorithm designed by means of Genetic Algorithm Toolbox MATLAB. The initial (guess) values for all 9 parameters selected orienting on a view of a created curve. The functional (6) could be interpreted as mean deviation of a constructed curve from points NURBS. This deviation has made for an outside contour of 0.14 mm, for interior contour 0.65 mm, that was quite supposed on goals of FE simulations. The completion of spline cinversion included shift of an origin in vertex of a leading edge that was suggested by convenience of the further FE model building and analysis. The obtained values of parameters were saved in model m-file of a spar description, from which the further FE pre-processing transformations were performed.

Dynamic analysis of the spar finite-element model

It is worth to compare the results of FE meshing for the spar 3D model converted by embedded Comsol Multiphysics converter from *.iges format, and for 3D model obtained by extrusion of optimized cross-sections. First FE model contain 196396 elements and second one contain 10347 elements. Our numerical experiments experienced that optimized model require in 20 times less operating memory and, as the minimum, in 20 times faster is calculated at modal analysis. The comparative static and modal analysis of both models has shown a good coincidence of the calculation results (see Fig. 5). Moreover, the time dependent analysis at given distributed aerodynamic loads is a success for the optimized FE 3D model only.

The developed optimization technique was succesfully used for structure adjusting on a stage of some composite structure design. In particularly it allow to enchance of carrying structures dynamic properties, to decrease stress intensity in the dangerous areas, and improve of technological equipment [3, 4].

Polymeric composite spars cure process. Control system design and simulation

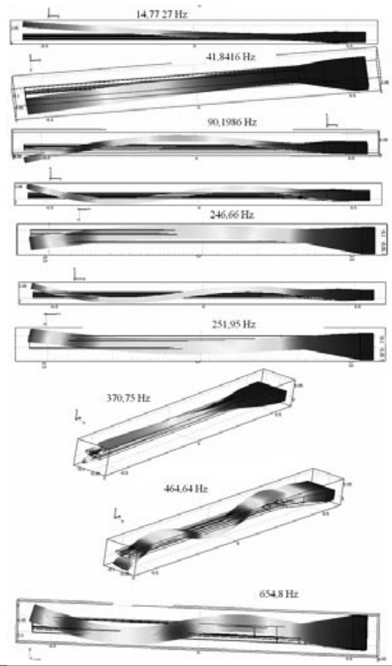
FEM-based dynamic computer model [4] of moulded spar polymerization distributed control was designed by authors earlier. The control system included a set of thermocouples located in a mould and electrical heaters. For the correct count of internal heat sources in the cured epoxy resin the data of exothermal heat and thermal capacity needed at all stages of solidification. The time history of a current heat quantity $Q\ (t)$ at a polymerization usually is described by kinetic differential equations linking a fractional conversion a ≡ $Q(t)/Q_0$ (where a ϵ $[0;1]$ and Q_0 is total reaction heat outflow at polymerization of a mass unit) with thermo physical constants and time.

Thus, for description of thermal processes in a molded work piece the FE model of a transient heat transfer should provide integration of a kinetic equation on each node of FE mesh. In this work on the basis of DSC – results the kinetic equation of a cure process in used epoxy resin was designed. Integration of this equation on each temporary step yields value of exothermal heat and actual value of thermal capacity. The designed hybrid model was implemented in joined software MATLAB – Comsol Multyphisics.

Half-mould for composite spar forming contains 4 lateral heaters and 4 thermocouples. The bottom of a mould is equipped with one long heater (see Fig. 5). Each heater is operated by automatic control system receiving signals from corresponded thermocouples.

Because of long time simulation 2D – models were created and analyzed separately: for longitudinal and transversal cross-sections. The above mentioned geometry models for different cross-sections were used. A mesh sizes was

Table 1. The natural modes and eigenfrequencies of nonrotating cantilevered composite spar of tail-rotor blade

No modes	Eigenfrequencies obtained by modal analysis, Hz		Explanation	Natural modes
	Optimized FE model	Imported from IGES		
1	14.7727	14.567660	Flapwise bend	
2	41.8455	41.737418	Chordwise bend	
3	90.1980	87.093390	Flapwise bend	
4	246.6600	229.022000	Flapwise -chord-wise bend	
5	251.9490	248.595100	Flapwise -chord-wise bend	
6	370.7470	359.767600	Twist	
7	464.6400	409.440000	Flapwise bend	
8	654.7900 Chord-wise bend	606.210600 Flap-wise bend		

generated small enough. So, one transversal section contained – 28 300 elements. For designed models the stationary solutions were found. During the analysis of stationary temperature fields (required temperature 160^{o}C) some undesirable phenomena are revealed. So, in cross section there are two segments with lower temperature – near leading and trailing zones of spar cross section (Fig. 6).

For using the heat transfer application modes the thermal parameters of mould parts, crude prepreg and polymerized spar were assigned according to the passport data of materials. Anisotropy of composite heat conductivity was neglected. In order to correctly consider an exothermal heat at epoxy resin cure process we tried the generalized cure equation [5]

$$\dot{\alpha}(T,\alpha) = \left[A_1 e^{(-E_1/RT)} + A_2 e^{(-E_2/RT)} \cdot \alpha^m\right] \cdot (\alpha_{max} - \alpha)^n ; \alpha_{max} = B_0 + B_1 T + B_2 T^2 \quad (7)$$

where $d\alpha/dt$ is the rate of conversion $\alpha \equiv Q(t)/Q_0$, A_1, A_2 –weight factors, E_1, E_2 – activation energies, R –gas constant and T is absolute temperature.

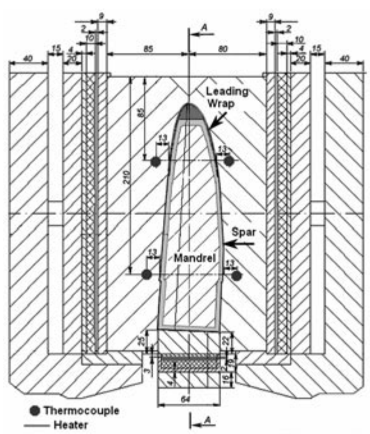


Fig. 5. Cross section of mould for composite spar cure process

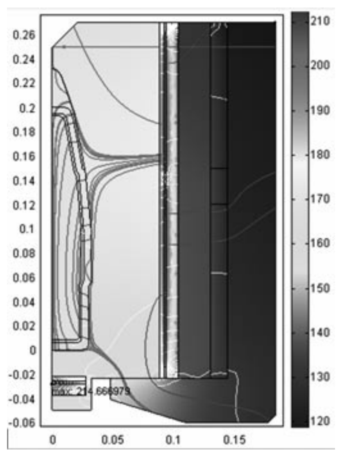


Fig. 6. Plot of the simulated stationary temperature field in a mould cross section

For determination of type and parameters values of the kinetic equation the thermal analysis experiment on NETZSCH DSC 204 F1 Phoenix® was carried out. The following temperature program was utillized: 1st and 2nd heatings from 20^0C up to 300^0C with temperature scan rate: 5, 10, 20 K/min; cooling back to 20^0C. Experimental results allow to obtaine the empirical dependences of the conversion rate on conversion current value (Fig. 7). Such way processed DSC-scan results were utilized for curing process kinetics model identification. As kinetics model (7) not agree with two modal kinetics curve (see Fig. 7) a new kinetics model were proposed

$$\dot{\alpha} = \left[A_1 e^{-E_1/RT} e^{-\alpha/\alpha_1} + A_2 e^{-E_2/RT} \alpha^m\right] \cdot (1-\alpha)^n \qquad (8)$$

For constructed model all 7 parameters are identified in Simulink MATLAB providing inaccuracy of exothermal heat reproduction up to 10 %. The significant property of the composite resin is the change of its thermal capacity during a curing reaction. The corresponding dependences constructed as a result of exothermal effect elimination from DSC-scan data, are shown on a Fig. 8. The constructed kinetic model utilized as a component of dynamic computer model of the spar polymerization control.

For analysis of the controlled heating in dynamics temperature of points, where the thermocouples were installed in the mould itself, was exported in Simulink – model of automatic control system (Fig. 9). Besides, temperature in several points of a molded spar is registered. The Simulink – model submit to the input of Comsol Multyphisics – subsystem the values of heaters power and the temperature of ambient air, which varied randomly.

In order to speed up of joined Simulink and Comsol models simulation the initial FE models was simplified as follows. The volumetric heat sources were replaced by surface sources with the conforming intensity. The sandwich structure of a mould was replaced by a homogeneous body which parameters were recalculated according to

$$\bar{k} = l\left(\sum_i l_i/k_i\right)^{-1}; \qquad \bar{h} = \sum_i h_i\left(T_i + T_{i-1}\right)l_i \Big/ \left(T_0 + T_n\right)l \qquad (9)$$

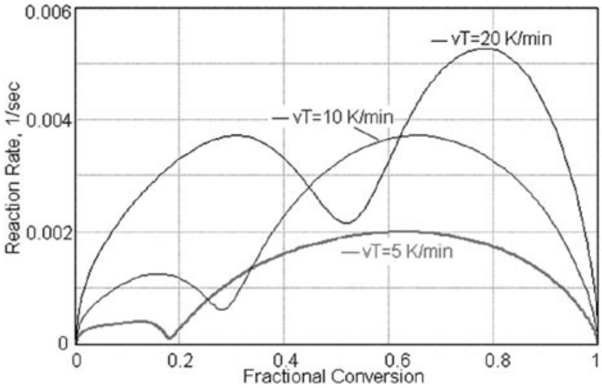


Fig. 7. Empirical kinetics curve at varied temperature scan rate

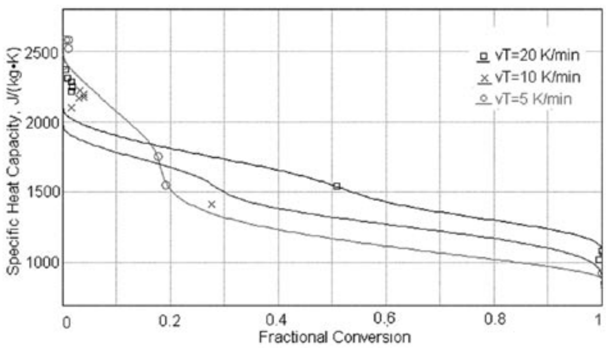


Fig. 8. Specific heat capacity dependence on conversion at varied temperature scan rate

where: *C, ρ, k* – heat capacity, density and thermal conductivity respectively, *h* – lateral boundary heat transfer coefficient; *l* – thickness of sandwich; T_i, T_0, T_n – temperature on interior, heated and cooled boundary respectively; subscript *i* – number of layer; line above letters means fitting to homogeneous body.

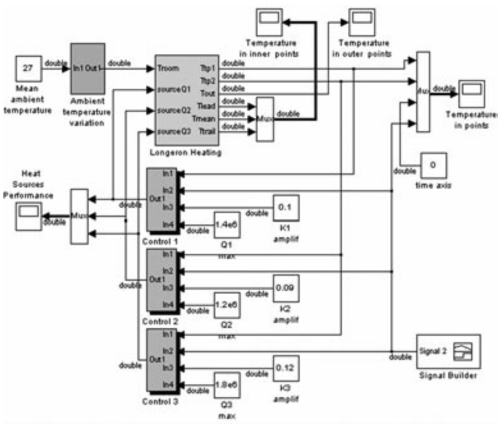


Fig. 9. Simulink-model of one channel heating control (top)

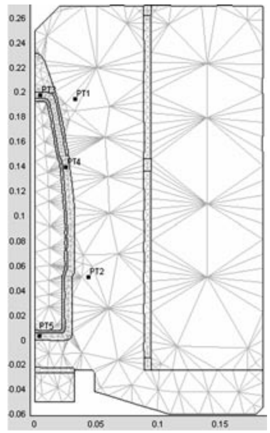


Fig. 10. The simplified FE-model of mould cross-section (right)

At given temperature schedule the simplified model has yielded a maximum deviation from experimentally measured temperature in the polymerized spar ±2° C. The reduced FE model of a mould cross section included 1720 elements and was imported in Simulink as the general dynamic model. To take into account a thermal inertia effect of a mould the prediction-correction of the thermocouples indications by polynomials of the 2nd order was used. The calculation time necessary for simulation of a complete cure cycle made 30…180 min that has allowed executing all necessary adjusting of automatic control system and mould design.

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References

1. Leishman J. G. Principles of Helicopter Aerodynamics. Cambridge University Press, 2000, 496 p.
2. Shene C.-K. Introduction to Computing with Geometry Notes. Department of Computer Science. Michigan Technological University (2003) http://www.cs.mtu.edu/~shene/COURSES/cs3621
3. Mitchell M. An Introduction to Genetic Algorithms. MIT Press, 1999, 376 p.
4. Shevtsov S.N., Hmelevska T.A., Axenov V.N. Computer Simulation of Distributed Thermal Control for Polymeric Composite Spar Curing Process. Proceeding on 6th Eurosim Congress on Modelling and Simulation, 2007, Ljubljana, Slovenija
5. Calabrese L., Celona A., and Valenza A. Thermal and Rheological Characterization of a Thermoset Matrix for Filament Winding Modelling, Advanced Composites Letters, 13, Issue 1, 2004