Face degradation analysis for body, having arbitrary geometry

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Abstract

A novel approach for representing 3D body, having arbitrary geometry is presented. A computational method for simulating the evolution of the burning surface of a complex, three-dimensional solid rocket motor propellant grain has been developed using the directress method. Presented ExSES system based on the developed by authors directress algorithm of description of solid bodies transformation under condition of significant change of boundary surfaces and allows motor grain design by integration with computer-aided-design (CAD) and computer-aided-engineering (CAE) programs. The presented software solution may be simple expanded for the account of new effects and design ideas.

1. Introduction

The problem of the account of dynamic changes of the form of the body is a typical problem for many areas. In the field of aerospace engineering there are also many tasks in which it is necessary to carry on analysis of the changes taking place with the body subjected to the effect of high energy environment the interaction with which results in body form transformation under external and internal forces, body degradation in the result of its material destruction and removal. The final result of the named processes is the change of construction dimensions and topology. One of the important areas of this type is the analysis of the degradation of the grains of the solid propellant and analysis of destruction of the parts which are protected from the effect of high temperature flows by coating with heat insulation materials. In all these cases it is necessary not only to trace the changes taking place in geometry of the object, but in most cases it is necessary to take into account the interaction of the named changes of geometry with the change in the processes responsible for body degradation. Among the most significant processes are the relation between degradation rate and pressure, flow velocity and tensions realized in the body.

1.2 Nomenclature

CAD = Computer Aided Design
CAE = Computer Aided Engineering
CSAR = Center for Simulation of Advanced Rockets
ExSES = Extensible Solid Engineering Subsystem
SP = Solid Propellant
SRM = Solid Rocket Motor
OS = Operating System
PLM = Product Lifecycle Management

1.3 Problem definition

Analysis of internal processes in SRM is a key problem of design of this type of the motors. The process of the degradation of motor grain may be considered as a leading one in determination of characteristics of motor operation. But propellant burning rate, which in its turn determines the grain degradation, strongly depends on internal pressure, propellant initial temperature and some other factors among which are acceleration, gas flow velocity, internal tensions in the grain, etc. [1].
In addition to the named problems during analysis of the internal chamber processes it may be necessary to carry analysis of irregularities of burning rate distribution over surface of the grain caused by nonuniformity of propellant characteristics or existence of some special devices for realization of local regulation of the burning rate. These may be embedded wires or some other devices.
The nonlinear relations between named above processes makes the problem very complicated and currently it is solved either on the base of rather simplified models, or it is necessary to use very complicated computational systems operating on very powerful computers [2].
This makes the systems of the last type very specialized and limits access to such systems for researches not associated with authorized organizations.
At the same time the progress in computers, software development and mathematical simulation of internal processes enables development of the systems of new type, based on conventional PLM technologies which are able to provide the platform for solution of the problems of such kind. And what is also important is that there is no need of building such system on the base of full scale PLM like CATIA, which in its turn will make such solution vary costly and limited in use by a narrow set of experts. Our goal is to develop some sort of the distributed system which will be able to operate on a set of PC's with moderate characteristics most of which are equipped by software of the level of the working place and connected with each other in one network.
In this case a configuration of software required on each working place may be determined by some nuclear providing solution of the problems specific for SRM mainly dealing with geometry description and a set of applications on the base of CAE systems adjusted for solution this or that specific problem like tension analysis or thermal or flow analysis. Operation in such system is more complicated for each user and requires higher level of person qualification. But at the same time it provides a possibility of free extensibility with relatively low costly developments from outside.
As it was already mentioned that the key element of such system should be a description of the object of analysis. Our approach is based on the idea that geometry description will be enough for most of the situations under analysis in the problem under discussion.
So the current paper is mainly devoted to development of solution of the most complicated problem of geometry description of SRM – analysis of grain degradation in 3D approach with the account of an arbitrary distribution of the form of the burning rate over the burning surface and in time.

2. Description of solid body geometry

Practically all convention design groups currently operate in one of the CAD systems in which realization of design of certain device is made in a form of a drawing or solid body model. Such form of presentation of information on geometry of analyzed device determines that realization of operations with the grain geometry analysis should be made in CAD system. Such decision determines the input and output formats and a possibility of the use of CAD internal functions for realization of a wide range of different operations required for grain degradation analysis.
The next step is the realization of description of the body with moving surfaces (grain degradation).
Some old methods of grain degradation analysis [3] are based on the splitting of the grain form to geometry primitives. These approaches are very fast, efficient and well adopted to the needs of the practical engineering, but have significant limitations in application with arbitrary 3D geometry and in case of the need of the account of the irregularities of burning rate distribution. As usual software realization of these algorithms is out of date.
There are some known rather new developments in the field of surface grain description [4]. In general, they may be classified into two broad categories of techniques for moving interfaces: Lagrangian methods, which tracks the interface using an explicit surface representation, and Eulerian methods, which capture the interface using an implicit representation Currently the hybrid methods which combine both of these approaches start to be very popular[5].
Currently for description of solid body the most popular approach is the application of triangulation methods. Huge amount of work was realized in this direction which was thoroughly investigated from different points of view. In the result all the systems of solid body design have embedded possibilities for realization of operations required for by this description of the surfaces. The specialized format was developed for saving the surfaces presented in this form. For example among the most popular formats recommended for storage of irregular triangulation grids are LandXml, TIN. For saving the models of the relief on the base of regular grids may be used DEM format.

Though the presentation of the solid body and corresponding surfaces by irregular triangulation has lot of advantages its application for solution of the problems of grain degradation meets with significant problems as huge computational resources are required for find specification of a body having significant dimensions and some low scale elements, which should not be lost in analysis.

2.1 Snakes algorithm

In current work a method based on application of sets of closed circuits for specification of arbitrary geometry is realized. This idea of this method is not new [6]. Due to this approach the geometry of some body is presented by a set of points of its contour connected by a closed curve, which should not have intersections with itself. The authors of [6] for the description of such closed smooth circuits suggested the term “snakes”. In the investigations of application of the snakes algorithm it was demonstrated its high efficiency for processing of geometry of different objects when analysis of the change of geometry is required [7, 8]. In most publications the snakes algorithm was used for analysis of 2D objects and few attempts were made to expand it to 3D applications [9]. This is determined by the need in realization of complicated algorithms in the area where a very well developed triangulation methods looks to be very competitive. But to our opinion such situation is not correct and the snakes algorithm having proper software realization may have significant advantages to triangulation approach.
For the proper evaluation of the possibilities provided by the application of the closed circuits for 3D bodies let us analyze on the different methods of generation of such curves. For simplification of the explanation of the basic idea the following description will be made for 2D case. The specifics of 3D analysis will be analyzed in the end of this paragraph.
The most popular solution for building a snake up till now was the application of the segments of straight lines for connection of the system of points which were determined to be located on the analyzed surface [10, 11].

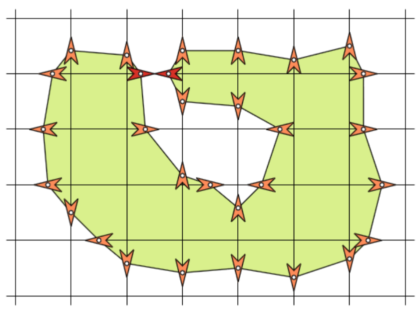


Figure 1: Example of a typical snake

In fig.1 such form of contour approximation is presented for 2D cross section. For generation of such snake it is possible to cover the area in which the analyzed body is located by a regular rectangular grid. The points located on the intersections of the grid lines with the analyzed contour form the snake and are called «snaxels». These «snaxels» are marked by arrows on fig.1.
It is obvious that each node of the flat grid is connected with its neighbors by four lines. Depending on location of the node referring the boundary of the body it is possible to distinguish three different situations:

1. The nodes located inside the body connection lines of which do not cross the boundaries of the body. They will be called the internal nodes.
2. The nodes located inside the body, but having at least one connection line crossing the boundary of the body. They will be named as boundary nodes.
3. The nodes located outside the body. They will be called external nodes.

For each boundary node is possible to determine the distance to the boundary of the body along each connection line. The system of snaxels determined in this way is used for boundary approximation. As it was already mentioned the simplest method of building the closed circuit in this case is the use of segmented line. But such approach is not perfect as accuracy of such approximation is low and the length of such segmented line may be significantly different from the length of the actual boundary. This error will also result in significant error in determination of the area of the body. For the bodies having the rounded contours such error of approximation may be a significant problem.
In [12] for compensation of this effect was suggested to use the grids more complicated then rectangle (regular triangle). But this modification results in the significant increase of complicatedness of description and does not look motivated (fig. 2).

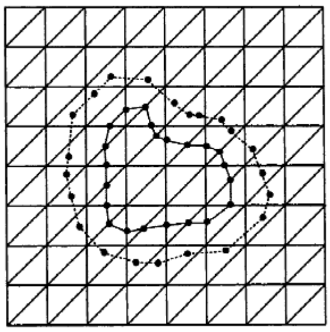


Figure 2: Snake expands (solid line) and moves relative to the grid during the deformation step (dashed line) using modified grid

We see another possibility of the increase of the accuracy of approximation saving the initially efficient description based on the regular rectangle grids. Our suggestion is to use Bezier curves for approximation of the contour presented by snaxels. The control points of Bezier curves in this case will be calculated on the base of information on the points neighboring the analyzed segment.

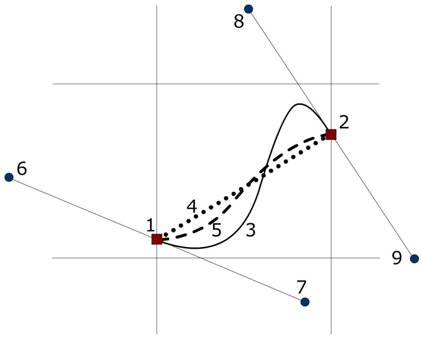


Figure 3: Part of a complex contour intersected with regular grid

Figure 3 presents the different forms of possible connection of the contour points. The snaxels (points of the intersection of the surface with the lines of coordinate grid) are marked on fig.3 by rectangles and are notated as 1 and 2. For contour closing the simplest solution is to use the segments of the straight line. Such connection is presented in fig.3 by dotted line and notated by number 4. Bezier curve connecting points 1 and 2 is marked by 5 and 3. Curve 3 illustrates additional possibilities of adjusting of connection to the required curvature value on the base of the use of control points 6, 7, 8, 9.
The difference in approximation provided by the described approaches most contrast may be illustrated in case of presentation of a sharp edge like the one presented in fig.4. The line that should be reproduced is presented in fig. 4 in red color.

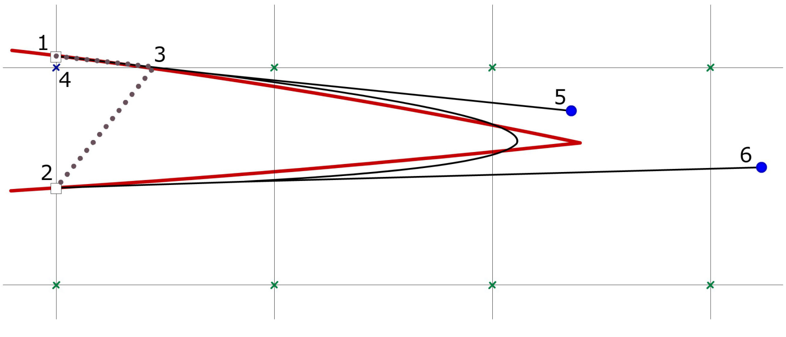


Figure 3: Approximation of a sharp edge contour using snakes and Bezier curve with control points

For selected step of regular grid only one node is inside contour (marked with blue *x*). All other nodes (marked with green *x*) are outside contour. The snaxels for this line are marked by numbers 1, 2 and 3. With snakes approximation the precision will be very low for this part of a complex contour (dashed line 1-3-2). Otherwise using Bezier curve (black solid curve 1-2) with setup control points (5, 6) the length and appearance will be very close to the original part of contour even for this example.

In the classic formulation of the active contour models the detailed description of which is possible to find in [10] it is supposed that all points located on the boundary of the object have translation in the same direction referring the initial contour, i.e. the object either is shrinking or expanding in all directions in which the change of dimensions takes place. In fig.1 the direction of the translation of the boundary points correspond to the direction of the arrows marking snaxels. Such assumption puts significant limitations on the area of application of the method of differentiated contours [10]. To overcome such limitation the authors of this work suggest the new approach, which they call the directress method. This approach was developed for 3D case and the author has found after this method was formulated has many ideas similar to those that were suggested in [11] but for much more simple case of 2D configuration.

2.1 Application of the directress method for the analysis of the degradation of the solid propellant grain in the process of burning

The key idea of the directress method is that each elementary volume (parallelepiped) formed by regular grid of planes parallel to coordinate planes of the global Cartesian coordinate system has its own local Cartesian coordinates system. This local coordinate system saves the information about the coordinates of the intersection of the burning propellant surface with coordinate lines. This enables for each node having number k and coordinates (x, y, z) of the directress grid to know the distance to the current location of the burning surface in direction of the neighboring nodes *k(x+1,y,z)*, *k(x-1,y,z), k(x,y+1,z), k(x,y-1,z), k(x,y,z+1), k(x,y,z-1)* (see fig. 5).

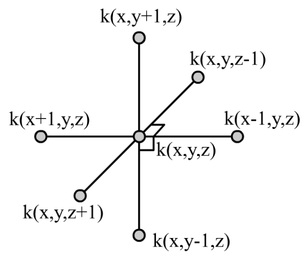


Figure 5: Node description

On the base of this information and with the account of the same information in neighboring nodes it is possible to build the closed surface similar to the procedure, which was presented in the previous paragraph in case of building contour by means of Bezier curves. In the first step it is possible to determine parameters of this surface only on the base of the information on the closest nodes. In more accurate approach it is necessary to specify additional parameters for specification of the curvature, which may be determined from analysis of the area exceeding a single step of the grid (see fig.4).
Additional information on the formation of the burning surface location may be extracted from the application of the Huygens principle to the expanding front of burning. This determines that each point currently located on the burning surface may be considered as the source of new disturbance , generating a new front of burning wave. The envelope of the secondary sources fronts forms the burning surface on the next time step. Application to realization of this idea Bezier curves looks much more accurate then triangulation approximations often used for solution of similar tasks.
In case if the burning is governed by isotropy relations the burning front in propellant expands in all directions with the same speed. At the moment t the burning front will cover the sphere having radius (1).

$$e = \int_0^t U dt \qquad \textbf{(1)}$$

This results in fact that the burning surface, which will be the envelope of these spheres will be located from initial burning surface on the same distance e. Figure 6 presents the example of the diffusion of the burning front in case of isotropy uniform over surface law of burning rate.

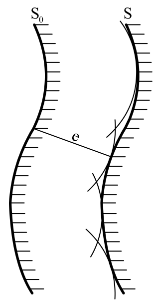


Figure 6: Moving of the burning front

The radius of the sphere of influence of each point is determined by the local burning rate in the point at current time. For operation in situation when the burning rate changes over the surface of burning in directress method it is enough to specify a required value of burning rate for each node in the body of the propellant. This distribution should be corrected in the process of grain degradation analysis in accord with changes that take place.

For the first glance it looks logic to determine location of the burning surface on the next time step only on the base of the snaxels, determined for initial location of the burning surface. In fig.7 is presented some burning surface having snaxels marked by letters (A to G). It is supposed that burning rate is the same in all these points. Fig. 7 demonstrates that if the new location of the burning surface will be determined only by the influence spheres of snaxels the presentation of resulting burning surface will not be accurate. For example for coordinate X having value 7 the new location of the burning surface determined by influence spheres will be significantly higher in Y direction then the actual one presented by bold solid line.

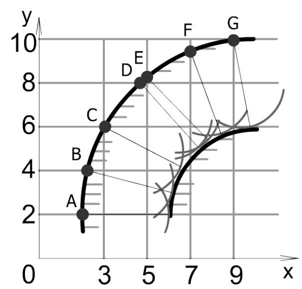


Figure 7: Low precision with using spheres

To overcome this problem in directress method is suggested to determine the new burning surface location not on the base of the envelopes of the influence spheres, but on the base of snaxels of initial burning surface to build approximation on the base of the closed Bezier curve. After that approximation is generated (it is presented in fig.7 by solid bold line connecting snaxels) an equidistant to this line is formed. This equidistant will be the burning surface of the next step.

3. ExSES description

Realization of directress method is not a big problem and this makes one of the main advantages of this method in comparison with other known approaches, for example Rocstar software suite (University of Illinois, USA) [1]. Our program realization requirements are very simple. All calculations can be done by common organization's network operating with well-known and popular Microsoft products. There are no special requirements to organization network – it can be simple or use multilayer architecture with encryption and access control – because computer-to-computer communication in our modules is implemented using common OS tools. For testing purpose (because of low calculation speed) it is possible to set up all components of our system on one computer. As an example of using our software solution for evaluation of the internal processes in SRM see fig. 8

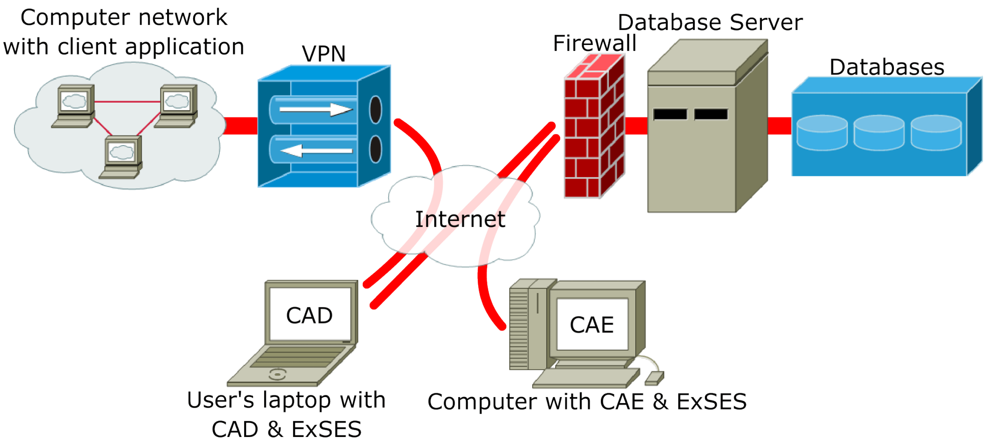


Figure 8: Example of using ExSES solution

As the “main” computer (management of all calculations) it is possible to use laptop with CAD-system installed. After 3D solid rocket motor model is created by means of CAD system with application of some simple rules for specification of burning surfaces, ExSES plug-in starts. User defines values for nodes mesh (nodes step) and set up connection parameters to database server. ExSES module using API functions provided by CAD start “scanning” model and saving information about solid, combustion chamber and nozzle block geometry. After saving information, tables in database contain full information for reproduction the initial model and can be used like “file” with 3D nodes structure. Databases tables store not only nodes information with distances to the borders, but each node has local burning rate value also. Local burning rate for each element can be set up from the laptop or by calculations made by means of CAE-programs responsible for analysis of internal flow or tensions in the grain, etc.. One of the ExSES modules calculates the evolution of the burning surface during each step time. To take into consideration all forces affecting the burning of grain our algorithm has to consider each contour in each cross-section in 3 orthogonal planes. It may take a lot of time in case of using one PC for all operations. But these calculations can be done using distributed network resources. Every PC included into the company network can work like a part of computation system. All modern computers have multi-core processors and it is possible to run many tasks at the same time without any troubles. Our client application should be installed on the computers you want to take part in calculations. ExSES client application has some settings (the amount of cores (processors) which can be involved for calculations and the possible servers which requests should be processed). In this case (fig. 8) the laptop is used just for management purposes – all calculations are produced on other computers. One of the important feature of this development is that results of all calculations are saved in DB tables. One of important advantages of ExSES is possibility to account the effect of any physical process affecting the character of solid propellant grain burning. Database has an open description and every application can read/modify data accordingly with the result of its operation. Everyone can create such program for his own concept of burning processes. If it is impossible to create plug-ins(add-ons) for CAE application, transfer of the geometrical information between applications can be carried out through CAD – system.
All ExSES components are:

1) Plug-ins for CAD&CAE – applications

2) Network application for distributed network

3) Database server for information storage

In a fig. 9 the possible circuit of carrying out of calculations of the solid-propellant engine is summarized.

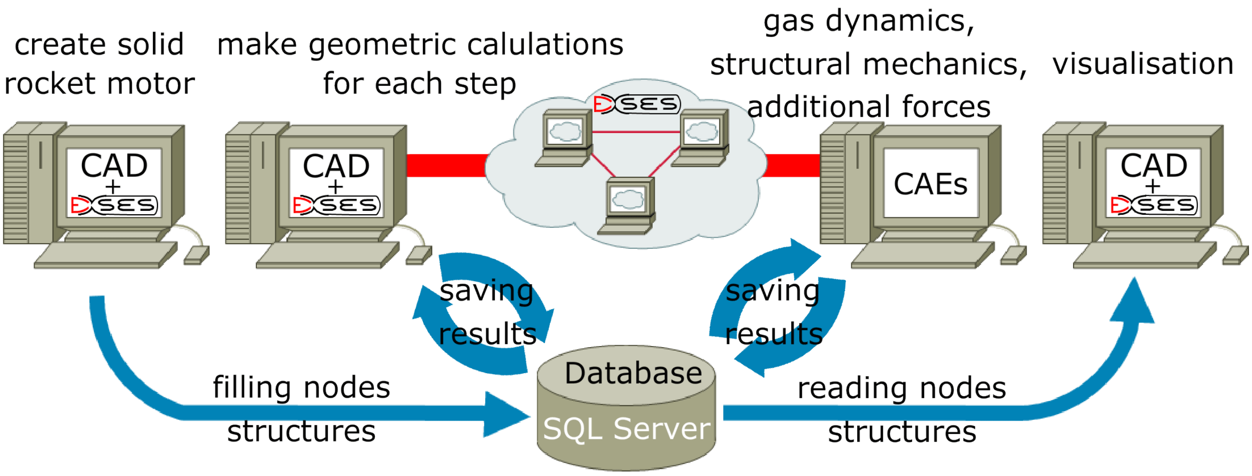


Figure 9: Possible circuit of carrying out of calculations of the solid-propellant engine

First step is creating 3D solid engine model (any method of creation and transformation of 3D solid body model are enabled). Second step is "scanning" model and saving nodes structures into the database. After each layer is "scanned" and saved into the database it is possible to start calculation of geometrical transformation of burning surfaces. The same procedure is realized for each *Δt* time step the all-round analysis of engine grain degradation and analysis of conjugant processes can be done by using external CAE applications. Geometry export/import is also led with DB usage. For each calculation moment it is possible to restore 3D model (by using nodes information) and by tools of CAD system to receive the most important characteristics like: the area of burning surface, internal burning chamber volume, gravity center characteristics. Example of using third party Structural Mechanics Solver for coupled simulation is in fig. 10.

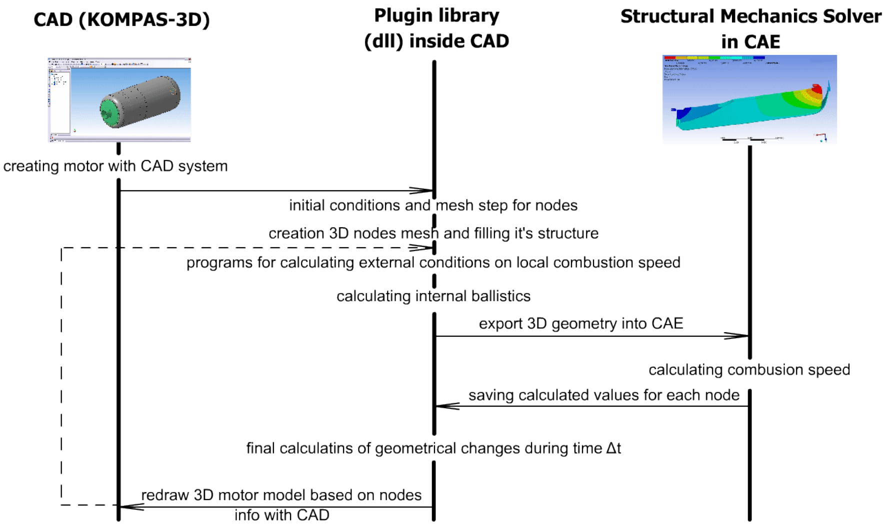


Figure 10: Using third party Structural Mechanics Solver for coupled simulation

3.1 Account of the effects of local burning rate disturbances

One of the possibilities provided by directress method is a possibility of the account of the effects of devices effecting on the local value of the burning rate. One of most popular solutions of this type is embedded wires [3]. The increase of the burning rate along these wires results in formation of the cones in the propellant surface. The need in the account of such effects makes grain degradation analysis much more sophisticated. Currently account of such effects in general form is not known. In directress method for the description of such local disturbances the special markers are introduced in the process of grain design. These markers are saved in DB in separate table after grain volume is scanned. For each element are saved not only geometry information, but also are saved characteristics, required for determination of the burning rate in the area affected by certain element. For each step of grain degradation analysis a special procedure checks if these elements are presented on the burning surface and if they are present then analysis of the cone formation and propagation is realized. Such analysis is made only for elements location as surfaces resulting from the presence of these elements are processed in regular procedure of burning surface transformation.

4. Examples of application of directress method to grain degradation analysis

Figure 11 presents results of simulation of degradation of the grain of the umbrella type. The burning of the grain having axial symmetry is realized over the internal channel. The external surface of the grain is inert and does not change in the process of analysis. Some different stages of operation starting from initial configuration and ending with practically full degradation are presented. On each step of motor operation it is possible to have a 3D model of the grain on the base of which designer is able to realize any analysis he requires.

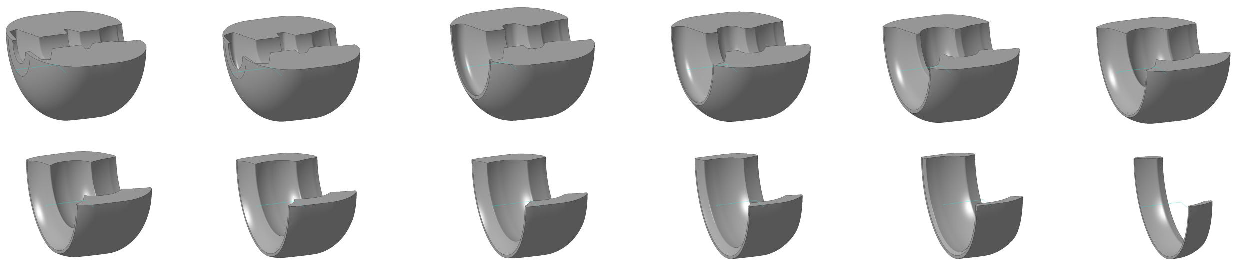


Figure 11: Example with 12 drafts for test solid propellant grain in case of isotropic combustion with constant in time burning rate

Though the problem of the type presented in fig.11 is very typical for SRM design, such problem may be efficiently solved by most of the existing programs.
The next example illustrates the application of ExSES for analysis in which the irregularity of the burning rate in time and over surface is a principle problem.
The burning of the grain initially having axial symmetry is analyzed. Grain initial configuration is presented in fig.12 a. In green are marked the surfaces that are subjected to burning. In gay color are presented the surfaces that are not subjected to burning.
In Fig.12 b presents the burning surface with account of acceleration, and c the same time moment, but without account of this effect.

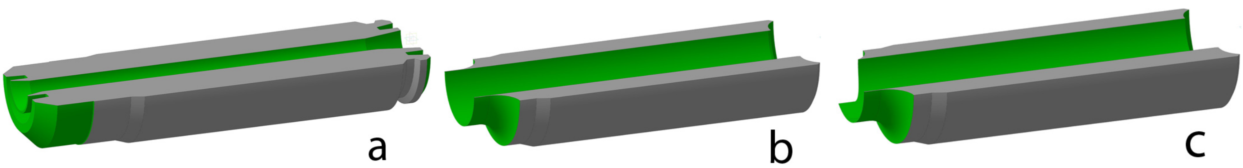
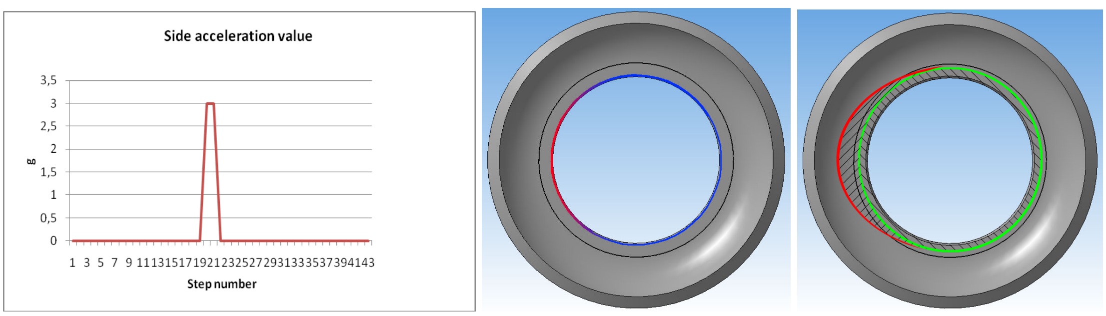


Figure 12: Example of solid geometry a) Initial state b) after 20 steps c) after 20 steps with side acceleration



a b c

Figure 13: Side acceleration value and acceleration gradient

It was supposed that at a certain moment the motor is subjected to significant acceleration in direction perpendicular to its main axis. The acceleration diagram is presented in fig.13 a. It is supposed that described acceleration causes during the period of its action cause the change in distribution of the burning rate over the burning surface. In points where acceleration vector is directed to burning surface it causes the increase of the burning rate proportional to the projection of acceleration vector to the normal to the surface. Resulting distribution of the burning rate in cross section of grain internal channel is presented in fig.13b. For comparison the undisturbed by acceleration burning rate profile is presented. After acceleration disappears the burning rate restores to the initial distribution. But the irregularity of the surface caused by the burning under acceleration result in the loss of axial symmetry of the grain and following degradation analysis demonstrates the burning of such grain with account of 3D effects. In fig.13c green – common burn speed, red – accelerated speed up to 3 times lager.

4.1 Results

Presented ExSES system based on the developed by authors directress algorithm of description of solid bodies transformation under condition of significant change of boundary surfaces may be a very useful tool for analysis of different engineering problems.
Initially this system was developed for SRM grain degradation analysis and is able to solve this task in case of the arbitrary 3D geometry of the body and arbitrary distribution in time and over burning volume of the burning rate.
Important feature of ExSES is that it does require sophisticated hardware and software support and may be operable as on the individual computers, so in the powerful systems.
The ExSES being CAD based system may be simple incorporated in to design practice of any group having software starting from the level of working place and higher.
The no less important feature is that it may be simple expanded for the account of new effects and design ideas.

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