Efficient Simulation of Grain Burning Surface Regression

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***Abstract*—The computation of grain burning surface regression plays a very important role in the internal ballistic performance evaluation of solid rocket motor, however, the traditional methods such as geometry-based one could not handle the self-intersection and characteristic geometric element disappearing problems. This paper presents an effective and efficient framework to simulate 3D grain burning surface regression with level set method which is combined with Fast Marching technique to constrain the calculation area only around the burning surface. At last, a typical grain example is given by our framework to verify our method's effectiveness and efficiency.**

Keywords- solid rocket motor; grain design; level set; burning surface regression component; simulation

I. INTRODUCTION

During the design of Solid Rocket Motor(SRM), grain combustion simulation play a very important role in the performance evaluation and structure analysis of SRM. On the one hand it will impact the internal ballistics attributes directly with different thrusts; on the other hand it decides the internal pressure and temperature, which give instructions to the structure design. Generally speaking, the burning area of grain changing with time is the key to the grain combustion simulation.

Early researchers often use analytical algorithm and graphing method[1] to compute the burning area of grain, such kinds of methods are easy to implement, however it is hard to process complex grains. Universal coordinate method[2] gives a general solution to the simulation, but it is complicated to implement and complex to operate. Boundary fitting method and volume element method[3, 4] both have the disadvantage of heavy computation burden.

Based on recent geometry modeling progress with many powerful software tools, such as UG[5], Pro/E[6], many researchers proposed grain burning surface simulation based on solid modeling with constructive solid geometry technique, which uses Boolean operators to combine complex objects. However the internal and external geometries of core moulds are pre-defined, the burning surface driven by parameters can not avoid the self-intersection and characteristic geometric element disappearing problems.

Reference [7] presents mesh regression method to simulate the burning of SRM grain by burning web to reconstruct the burning surface based on the initial geometry. Though such method is general, it is still hard to process intersection, separation and deformation during regression for those complex SRM grains.

The reality is that demands for ballistics are so divergent, often different shapes are designed for special purposes. However this also results in the difficulty to simulate the grain combustion, so flexible method is needed to work with the complex shapes. As one general surface tracking solution, level set method becomes more and more popular. Wang et al uses 2D level set to simulate the anisotropic SRM grain burning[8], Qing [9] demonstrates the application of level set in grain burning surface calculation. However available researches only solve some simple cases of combustion, and with heavy time consumption.

In this paper we present an effective and efficient framework which can simulate 3D SRM grain combustion for any complex shapes. The simulation is based on level set method. To improve the efficiency, fast marching technique is used to constrain the calculation just around the interface. For a general case, the computation could be done interactively, even real-time. For a large scale problem, we can still simulate it quickly.

II. GENERAL SRM GRAIN COMBUSTION SIMULATION

A. Level Set Method

Level set method is a general interface tracking method, which is used to track the water surface in fluid simulation, to track the organ interface in medical image processing, etc. Assuming interface Γ, the internal area Ω, ϕ defines the shortest signed distance of one point to the interface Γ, so level set holds the following properties:

$$\phi(p) > 0 \;\; if \;\; p \notin (\Omega \,;\, \Gamma)$$
$$\phi(p) = 0 \;\; if \;\; p \in \Gamma$$
$$\phi(p) < 0 \;\; if \;\; p \in \Omega$$

To simulate the burning procedure, the following equation is used to control the interface motion:

$$\frac{\partial \phi}{\partial t} + \vec{v} \cdot \nabla \phi = 0 \tag{1}$$

where $\vec{v}$ is the driving velocity, ϕ is the implicit signed distance function and its initial value comes from the signed distance field. To simulate the SRM grain combustion phenomena, we use the following velocity field (2) to drive the level set equation,

$$\vec{v} = -\vec{N}r \tag{2}$$

where r is the burning rate constant, it is used to control the burning surface advance speed. In SRM design domain, parallel regression assumption is often used so that r is the same everywhere. However, if internal fluid simulation is coupled with the combustion, r should be different. $\vec{N}$ is the surface normal of the implicit distance function, which can be attained by (3),

$$\vec{N} = \frac{\nabla \phi}{|\nabla \phi|} \tag{3}$$

This direction always follows the burning into the grain itself, which obeys the combustion rule with fuel disappearing progressively.

B. SRM grain surface regression simulation

SRM grain is a kind of high-energy fuel which propels the whole missile to attack enemy target. So it combusts very fast, which often takes just few minutes. To attain required ballistics, the grain is designed into different shapes to provide different burning area resulting in different thrust.

Level set is suitable to any complex grain shapes since it never cares the geometry shape, in consequence, the self intersection problem could be handled naturally which is often a headache in solid modeling methods. More important, level set gives a possible solution to the coupling of SRM grain combustion with the internal fluid simulation by fuel pressure and gas velocity. Those grain regression methods based on geometry computation can not integrate such kind of advantages.

The whole computation consists of two steps, including pre-processing and simulation as shown in Fig.1. The pre-processing step is given in detail as follows:

1) Modeling tool is used to construct the geometry data for the SRM grain. Here UG, SolidWorks etc. software packages could be used to accomplish the design, in this way, the powerful modeling function is taken full advantage with the help of these mature popular software and many existing designed results could be used.
2) With file format converting tool the geometry data is discretized into triangle mesh.
3) Define the computation domain by calculating the bounding box of the triangle mesh, assign the resolution according to the task demand, and divide the domain into grid.
4) Compute the signed distance field as the initial value of level set from the grid. If some surfaces are covered by fire resistance, then we can assign the according property interactively to the closed nodes.

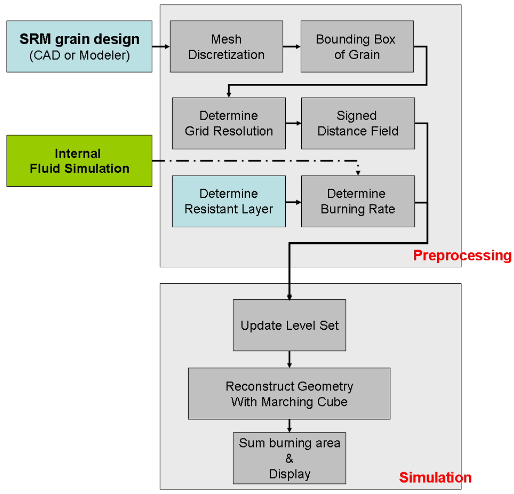

Figure 1. SRM grain combustion simulation procedure

During the simulation stage, level set is solved with parallel regression assumption along with the local normal direction at constant rate. The details are given below:

1) The first order Semi-Lagrange method is used to solve (1) so that it is still stable even with large time step. Certainly higher order methods could be used, such as Runge-Kutta, with more time consumption.
2) Re-initialize level set. As to level set, the numerical result should always keep $\phi(x,t)$ as the signed distance function. However during continuous calculation, $\phi(x,t)$ will diverge from the interface, especially when the gradient of $\phi(x,t)$ around the interface becomes very large or very little. Re-initialization will constrain level set to the signed distance field.
3) If no optimization technique is used, the computation cost will rise quickly with the resolution going up. Obviously, during the combustion, not all nodes are involved. To avoid unnecessary computation, Fast Marching technique is used to constrain the solving only happen in the narrow band around the interface as shown in Fig.2(the yellow part is the combusting object while the gray area is the area needed to update with level set).

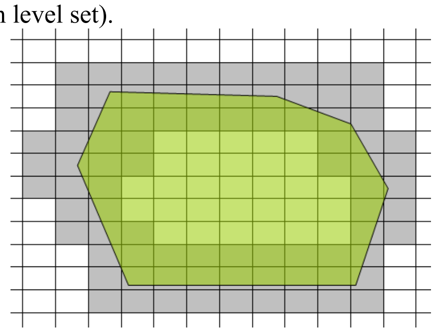

Figure 2. Narrow band illustration of computation domain

4) After level set field is updated as ϕ, Marching Cube algorithm is used to reconstruct the geometry. From the procedure, it is clear that the burning computation has no relation with the geometry of SRM grain. It is independent on the topology of the geometry. So the algorithm we present is suitable to any shapes of SRM grain.
5) With the geometry reconstructed, it is easy to get the burning area by summing up the area of all triangles. However, the cover layer will resist the burning in some area, we need to classify the triangles into burning triangles and non-burning triangles. So from the beginning of the simulation, the nodes of the grid will be marked from the initial triangle mesh. During the simulation, the new generated triangles' property inherits from the surrounding nodes. By summing up the burning triangles' area, the total burning area is attained easily.
6) Then different rendering techniques can be used to visualize the combustion procedure, such as ray-tracing, X-ray, etc.

III. Experiments and Results

Based on the present algorithm, a typical SRM grain model is used in the experiments. Its structure is shown in Fig.3 with internal exposed by slicing along the axis. To observe the internal airfoil shape, another rendering technique, simulated X-Ray is used as shown in Fig. 4.

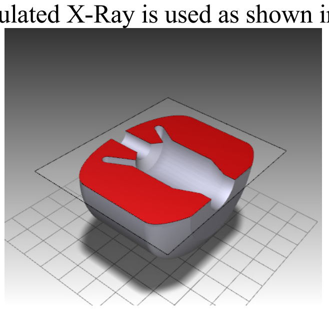

Figure 3. Structure display with slicing

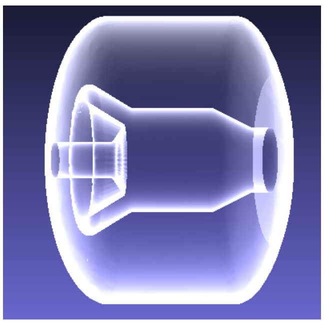

Figure 4. The simulated X-Ray illustration of the initial structure

With human computer interaction, we can assign the cover layer to determine those burning resistance which stops the combustion. In this case, the external outline of the SRM grain is the burning resistant layer as shown in Fig.5(the red is the initial burning surface, the blue is the burning resistant layer). This is a preprocessing step, and other technique could be used. Here we also present an alternative way by comparing the internal burning geometry with whole geometry to classify the triangles into burning surface or non-burning surface, which can run automatically and quickly.

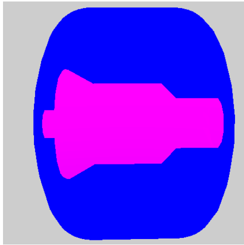

Figure 5. The transparent display showing the burning and non-burning surfaces.

Fig.6 gives the simulated X-Ray results at four different time instances. It is clear that with combustion, the surface will progressively regress until the resistant layer is reached. At last the whole grain will burn out.

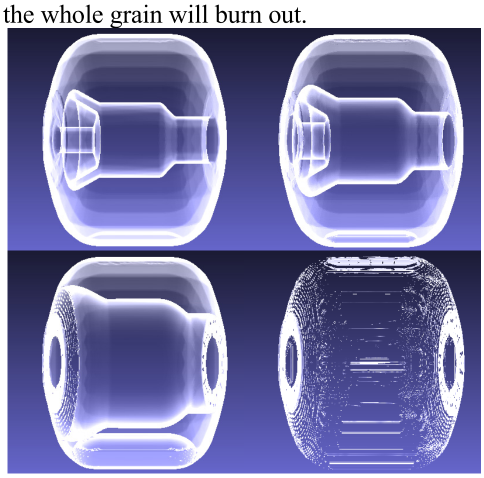

Figure 6. Simulated X-Ray regression consequence

The experimental platform is equipped with Intel Core I3 M330 processor, Windows 7 OS. And two different resolutions are given for the same grain in Table I.

TABLE I. Performance at Different Resolutions

Case	*Grid resolution*	*Reconstruction resolution*	*Total time(s)*
1	50^3	50^3	0.067
2	100^3	100^3	0.5

From Table I, obviously our method is fast even including the rendering time. Here the geometry is rendered in simulated X-Ray to display the internal structure progress, which is implemented with OpenGL Shading Language.

Fig.7 gives the regression curve of the burning surface area to web. To verify our method's effectiveness, our method is compared to the geometry method[7] with 100^3 and 50^3 two resolutions, while the later one is thought as the accurate result. It is found that two methods can get very close results except the end of the curve because of the number of finely triangles increasing. But with the increasing of resolution, our method will be closer to the accurate result. However our method is more flexible and extendable.

IV. CONCLUSION AND FUTURE WORK

In this paper we present an effective and efficient framework to simulate SRM grain regression with combustion. With level set used to track the burning surface, our method is robust and suitable to any shapes of SRM grain without any requirement for the model.

To accelerate the computation, we constrain the computation to the narrow band around the interface with fast marching technique. So we can achieve interactive or even real-time performance for the combustion simulation. The experimental results prove our method.

In the future, we would like to investigate the coupling between the SRM grain combustion and internal fluid simulation. And we will also improve the precision of our method further.

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REFERENCES

[1] R.Hartfield, R.Jenkins, J.Burkhalter, "A review of analytical methods for solid rocket motor grain analysis". AIAA-2003-4506,2003.

[2] G. Liang, H. Wang, "Generalized Shape Simulation Method of Three Dimensional Grain Geometry", Journal of Propulsion Technology, 1991(03), pp.26-35. (in Chinese)

[3] X. Wang, J. Yang, "Generalized Grain Simulation Method-Volume Element Method". Journal of Propulsion Technology,1988 (4), pp.26-30.

[4] W. Xiong, Y. Liu, J. Ren, X. Zhang, "Generalized Burning Surface Calculation of Three Dimensional Propellant Based on Element Method", ACTA Aeronautica Et Astronautica Sinica, 2009, 30(7), pp.1176-1180. (in Chinese)

[5] X. Yan, S. Yu, Q. Wang, "The solid modeling technology and the grain-burning-area calculation", Journal of Solid Rocket Technology, 2003 26(2), pp.20-22. (in Chinese)

[6] S. Yu, R. Zhao, H. Zhou, Z. Guo, "Burning area regression simulation and calculation of solid rocket motor grains based on Pro/E feature modeling technology", Journal of Solid Rocket Technology, 2005, 28(02), pp.108-111. (in Chinese)

[7] Q. Cai, F. Bao, "Grain design of solid rocket motor based on ACIS geometric modelling platform", Journal of Solid Rocket Technology, 2008, 31(3), pp.236-242.

[8] X.Wang, T. L. Jackson, L.Massa, "Numerical simulation of heterogeneous propellant combustion by a level set method". Combustion Theory and Modelling, 2004, 8(2), pp.227-254.

[9] F. Qing, "Method Research for Burning Surface Calculation Of Solid Rocket Motor With Complicated Grain", Northwestern Polytechnic University, Master Thesis, 2003.(in Chinese)

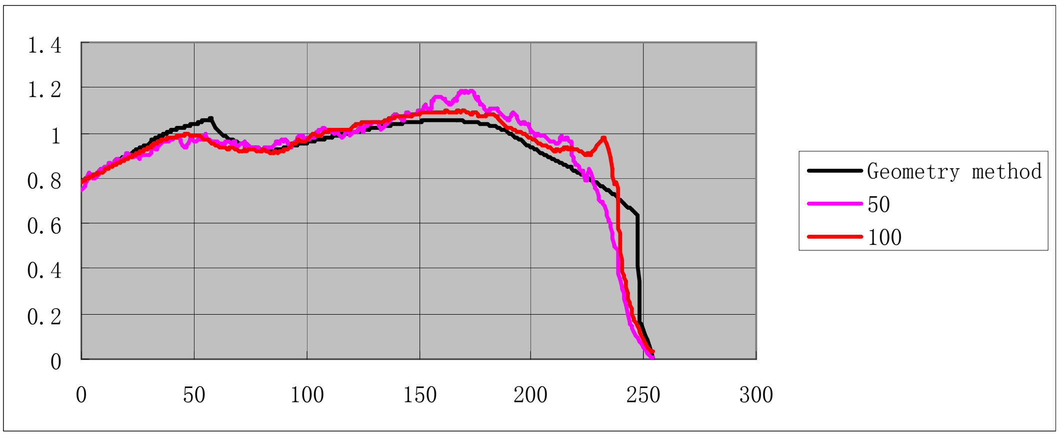

Figure 7. The regression curve of burning surface area to web