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Study on dynamic numerical simulation of string damage rules in oil-gas well perforating job

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Abstract

The technologies of high charge perforator and high density perforator are widely used in domestic and international oil-gas wells perforating job, which leads to the increase of the explosion load intensity, resulting in more string damage accidents, and seriously affects the normal production of oil and gas. The software of LS-DYNA was used to measure the dynamic response of the perforating gun under four types of perforation conditions. It analyzes perforating gun head's forms and characteristics of output load under different working conditions, and also analyzes the impact on perforating gun's structural strength under different axial and radial load. These conclusions provide an important theoretical reference for reasonable arranging the perforating technology, improving perforation safety and reducing the well perforating accidents.

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Keywords: Perforating operation; the dynamic response under explosionimpact; torsion effect; the numerical simulation;

1. Introduction

In perforating job, the main reason of string system shake, variant and even be damaged is the overload impact by-the gun explosion. Because of the shell effect of perforating charge, the pipeline effect of perforating gun and the impact wave coupling effect of multipoint explosion, perforated interval shock wave loading rules and string dynamic response rules become extremely complex[1]. We will experience a huge workload, a long test cycle and a

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high test cost if we use the method of experiment to analyze the explosion impact load characteristics and forms of gun head under different working conditions of perforation in the output. In addition to that, the existing test methods neither fully access to oil well string under explosion impact dynamic load information, nor accurately reflect the stress of the pipe string structure movement.

Using the finite element simulation software through the simulation calculation of mature is efficient to solve such problems. This paper is using grid generation pretreatment software-True grid, numerical simulation software-ANSYS/Ls-dyna and the LS - repost post-processing software. By using the finite element method and thought in the process of perforating job to study of dynamic response process under explosion impact, building specialized applications in explosion impact numerical computation model of dynamic response analysis, forming a set of effective calculation method. Using numerical simulation calculation, to get the output of the explosion impact load characteristics and superimposed enhancement pattern under different perforation phase and number of ammunition work conditions. It will provide an important theoretical reference for reasonable arranging the perforating charge and improving perforation safety.

2. Oil perforating model

2.1. Division of the model structure

Perforating job systems including perforating charge, barrel and string. The air stays inside the barrel and the drilling fluid stays outside. Perforating charge includes three components, liner, charges and case. Barrel and string are tubular structure, but perforating charge body is tapered structure[2]. The structure is shown in Fig. 1.

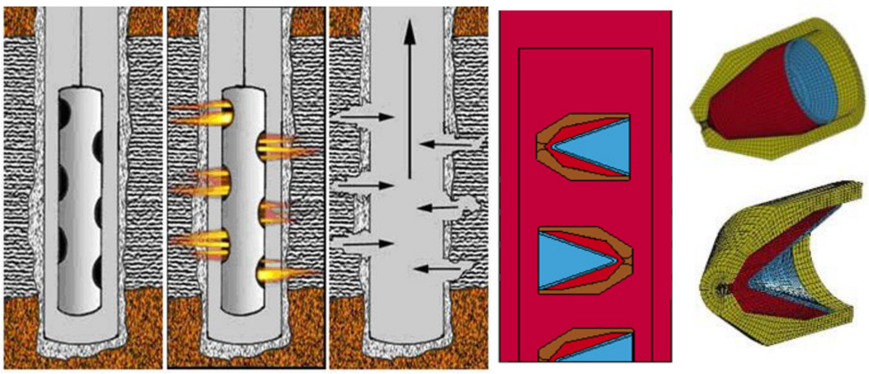

Fig.1. Perforating process and charge structure.

In modeling, in order to effectively capture the movement and deformation of the construction of the material, and to ensure energy between the partial grid effective transmit, we must ensure that each part of the material on the joined interface has the common mesh node; While we also need to make sure the interface shape of each part of the structure, thus we found the meshing the fluid region model is more complex. The grid structure of junctions which in two adjacent perforating charge is shown in Fig. 2.

Drilling fluid and air were filled in casing and barrel, so the mesh model fluid field structure is in a tubular structure or in vertical cylindrical. Charge and liner are in horizontal cone-shaped structure. To ensure that the material boundaries of the mesh have common nodes, we are required to make the upward air drilling fluid grids, charge and liner cover in the same horizontal cylindrical grid model.

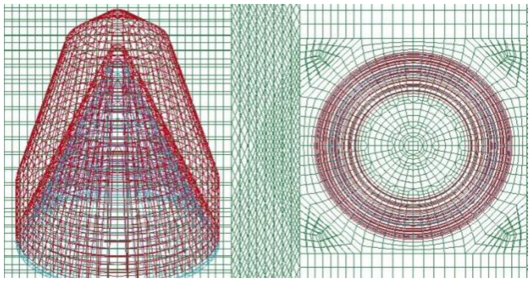

Fig.2. Charge in the air domain model.

2.2. Material models and methods of computation

In the perforating charge, the liner and air field are fluid material in the model, and they are defined as the ALE unit algorithm; barrel and shell of perforating charge is using Lagrange unit algorithm. Charge of Perforating charge as HMX, using MAT-HIGH-EXPLOSIVE-BURN high explosive burning material models, and JWL equation of state to describe, the air using MAT_NULL material models and LINEAR_POLYNOMIAL linear polynomial equation of state, shell of perforating charge and barrel are using MAT_PLASTIC_KENEMATIC kinematic hardening model to descript.

Finally the complete simulation model is input to the Ls-dyna program in the form of k file. The simulation modeling process is the process of editing and improving the k file. K file simulation model parameters are defined by keywords. By using the keyword * INITIAL_DETONATION", we can figure out the explosive detonation point and initiation time. By using the keyword *ALE_MULTI - MATERIAL_GROUP", we are able to define the material of fluid field grids which can flow in each other. The fluid material includes explosive, liner and air in this simulation model. By using the keyword *CONTACT_ERODING_SURFACE_TO_SURFACE, we can define the erosive face to face contact algorithm. The contact between barrel and fragment that formed after charge detonated is defined. We can use the keyword *CONSTRAINED_LAGRANGE_IN_SOLID and *SECTION SOLID ALE to define the fluid-solid coupling.

2.3. Calculationofworkingcondition

Simulation calculation for the barrel and charge is type 127, set up 60 degrees phase of 1, 2, 4, 5 and 10 medal charge simulation model. Perforating charge use 16/m arranged density, string size is $\emptyset 12.7 \times 60 \times 1.1$, and single charge weight is 45g. The cm-g-μs units system is adopted to establish the calculation model.

3. Analysis of computing result

3.1. Number of ammunition influence on the peak load output of gun head

Fig. 3 and Fig. 4 show 60 degrees perforation phase, the number of ammunition are 1, 2, 5, 10 respectively, under the four conditions of gun head on the x, y, z three directions of the maximum overload peaks.

From the graph, with the increase of perforating charge in gun, the load peak of gun head output is approximate linear growth. In this situation, when the number of ammunition is same, z axis overload peak is higher than x, y, two directions of overload. If we change the graph into ladder diagram, and we can visually see the different loaded quantity and directions on peak are obviously contrasting the differences of overload.

Also, this paper makes research on the quantity have influence on overload peak on three directions, abscissa will changed from the number of ammunition to axis. It can be seen from the diagram that in the process of the perforating, the stress of the gun in the x, y plane is not balanced. Under 60 degrees perforation phase, overload peak of gun in the y direction is reaching the minimum.

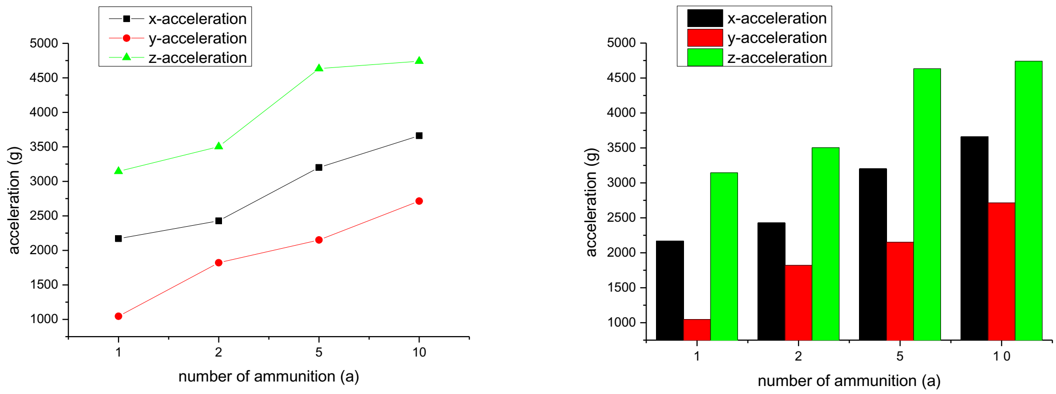

Fig.3. Load curve of gun head in three directions under different number of ammunition conditions.

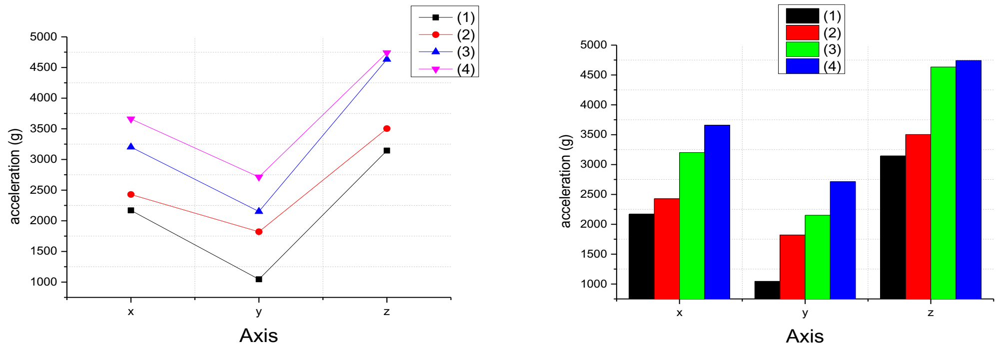

Fig.4. Load curve of gun head under different number of ammunition conditions in three directions.

3.2. Number of ammunition influence on structural strength of string

For oil well string, under the explosive load and its own gravity, its load of form is effect by axial force and lateral force (including shear and torsion force). Under the action of axial force, the main failure form of string is to be pulled or crushed, at this point, the force of string on the interface achieve its tensile or compressive strength condition; when the transverse force of string achieve its torsional strength or shear strength condition, torsional deformation and bending fracture of string occurred.

Because the string is placed within the wellbore, the maximum unilateral radial direction displacement of the gun is less than 100 mm, and because the perforation string is hanging in wellbore, the biggest radial direction displacement is not enough to cause string shear fracture and deformation. Therefore, we only need to consider the influence of perforation string axial forces.

In view of the string of axial tension and compression, on formula:

$$\sigma = \frac{F}{A} \tag{1}$$

we can find out the gun body stress curve of axial direction under four kinds of conditions, the positive one means gun head has a tensile stress, and negative one means compressive stress. Table 1 shows the tensile stress (positive) and compressive stress (negative) of gun head under four kinds of conditions.

Table 1. Load of the gun head under four kind of condition.

Number of ammunition（a）	1	2	5	10
Maximum tensile stress (MPa)	171.42	141.9	208.7	248.3
Maximum compressive stress (MPa)	138.43	189.3	255.3	266.7

From the table, we can see a single charge explosion in the cross-section of gun head forms the tensile and compressive stress. When the steel is under compression, with the increase of stress deformation is forming and final failure mode is shear failure, rather than under tension with obvious yield point. Therefore, there are no compressive strength physical properties in the steel material. In general, the allowable compressive strength of unquenched steel could similarly regarded as tensile and compressive strength.

With the increase of charge quantity, explosion impact load on the gun with the axial direction of tension and compression stress are increasing accordingly. The compressive stress in string is higher than tensile stress.

In actual perforating job, the tensile strength of the string material σ_s (MPa)：≥700, from table 1 it can be found that in less than ten charges, explosion in an instantaneous produces tension and compression stress is not enough to make the material of string occur yield deformation.

3.3. Explosion impact on the structure of torsional shear effect

In the process of the asymmetrical explosion, the spiral distribution of cyclic impact load in the gun head, it made the gun body cause obvious torsional or shear effect, the torsional and shear effect acted on perforating gun head and transferred it to the string, because the entire string reached hundreds or thousands of meters, the torsional and shear effect in the process of delivery will be amplified, eventually the regional area of string form relatively strong torsional stress concentration, and it caused material of string structural strength failure.

In order to further study about the cyclic multipoint explosion dynamics for torsional or shear load of string system, we also select the acceleration curve of typical node which in the perforating gun's end to analyze, Fig.5 shows three nodes on respectively symmetrical both sides of the yz plane in the end of the barrel on the X direction. Figs. 6–9 shows the comparison of the acceleration curve of typical node group.

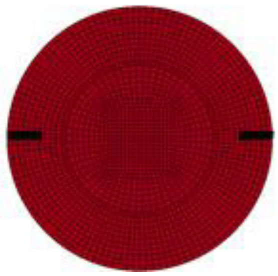

Fig.5. Typical symmetric nodes on the yz plane(black points)

Fig. 6 and Fig. 8 give the acceleration curve trend of single node group, we can obviously find such curves with the same cycle and phase, but different amplitude. It shows the string's axis of symmetry nodes are on the same side movement trend.

In the condition of the phase periodic arrangement of perforating charge in perforating gun, the explosive charge system form cyclic side direction load will integrate torsion and shear vibration around the axis of string, the vibration coupling with the axial impact and radial asymmetric impact on the string system, it will be easier to make the string system produces serious distortion and even damage fracture.

Fig. 10 and Fig. 11 give the acceleration curve trend of the lateral pair of symmetric nodes, we can obviously find such kind of curves have the opposite phase, but the same cycle and amplitude. This means, on both sides of the material node is always characterized by torsional vibration around the axis of symmetry.

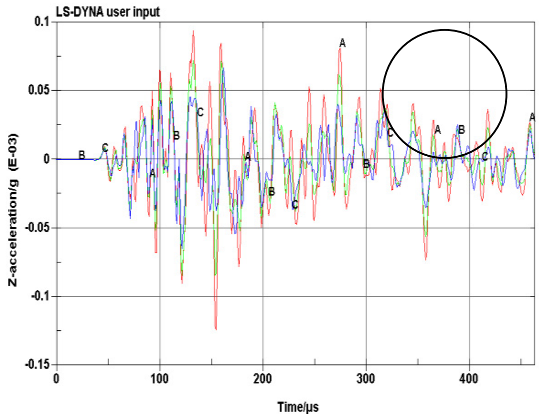

Fig.6. The z direction acceleration on the left side of the three nodes.

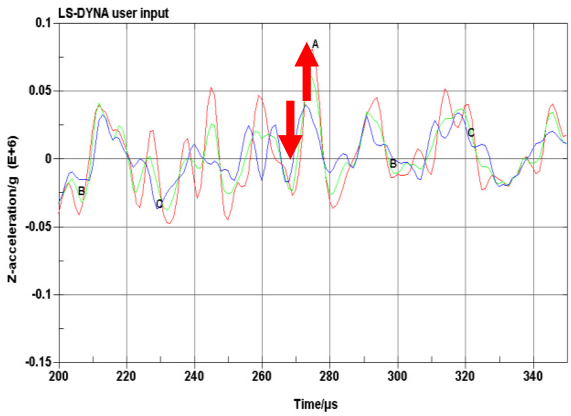

Fig.7.The enlarged locally curve ofthe z direction accelerationon the left side of the three nodes

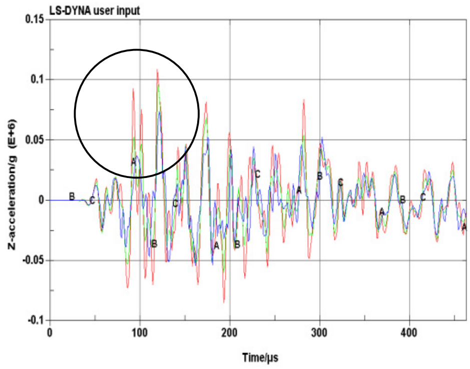

Fig.8.The z direction acceleration on the right side of the three nodes

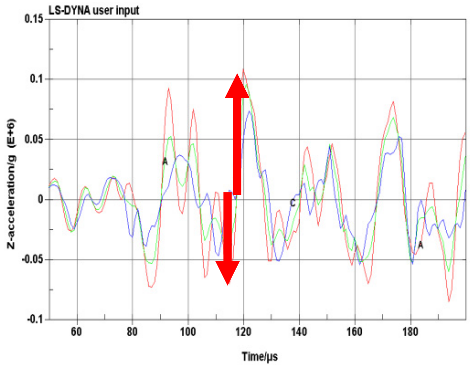

Fig.9. The enlarged locally curve of the z direction acceleration on the right side of the three nodes

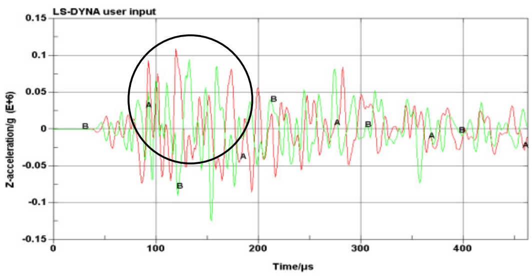

Fig.10. Comparison in the lateral pair of symmetric nodes' acceleration on the yz plane

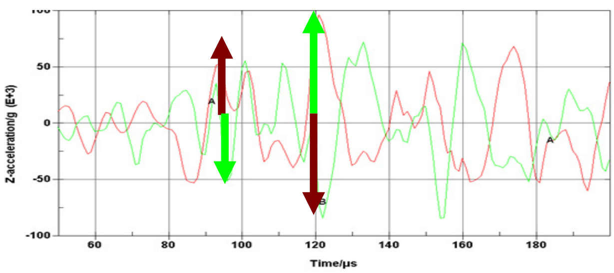

Fig.11.The enlarged locally curve of the acceleration.

Fig. 12 and Fig. 14 give the acceleration curve trend of the up and down on both sides nodes, the law of the curves are same as on both sides. It shows that in the condition of the phase periodic arrangement of perforating charge in perforating gun, the explosive charge system form cyclic side direction load which integrated torsion and shear vibration around the axis of string, the vibration coupling with the axial impact and radial asymmetric impact on the string system, it will be easier to make the string system produces serious distortion and even damage fracture.

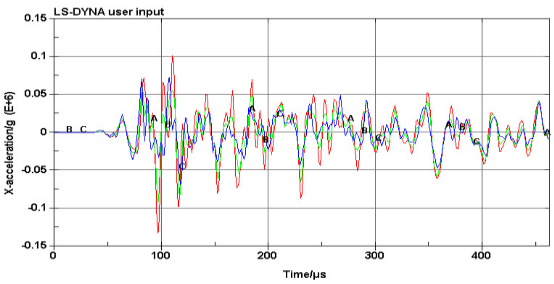

Fig.12.Comparison in a set of typical upper nodes' acceleration on the yz plane

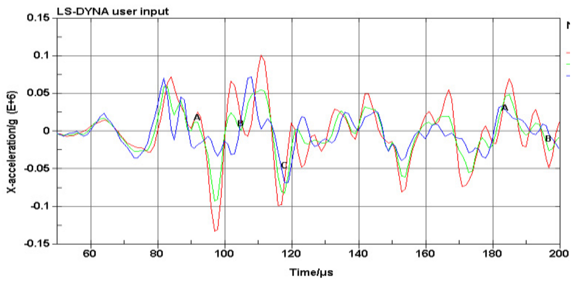

Fig.13. The enlarged locally curve of the acceleration.

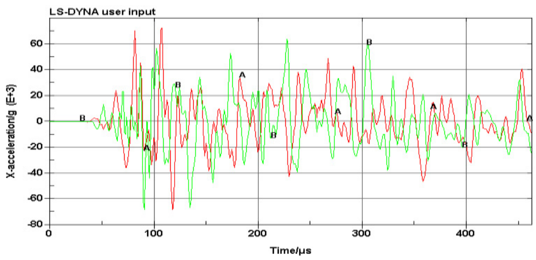

Fig.14. Comparison in up and down on both sides of a typical nodes' acceleration on the yz plane.

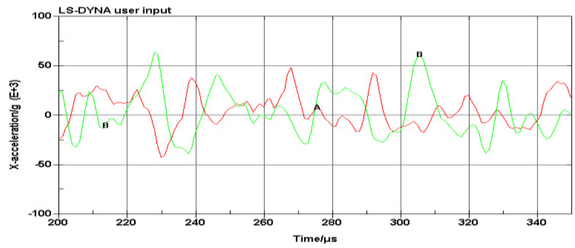

Fig.15.The enlarged locally curve of the acceleration

3.4.The effect of torsional on structural strength

The explosion impact form torsional or shear effect on the oil well string characterized by the changed strength of the structural material, when the torsional stress in cross section of string reached at the maximum allowable shear stress can cause the failure of the strength of the structural[3].

The strength of a circular shaft：

$$\tau_{max} = \frac{T_{max}}{W_t} \ll [\tau] \tag{2}$$

From the formula, the maximum torque corresponds to the maximum shear stress. If we treat the oil well string as a thin-walled circular tube, we can think along the thickness of the wall shear stress is constant, and since they are exactly the same at various points on the same circumference of a circle, they should be with the same stress. Aimed at 60 degrees numerical calculation model under different working condition of charge quantity, we can extract the infinitesimal of maximum shear stress on outer ring of gun head (the same as the tubing cross section size), under different working conditions, we can compare the maximum shear stress on the section of oil well string whether it satisfy strength conditions. The maximum shear stress under different working conditions is shown in table 2:

Table 2. The maximum shear stress under different working condition (MPa).

Number of ammunition	one	two	five	ten
τ_{max}	36.58	40.87	43.46	47.18

As can be seen from the table, the maximum stress of the cross section is no more than 70 MPa under four kinds of working conditions, and it is far less than the allowable shear stress of material (more than 700 MPa). However, with the increase of the number of ammunition, the shear stress on cross section of the gun body also increases therefore, the number of ammunition need to be controlled in a certain range in order to ensure the strength condition of string.

4. Conclusions

Based on 60 degrees phase arrange perforating charge, using grid generation pretreatment software- True grid, numerical simulation software-ANSYS/Ls-dyna and the LS-repost post-processing software. Finally we get the output of the explosion impact load characteristics and superimposed enhancement pattern under different perforation phase and number of ammunition work conditions, end up with output load law of explosion impact load, and the conclusions are as follows:

(1) With the increase of charge quantity, explosion impact load on the gun with the axial direction of tension and compression stress are increasing accordingly, the compressive stress in string is higher than tensile stress. In actual perforating job, the tensile strength of the string material σ_s (MPa)：≥700, so it can be found that in less than ten charges, explosion in an instantaneous produces tension and compression stress is not enough to bend deformation of string material.

(2) The maximum stress of the cross section is no more than 70 MPa under four kinds of working conditions, and it is far less than the allowable shear stress of material (more than 700 MPa). However, with the increase of the number of ammunition, the shear stress on cross section of the gun body also increases therefore, the number of ammunition need to be controlled in a certain range in order to ensure the strength condition of string.

(3) In view of actual perforating job, by using the existing model with specific design and calculation, we can get the forms and rules of charge explosion output load as well as the damage deformation of string, thereby we can conduct an oil well string prediction and a safety assessment. On this account, it provides an important theoretical reference for reasonable arranging the perforating charge, improving perforation safety and reducing the well perforating accidents.

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