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MODELLING AIR PERFORATORS FOR SERVICEABILITY

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Perforating is important to oil and gas production. It is accomplished by detonating a plurality of shaped charges packaged inside a sealed tubular carrier of the perforating gun run into an oil or gas well. While the metallic jets generated from the detonated shaped charges create passages for oil or gas flowing from reservoir into well, the detonation may also cause damage or swell to the carrier in addition to the perforated holes. A split or over-swollen carrier will be stuck inside the well. It will obstruct production and is commonly regarded as a catastrophic failure. Therefore, it is necessary to have a reliable method to accurately predict the post-detonation conditions of the carrier before a perforating job is carried out. In this paper, we developed an energy based model to simulate the swell of perforator carriers after service used for gas wells. A serviceability or failure criterion was proposed and verified by both computational and experimental results. The model and serviceability criterion yield very good results consistent and confirmed to the data collected by laboratory tests.

INTRODUCTION

Oilfield Perforator

An oilfield perforator or perforating gun consists of shaped charges, jackets (charge holders), loading tube, tubular carrier, and adapters (upper and lower). The shaped charges are packaged inside the loading tube and arranged in certain patterns for different perforating objectives. The carrier and adapters work together to isolate the shaped charges from the downhole environment. A detonating cord connects the shaped charges and fires them sequentially. The jet formed by the charge will perforate through its carrier, wellbore, casing and formation as shown in Figure 1.

There are many kinds of oilfield perforators. In this paper, we focus on the most popular one – continuously phased air or gas perforator. Shaped charges in a continuously phased perforator are angularly distributed inside their carrier at a given angular interval and given shot density in longitudinal direction. A gas perforator can be used to work in gas wells as well as oil wells. For our concerns in this study, the wellbore medium indicated in Figure 1 is "air" specifically.

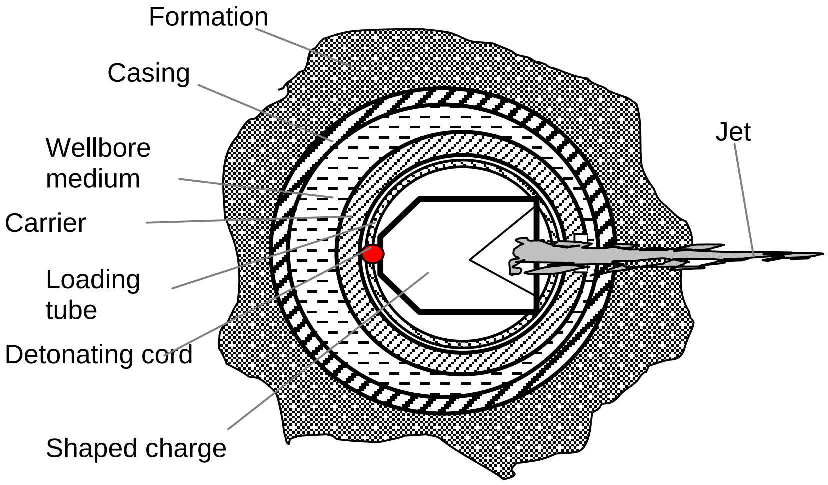

Figure 1. Schematic of a Typical Oilfield Perforator Used in Downhole

Explosives

The shaped charges can be made of different explosives to cope with different elevated downhole temperatures. The most commonly used explosives are RDX, HMX and HNS. HMX is the most powerful of these high explosives. If a perforator survives HMX shaped charge detonation, it should survive other explosive charges such as HNS given the same amount of explosive loads. Both HMX and HNS charges are discussed in this paper.

Perforator Serviceability

Interactions of different components inside a perforator and damage mechanisms of oilfield perforators were discussed by Grove, *et al* [1]. For continuously phased and gas or air perforators, the major damage to the carrier after detonation is swell or cracks due to high velocity impact by fragments from shaped charges in addition to the perforated holes. A serviceable gas or air perforator should not only successfully perform the perforating job but also result in no substantial damages in its carrier. An over-swollen carrier may become stuck or too large to be removed through a restriction.

The impact process inside a perforator due to shaped charge detonation is extremely complicated. In this paper, we take a simpler approach and establish a global analytical model based on energy conservation to predict the swell of continuously phased oilfield perforators for gas well applications. Such a model can be used for survivability or serviceability management before a perforating job is conducted.

MATHEMATIC MODEL OF SWELL

Assumptions

The detonation of oilfield perforators is a complicated process. For simplicity, we assume continuously phased perforators as follows:

- Explosion and interaction of different components inside perforators are axially symmetric, adiabatic and instantaneous;
- Deformation of perforator carrier is uniform in both radial and hoop directions;
- Interference and effect of the exit hole made by the jet in the carrier are negligible;
- Boundary effect from casing or adjacent shaped charges is negligible.

Under these assumptions, we used the principle of energy conservation and established a concise mathematical model to predict swell or permanent deformation of perforator carriers based on one charge. Explosive energy is conserved by kinetics, deformation, heat, thermal expansion or compression work and shock energy, which are discussed in the following sections, respectively.

Kinetic Energy, W_k

Kinetic energy involves the jet, case, loading tube, carrier as well as the explosive product. Kinetic energy of the jet was dealt with separately from other parts. The latter were lumped up in one. The total kinetic energy can be expressed as

$$W_k = W_{k,j} + W_{k,\Sigma} \tag{1}$$

where $W_{k,j}$ is kinetic energy of the jet; and $W_{k,\Sigma}$ is combined kinetic energy of case, loading tube, carrier and explosive product.

Kinetic Energy of Jet, $W_{k,j}$

Applying Gurney formula [2] to shaped charge jet, we found the jet kinetic energy

$$W_{k,j} = \frac{1}{2} k_{v,j} m_j G^2 \left(\frac{1}{m_j / m_e + f} \right) \tag{2}$$

where $k_{v,j}$ is constant for a given explosive, ranging from 1 to 1.6; m_j is the mass of the jet; G is Gurney energy; m_e is the mass of the explosives; f is a geometrical factor, equal to 0.33.

Other Kinetic, $W_{k,\Sigma}$

In the same way, applying the Gurney formula to charge case, loading tube and carrier as a whole, we got the kinetic energy of charge case, loading tube, carrier as well as detonation product

$$W_{k,\Sigma} = \frac{1}{2} k_{v,\Sigma} \left(m_c + m_t + m_g + \frac{1}{2} m_e \right) G^2 \left(\frac{1}{(m_c + m_t + m_g + \frac{1}{2} m_e) / m_e + f'} \right) \tag{3}$$

where $k_{v,\Sigma}$ is constant for a given explosive, ranging from 0.9 to 1.0; m_c is the mass of the charge case; m_t is the mass of the loading tube per charge; m_g is the mass of the carrier per charge; m_e is the mass of the explosives; f' is a geometric factor, equal to 0.5.

Deformation Energy, W_d

We took into account both elastic and plastic deformation energies, but neglected the deformation energy to collapse the liner for jet because of its relative low mass. Assuming that the charge case, loading tube and carrier are made of elastic-perfectly plastic materials, we found deformation energy [3], W_d as

$$\begin{aligned} W_d = {} & \frac{1}{2} \left(\frac{m_c \sigma_{Y,c}^2}{E_c} + \frac{m_t \sigma_{Y,t}^2}{E_t} + \frac{m_g \sigma_{Y,g}^2}{E_g} \right) + \\ & + \frac{2}{\sqrt{3}} \left[\frac{m_c \sigma_{Y,c}}{\rho_c} \ln\left(\frac{R_c}{R_{c,0}} \right) + \frac{m_t \sigma_{Y,t}}{\rho_t} \ln\left(\frac{R_t}{R_{t,0}} \right) + \frac{m_g \sigma_{Y,g}}{\rho_g} \ln\left(\frac{R_g}{R_{g,0}} \right) \right] \end{aligned} \tag{4}$$

where m is mass; σ_Y is yield strength; E is Young's modulus; and ρ is density. Subscript "*c*" represents shaped charge case; subscript "*t*" represent loading tube;

subscript "*g*" represents carrier; and subscript "*0*" represents initial state; $R_c/R_{c,0}$ equals to 1.1; R_t relates to R_g with the difference of the carrier tubing thickness.

Thermal Work, W_T

Let's assume the gaseous product behaves as ideal gas. Referring to the relationship between detonation pressure and detonation energy and neglecting the ambient effect, we found the thermal work done as

$$W_T = m_e \left(\frac{r_0}{r} \right)^{2(\gamma-1)} Q \tag{5}$$

where r_o is the initial radius of the explosive charge assuming it is solid and in spherical shape; r is the radius of area swept over by particles of explosion product, equal to R_t as in eq. (4); Q is detonation energy, known for a given explosive [4,5,6].

Shock Energy, W_s

For strong shock, we found the shock energy [2] outside of perforator carrier as

$$W_s = \pi \rho_{a,0} l \frac{\alpha R_g^2 - R_{g,0}^2}{\alpha - 1} G^2 \left(\frac{1}{(m_c + m_t + m_g + m_e)/m_e + f'} \right) \tag{6}$$

where $\rho_{a,0}$ is initial density of medium (air); l is the length of the carrier per shot or per charge; and $\alpha = \frac{\gamma'+1}{\gamma'-1}$; γ' is ratio of specific heat of medium (air).

Energy Conservation

Energy released by the explosive charge, called detonation energy, Q is conserved by the energies discussed in the previous sections, and can be expressed as

$$F(R_g) = Q - (W_{k,j} + W_{k,\Sigma} + W_d + W_T + W_s) = 0 \tag{7}$$

where Q is known to a given explosive; $W_{k,j}$ and W_{kS} can be found from eq.s (2) and (3), and are independent of R_g. W_d, W_T and W_s, as expressed in eq.s (4) through (6), are functions of $R_{g,}$ which is the only unknown. Hence, the permanent deformation of perforator carriers can be readily solved by eq. (7).

MODEL VALIDATION

A variety of air perforator designs were examined. They ranged in diameter from 2.00 inches to 4.50 inches. A number of shaped charges were investigated containing either HMX or HNS explosives. Final or swell OD (outer diameter or $2R_g$) of perforator carrier was predicted using the model. Sample perforators were built and test fired in air. Their maximum final diameters were measured.

The results are plotted in Figure 2 and show good agreements of the final ODs from the model ("Model") and laboratory tests in air ("Test") for perforators with either HMX or HNS explosives, respectively. Each datum point in the figure corresponds to a specific size of perforator, shown by its original OD in the horizontal axis. Detailed information of the final OD is also listed in Table 1. The errors of the modeled final ODs to the tested final ODs are almost negligible. For the six perforators with HMX explosives, the error is no more than 2.8mm, while no more than 0.8 mm error is found for the four perforators with HNS explosives. Table 1 also shows the survivability of the perforators in air test based on criteria presented by Grove *et al* [1]. Final ODs from air test are meaningless if perforators do not survive air test, therefore, they are not available in the table.

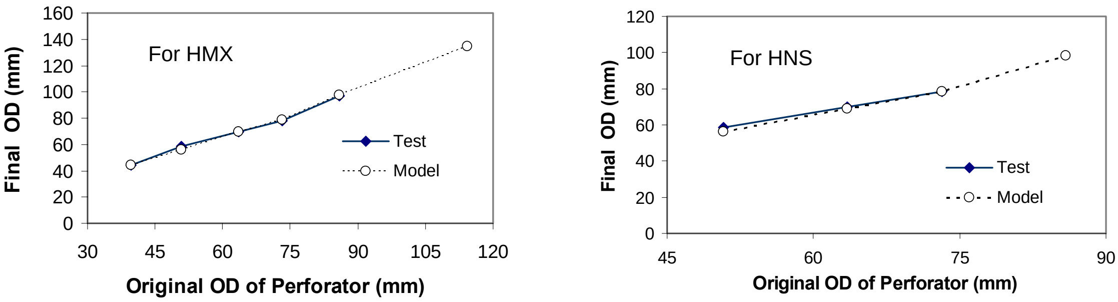

Figure 2. Comparison of Computed Final OD and Test Data for Perforators Detonated in Air

PERFORATOR FAILURE CRITERION

Oilfield services require oilfield perforators that are not split or over swollen after detonation. The latter can be resolved by models shown in previous sections, while the former deserves further discussions. We compared the model and test results with the expansion of the perforator carrier at given radial expansion rates, and found a good correlation to the survivability or serviceability of perforators. Typical elongation of the material of perforator carriers is at about 16%, which provides us a good reference to the swell limit that a perforator can undertake before it fails.

Table 1. Final ODs of Perforators from Test and Model

Perforator	Original OD (mm)	(A) Final OD by Test (mm)	(B) Final OD by Model (mm)	|(A)-(B)| (mm)	Remark*
1.56-in HMX	39.6	44.5	44.2	0.3	Air Survivable
2.00-in HMX	50.8	58.7	55.9	2.8	Air Survivable
2.50-in HMX	63.5	69.9	69.6	0.3	Air Survivable
2.88-in HMX	73.2	78.2	79.0	0.8	Air Survivable
3.88-in HMX	85.9	96.8	97.3	0.5	Questionable
4.50-in HMX	114.3	--	134.4	--	Not Air Survivable
2.00-in HNS	50.8	56.1	55.9	0.3	Air Survivable
2.50-in HNS	63.5	69.9	69.6	0.3	Air Survivable
2.88-in HNS	73.2	78.2	79.0	0.8	Air Survivable
3.88-in HNS	85.9	--	97.3	--	Not Air Survivable

* As determined by criteria discussed in [1].

Figure 3 shows the OD expansion percentages by the model against the presumed ones when the average diameters of OD and ID are expanded at 16% and 18% for perforators with HMX and HNS explosives, respectively. Vertical axis, ΔOD/OD represents the OD expansion percentage of perforators.

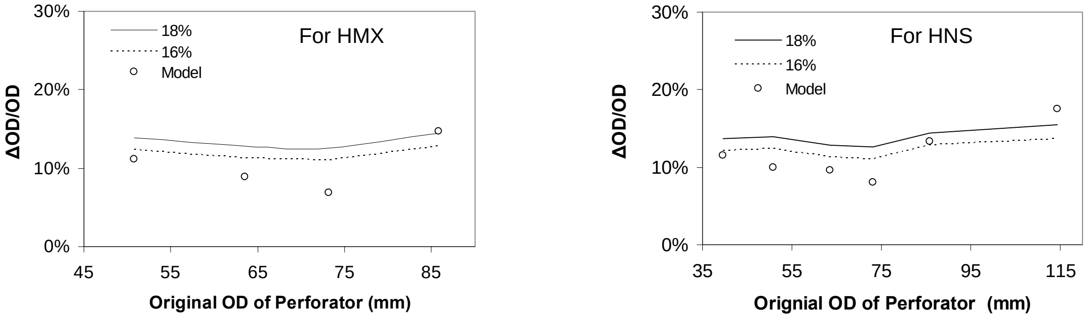

Figure 3. OD Expansion Percentages of Perforators after Detonation in Air by Model and Presumption

With the results presented in Table 1 and Figure 3, we proposed a criterion of serviceability or survivability for the examined oilfield perforators as follows:

- Serviceable if ΔOD ≤ 16% original OD.
- Questionable if ΔOD < 18% original OD but > 16% original OD.

- Non-serviceable if ΔOD ≥ 18% original OD.

Above service criterion serves the studied perforators very well and can be used together with the swell model for swell modeling and serviceability prediction.

CONCLUSIONS AND FUTURE WORK

An energy-based analytical model to predict perforator swell in gaseous environment has been derived; an expansion-based failure criterion for the perforator has been defined. The predicted results by the model have been confirmed with the test data. The conclusions and the projected future research work are as follows:

1. The mathematical model predicts the swell of oilfield perforators well for applications in air or air equivalent environments for various sizes, continuously phased and HMX shaped charges
2. The model also yields accurate results of the swell for continuously phased perforators with HNS charges used in air or air equivalent environments.
3. A serviceability criterion has been developed by analyzing swell data for a real family of perforators.
4. The model can be used to predict swell of new perforators and help determine whether or not they will be serviceable.
5. Further work needs to be done for oilfield perforators used in environments other than air or gaseous applications. The model can be further fine tuned with inclusion of downhole environmental conditions such as temperature and pressure.

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