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Simulation of the vibration load impact on the powder charge consisting of granulated powder elements

The paper focuses on the vibration load impact on the formed powder charge consisting of granulated powder elements. The purpose of the study is to develop a model that takes into account the compaction of the powder charge and mixing of the powder elements under the action of vibration loads.

Keywords: porosity of powder charge, powder charge formation, powder elements, vibration loads, shock loads.

Nowadays, the gas-dynamic approach is widely used to calculate intraballistic characteristics during firing. In many works devoted to firing process simulation based on this approach, porosity of the powder charge is assumed to be the constant value for the whole charge volume at the beginning of computation [1–3].

Porosity is the void volume in the unit of volume occupied by powder elements. It is assumed that granulated powder elements are uniformly distributed within the entire volume behind the shot. Such an assumption does not comply with real processes observed during firing; that is why a model simulating the formation of a powder charge consisting of granulated powder elements was developed with account for non-uniform distribution of powder elements along the charge length [4]. The developed model allows to simulate the falling of individual powder elements when the shell is filled with powder. At that, force interactions between elements, as well as the motion of falling powder elements along the side surfaces of the formed powder volume are taken into account (“falling” of charge). Thus, numerical simulation results in the formation of a powder element with non-uniform distribution of powder elements along the length.

When filling the shell with granulated powder elements, various devices are often used to increase the filled density of the shell with powder (i.e. to decrease porosity). The design of such devices is based on the generation of oscillations with a certain amplitude and frequency that are transmitted to the shell and to the powder elements inside. Oscillations make powder elements move; as a result, the volume of air spaces is decreased inside the volume filled with powder. The generated oscillations most often act in the longitudinal direction (i.e. along the shell axis) and make powder elements follow this vector as well. Movements perpendicular to the shell axis are also possible, but they are much less important in the process of redistribution of powder elements inside the shell. Besides, during storage, transportation, and multiple relocations shells are exposed to shock loads that lead to redistribution of powder elements inside the shell as well. Thus, the impact of shock and vibration loads on the shell is an important factor affecting the porosity of powder charge. That is why, we developed a simulation model with account for the vibration load impact on the formed powder charge.

Two processes take place due to exposure of the shell and powder elements to oscillations. First, the volume occupied by the mass of powder elements inside the shell reduces, which means porosity decreases. Second, certain equalisation of porosity takes place within the entire shell volume filled with powder. Both processes are interrelated and occur due to transfer of powder elements from the areas with low porosity values to the areas with high porosity values, i.e. to the areas with a larger void volume.

When simulating the impact of vibration loads on the shell, in order to simplify computations, it was assumed that both processes – reduction of the volume occupied by the mass...
of powder elements inside the shell and porosity equalisation – occurred independently of each other. Therefore, the entire computation process is divided into two stages: at the first stage porosity values are corrected to take into account a change of the volume occupied by the mass of powder elements inside the shell while the porosity distribution along the shell length remains unchanged. At the second stage, the porosity distribution along the shell length is corrected.

To estimate the extent of porosity reduction as a result of vibration load impact (first computation stage), value $K_y$ was used:

$$K_y = \frac{V_y}{V_0},$$

where $V_y$ – volume occupied by the powder element inside the shell with account for vibration load impact;

$V_0$ – volume occupied by the powder element inside the shell after it is filled by powder, but with no account for vibration load impact.

Factor $K_y$ is the value reciprocal of compaction factor $K_{y\text{mat}}$ which is used to estimate the compaction of loose substances exposed to shock and vibration loads [5]:

$$K_y = \frac{1}{K_{y\text{mat}}},$$

Factor $K_{y\text{mat}}$ is determined for various types of loose materials based on experimental data.

Volume $V_y$ occupied by the powder element after vibration load impact is calculated as follows:

$$V_y = K_y V_0.$$  \hspace{1cm} (1)

When simulating the formation of a powder charge, the filled volume was divided into layers by horizontal cross-section, and porosity value $m_i$ ($i$ – layer number) was calculated for each layer. The number of layers $n$ (Fig. 1) can be calculated as follows:

$$n = \frac{4V_0}{\pi D^2 h},$$

where $D$ – diameter of filled volume;

$h$ – spacing along the cylinder axis (layer height).

\[ \begin{array}{c}
\text{Fig. 1. First computation stage diagram:} \\
\text{D – diameter of filled volume; h – powder layer height;} \\
\text{n – amount of powder layers before vibration load impact;} \\
\text{\(\Delta n\) – change of number of layers due to vibration load impact;} \\
\text{\(V_x\) – volume occupied by powder charge after vibration load impact;} \\
\text{n_y – amount of powder layers after vibration load impact} \\
\end{array} \]

After vibration load impact, the volume occupied by the powder element will be reduced by value $\Delta V$:

$$\Delta V = V_0 - V_y = V_0 \left(1 - K_y\right).$$  \hspace{1cm} (2)

The number of layers occupied by the powder element will be reduced by value $\Delta n$ as well:

$$\Delta n = \frac{4\Delta V}{\pi D^2 h} = \frac{4V_0 \left(1 - K_y\right)}{\pi D^2 h} = n \left(1 - K_y\right).$$

Then the number of layers $n_y$ to be occupied by the powder element after vibration load impact will be

$$n_y = n - \Delta n = nK_y.$$  \hspace{1cm} (3)

The porosity value for each layer with regard to volume change due to vibration load impact will be equal to $m_y$. The average porosity
value for the entire volume filled by powder after vibration load impact will be equal to $m_y$. In order to determine these values, values $V_0$, $V_y$, and $\Delta V$ are expressed as the following sums:

$$V_0 = V_{\text{п.э}} + V_{\text{пуст}},$$

$$V_y = V_{\text{п.э}} + V_{\text{пуст.у}},$$

$$\Delta V = V_{\text{п.э.д}} + V_{\text{пуст.д}},$$

where $V_{\text{п.э}}$ – volume occupied by powder elements in the total volume of powder charge; $V_{\text{пуст}}$ – void volume inside powder charge before vibration load impact; $V_{\text{пуст.у}}$ – void volume inside powder charge after vibration load impact; $V_{\text{п.э.д}}$ – volume occupied by powder elements within volume $\Delta V$; $V_{\text{пуст.д}}$ – void volume occupied by powder elements within volume $\Delta V$.

Then, value $V_{\text{пуст.у}}$ can be calculated with the help of the first two equations of system (4) with regard to (1)

$$V_{\text{пуст.у}} = V_0 K_y - V_y + V_{\text{пуст}},$$

As porosity is the void volume in the unit of volume occupied by the powder elements, the following formulae are true:

$$\bar{m} = \frac{V_{\text{пуст}}}{V_0},$$

$$\bar{m}_y = \frac{V_{\text{пуст.у}}}{V_y},$$

where $\bar{m}$ – average porosity value for the whole volume filled with powder before vibration load impact. Value $\bar{m}$ is determined for the formed charge using the following formula

$$\bar{m} = \frac{\sum_{i=1}^{n} m_i}{n}.$$ 

If we put values $V_{\text{пуст.у}}$ and $V_y$ into formula (7) from expressions (5) and (1) and with account for ratio (6), we can determine the average porosity value for the whole volume filled with powder after vibration load impact $\bar{m}_y$:

$$\bar{m}_y = \frac{V_0 K_y - V_0 + V_{\text{пуст.у}}}{V_0 K_y} = 1 - \frac{1}{K_y} + \frac{\bar{m}_y}{K_y}.$$

To calculate values $m_{ij}$, the following formulae are used for the volume element corresponding to the layer $n_l$:

$$V_{i0} = V_{n\text{.п.э}},$$

$$V_{i0} = V_{n\text{.пуст}},$$

$$\Delta V_i = V_{n\text{.пуст.д}},$$

$$m_i = \frac{V_{\text{пуст.д}}}{V_{i0}},$$

$$m_{ij} = \frac{V_{\text{пуст.у}}}{V_{i0}},$$

where $V_{i0}$ – layer volume $n_l$ before vibration load impact; $V_{n\text{.п.э}}$ – volume occupied by powder elements inside layer $n_l$ before vibration load impact; $V_{n\text{.пуст}}$ – void volume inside layer $n_l$ before vibration load impact; $V_{n\text{.пуст.у}}$ – void volume inside layer $n_l$ after vibration load impact; $\Delta V_{ij}$, $V_{n\text{.пуст.д}}$ – change of volume occupied by powder elements inside layer $n_l$ due to transfer of powder elements from volume $\Delta V$ to lower layers of the powder elements; $m_i$ – porosity value for layer $n_l$ before vibration load impact.

Volume $V_{i0}$ is calculated as follows

$$V_{i0} = \frac{V_0}{n},$$

or

$$V_{i0} = \frac{\pi D^2 h V_0}{4V_0} = \frac{\pi D^2 h}{4}.$$
filled with powder and after change of the total volume occupied by the powder charge, the layer volume will not change, i.e.

\[ V_y = V_{i0}, \]
\[ m_y = \frac{V_{\text{myt},y}}{V_y} = \frac{V_{\text{myt},y}}{V_{i0}}. \] (12)

Under vibration load impact, the relation between the volume occupied by powder elements and the void volume inside the considered layer \( n_i \) will change. This process is caused by the movement of powder elements under the effect of oscillations from the upper layers of the powder charge (in particular, from volume \( \Delta V \)) to the lower layers. At the first stage of computation, it is assumed that powder elements from volume \( \Delta V \) are uniformly distributed in the lower layers (from layer \( n_1 \) to layer \( n_y \)). In this case, taking into account the third equation of system (4)

\[ V_{\text{myt},y} = V_{\text{myt}} - V_{\text{m}\Delta}; \] (13)
\[ V_{\text{m}\Delta} = \frac{V_{\text{m}\Delta}}{n_y}. \] (14)

Value \( V_{\text{m}\Delta} \) can be determined as follows

\[ V_{\text{m}\Delta} = \Delta V (1 - m_\Delta), \] (15)

where \( m_\Delta \) – average porosity by volume \( \Delta V \) before vibration load impact, i.e.

\[ m_\Delta = \frac{\sum m_i}{\Delta n}. \]

Then, with account for formulae (2) and (3) value \( V_{\text{m}\Delta} \) will be equal to

\[ V_{\text{m}\Delta} = \frac{V_{\text{m}\Delta}}{n_y} = \frac{V_0 (1 - K_y) (1 - m_\Delta)}{nK_y}. \] (16)

After putting expression (13) into expression (12) and with account for formulae (1), (10), and (16), porosity values are determined for each layer \( m_y \):

\[ m_y = \frac{V_{\text{myt},y}}{V_{i0}} = m_y + 1 - \frac{1}{K_y} + \frac{m_\Delta}{K_y} - m_\Delta. \] (17)

Therefore, the first computation stage is intended to determine the average porosity and porosity values for each layer without regard to mixing of powder elements located in the lower section of the powder charge (in cross-sections with coordinates from \( i = 1 \) to \( i = n_y \)). It is assumed that a change of porosity for these layers is caused only by movement of powder elements from the upper layers of the powder charge (from volume \( \Delta V \)), while the transferred powder elements are uniformly distributed in the lower layers. The actual process of exposure of the powder charge to oscillations involves mixing of the powder elements within the entire volume of the charge; that is why, porosity values for each layer are updated at the second computation stage.

To estimate the extent of porosity equalisation (second computation stage), value \( K_n \) was used:

\[ K_n = \frac{S_n}{S_0}, \]

where \( S_n \) – root-mean-square deviation of porosity value by the volume occupied by the powder charge with regard to mixing due to vibration load impact;

\( S_0 \) – root-mean-square deviation of porosity value by the volume occupied by the powder charge without regard to mixing due to vibration load impact.

Values \( S_0 \) and \( S_n \) are calculated as follows:

\[ S_0 = \sqrt{\frac{1}{k} \sum_{i=1}^{k} (m_y - \bar{m}_y)^2}; \]
\[ S_n = \sqrt{\frac{1}{k} \sum_{i=1}^{k} (m_m - \bar{m}_y)^2}, \]

where \( m_m \) – porosity value for each layer with regard to a change of porosity distribution along the length of the filled volume due to mixing.

After several transformations, value \( K_n \) can be obtained

\[ K_n = \frac{\frac{m_m - \bar{m}_y}{m_y - \bar{m}_y}}{\frac{m_m - \bar{m}_y}{m_y - \bar{m}_y}}. \]

Value \( m_m \) will be equal to:

\[ m_m = \bar{m}_y + K_n (m_y - \bar{m}_y). \] (18)
As a rule, value $K_n$ is unknown, but it can be calculated approximately using the formula

$$K_n = \frac{S_0}{S_n},$$

where $S_n$ – root-mean-square deviation of porosity value by the volume occupied by the powder charge before vibration load impact.

Value $S_n$ is determined by the expression

$$S_n = \sqrt{\frac{1}{k} \sum_{i=1}^{k} (m_i - \bar{m})^2},$$

Value $m_n$ as per formula (18) is obtained with regard to the influence of all the layers located above and below the given layer on variations in porosity of layer $i$. During oscillations caused by exposure to shock loads (vibration), the powder elements located in the given layer are constantly relocated and interact with the elements located in the adjacent layers (above and below the given one), while intense mixing of these layers occurs. Moreover, if free space is available, powder elements can move to the lower layers of the charge, which are located at a distance considerably higher than the oscillation amplitude from the given layer. The process of relocation of powder elements from the upper to lower layers of the charge is a random process and depends on the relative position of powder elements in the adjacent layers of the charge. Due to oscillations, positions of all powder elements constantly change, the powder elements are moving, turning over, colliding with one another, etc. Therefore, the process of mixing of powder elements is rather complicated and it is very difficult to calculate the direction and trajectory of each powder element when it moves from the upper to lower layers of the charge. Ratios (17) and (18) disregard the motion of each individual powder element when exposed to oscillations. These ratios are dependencies allowing to determine the variation of average porosity for different layers of the powder charge.

When developing the model of formation of a powder charge, we may assume that porosity in the given layer of powder is mostly affected by surrounding layers within a narrow area determined by oscillation amplitude $A$ (Fig. 2).

![Fig. 2. Powder elements mixing computation diagram:](image)

- $n_a$ – number of powder layers with the total height equal to oscillation amplitude; $A$ – oscillation amplitude; $m_i$ – porosity of layer $i$; $m_{ci}$ – average porosity of several powder layers affecting porosity variation in the given layer ($m_i$); $k$ – total number of powder layers.
Therefore, the porosity of layer $i$ will be changed depending on the values of porosity of several layers of powder elements that surround the given layer, and on the average porosity in the given area. In this case, ratio (18) will be changed to some extent.

The number of layers of powder elements affecting the given layer $i$ can be calculated as follows

$$n_a = \frac{A}{h}.$$  

Average porosity in the given area $m_{\text{cp}i}$:

$$m_{\text{cp}i} = \frac{\sum_{i=i-t}^{i+t} m_y}{n_a};$$

$$t = \frac{n_a - 1}{2}.$$

In this case, the porosity value of the given layer $m_n$ can be determined by changing formula (18) with regard to the influence of only surrounding layers within the oscillation amplitude on redistribution of powder elements inside the given layer:

$$m_n = \frac{\sum_{i=i-t}^{i+t} \left[ m_{\text{cp}i} + K_n (m_y - m_{\text{cp}i}) \right]}{n_a} = K_n m_y + \frac{\sum_{i=i-t}^{i+t} m_{\text{cp}i} (1 - K_n)}{n_a}.$$  

(19)

Average porosity within the given volume upon completion of the second computation stage $\bar{m}_n$:

$$\bar{m}_n = \frac{\sum_{i=i-t}^{i+t} K_n m_y}{k} + \frac{\sum_{i=i-t}^{i+t} m_{\text{cp}i} (1 - K_n)}{kn_a} = K_n \bar{m}_y + (1 - K_n) \bar{m}_y = \bar{m}_y,$$

where $k$ – amount of powder element layers to be summed.

Upon completion of the second computation stage, the average porosity by volume remains unchanged, but porosity equalisation occurs over the entire volume of the shell.

According to the compiled dependencies (17) and (19), we estimated the effect of oscillations on the porosity of the powder charge for the AK-230 gun. Computations were conducted based on porosity data acquired during simulation of shell filling with powder elements. When simulating the formation of the charge for the AK-230 gun, the weight and length of the charge were similar to the characteristics of the charge used for testing at FSOE “NTIIM” test site. Compaction factor $K_{\text{ynt}}$ was determined based on data specified in [5, 6]. According to the work [6], the compaction factor value depends on material humidity, fraction size, vibration exposure time, and oscillation frequency. In the case study, the powder humidity was assumed equal to 0 %. The compaction factor is: $K_{\text{ynt}} = 1.045...1.050$.

Computation results are given in the Table below. Here, $\bar{m}$ – average porosity of the charge before vibration load impact, $\bar{m}_y$ – average...
The nominal value of average porosity for real charges is $m_n = 0.4700$.

After simulating the vibration load impact on the powder charge, porosity distribution along the charge length has become more uniform in all cases. Moreover, the porosity and the length of powder charges have been reduced while the parameter values have become near to nominal values.

The disadvantages of the developed model for simulating the formation of powder charge with regard to the impact of shock and vibration loads on the charge is an approximate determination of “mixing factor” $K_n$. Since this factor cannot be determined with the required accuracy, there appear errors that are difficult to be estimated at the second computation stage (mixing of powder elements). At the same time, completion of the second computation stage allows to simulate the process of porosity equalisation inside the shell under vibration load impact. This process is an integral part of the whole redistribution of powder elements inside the shell and general porosity reduction.

Thus, simulation of the shock and vibration load impact on the powder charge allows to form charges with their characteristics close to real ones. Such models of powder charges can be used for further simulation of the powder burning process and for calculating intraballistic characteristics in the gas-dynamic approach equations.

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Моделирование воздействия вибрационных нагрузок на пороховой заряд, состоящий из зернистых пороховых элементов

Рассмотрено воздействие вибрационных нагрузок на сформированный пороховой заряд, состоящий из зернистых пороховых элементов. Целью работы является создание модели, учитывающей уплотнение порохового заряда и перемешивание пороховых элементов под действием вибрационных нагрузок.

Ключевые слова: пористость порохового заряда, формирование порохового заряда, пороховые элементы, вибрационные нагрузки, ударные нагрузки.

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Область научных интересов: внутренняя, внешняя и конечная баллистика, поведение материалов при импульсных нагрузках.

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