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Failure Analysis of Set-Back Arming Process of MEMS S&A Device

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Abstract: Failure is one key problem of MEMS S&A (safety and arming) device for its practical application. To make research of failure of MEMS S&A device in action process, a method based on FTA was employed to make analysis on arming process of the set-back arming mechanism of typical MEMS S&A device. Result obtained with theory computation was verified to be right by simulation analysis and which could prove rationally of the method. Conclusion of the article could provide theory reference for structure designing and optimization of MEMS S&A device. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: MEMS S&A device, Set-back arming mechanism, FTA (failure tree analysis), Failure analysis.

1. Introduction

It is an effective way to implement microminiaturization of fuze with the application of MEMS technology, and MEMS S&A device is one of the important directions of practical application [1, 2]. Compared with the traditional things, MEMS S&A device has such advantages as simple structure, small volume and high reliability which could reduce the occupied space of fuze to increase the charge of projectile and achieve the functions of information detection and processing within a limit space. Therefore the development of the fuzes based on MEMS technology has became a trend for the future of fuze [3-5].

Failure is one key problem of MEMS S&A device which hindered its practical application. To make research of failure during the action process, a method of analysis based on FTA was employed in the article, and rescission of recoiling insurance of one typical MEMS S&A device had been analyzed with it for example. Conclusion of the study could be used to provide theory reference for structure designing and optimization of MEMS S&A device.

2. Method of Failure Analysis to MEMS S&A Device

The method of FTA (failure tree analysis) is an effective way with the advantage of simple and reliable, During the process of designing for system, through make research of various reasons for system failure and refinement analysis according to inverted treelike from system to part, logical diagram would be drawn to find probably combination of various reasons for system failure with their occurrence probability. The influence of basic event on top event was analyzed by basic event importance. And corresponding action would be taken for correction to improve the reliability of system [6].

Failure analysis of the system should be implemented before production in order to test rationality of the structure designing due to complexity and particularity of machining processing of MEMS S&A device [7]. A new method was employed to make failure analysis of MEMS S&A device to deal with this problem and the flowchart was shown in Fig. 1.

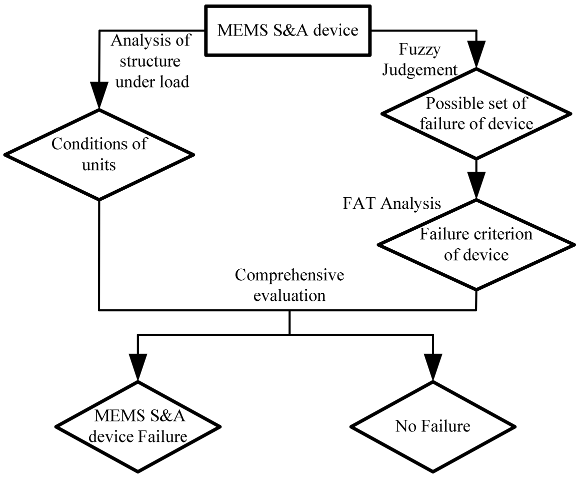


Fig. 1. Flow-chat of failure analysis to MEMS S&A device.

Possible set of failure could be obtained by making fuzzy judgement at first, and failure tree would be built to make failure criterion of system; condition of each part under environmental load would be investigated and a judging of the system would be made through comprehensive evaluation.

3. Typical MEMS S&A Device

The Structure of typical MEMS S&A device was similar to that of MEMS fuze of 20 mm shrapnel which used in OICW [3]. The typical MEMS S&A device could be divided into three function units according to different functions of its composition, each unit has its own specific function independently which couldn't be implemented by others. The established function of system only could be realized with interaction of all units. With recoil force caused by launching of the projectile, the set-back arming mechanisms unit made action firstly to loose one restriction of the centrifugal slide; and the long distance arming mechanisms unit acted to loose another restriction of the centrifugal slide after projectile out of muzzle; at last, centrifugal arming mechanisms unit moved with centrifugal force and made the explosive train alignment. Structure diagram of the typical MEMS S&A device was shown in Fig. 2.

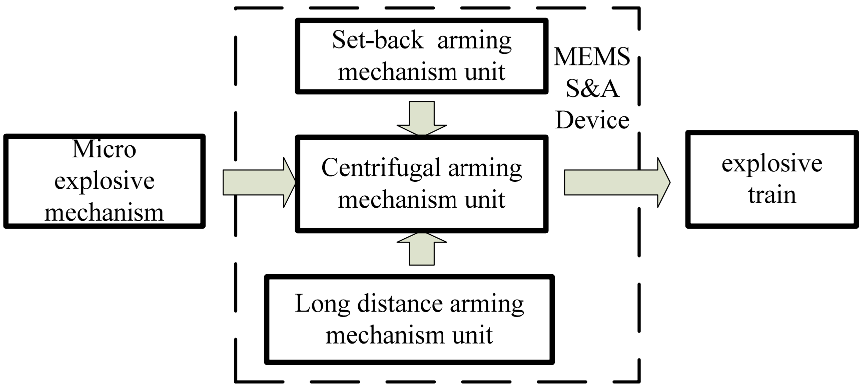


Fig. 2. Structure diagram of the typical MEMS S&A device.

3. Failure Tree of the Set-back Arming Mechanism unit of MEMS S&A Device

The set-back arming mechanism unit of typical MEMS S&A was taken to make failure analysis of its arming process for example, and the unit consists of three parts: frame of substrate (holder), set-back slide (chuck) and micro-spring, which was shown in Fig. 3(a). There contained two aspects of failure for the set-back arming mechanism unit in arming process: one was performance failure for the system can't realize its specific function; one was failure for the system can't realize its function on time. Failure reasons of the function unit would be distinguished step by step and logical relationship of all events would be studied, with the conclusion we built failure tree of the function unit which could be used to investigate failure relationship between single device and system. Deviation of the action time was also taken as one of the basic events to give an overall investigation on the failure of system. Failure tree of the unit in action process of the set-back arming mechanism unit was shown in Fig. 3(b), and the meanings of symbols were shown in Table 1.

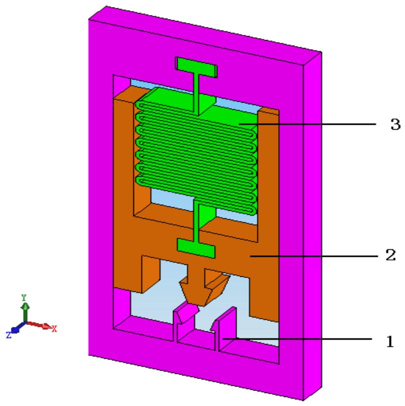


Fig. 3 (a). Structure of the set-back arming mechanism unit.
1 – frame of substrate (holder); 2 – set-back slide (chuck); 3 – micro-spring.

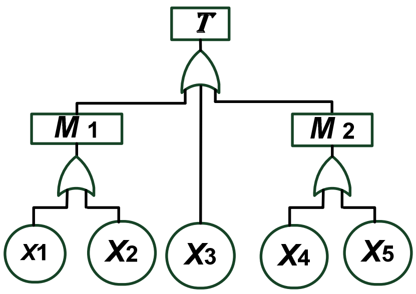


Fig. 3 (b). Failure tree of arming process.

Here T represents the top event, X_i are basic events, and M are mid events; and the two conditions of top event and basic events, including normal and invalid, were only considered.

The table of meaning of symbols of failure tree is shown below.

Table 1. Meaning of symbols of failure tree.

Symbol	Meaning	Symbol	Meaning
T	Failure of the unit	X_2	chuck can't enter into holder
M_1.	Set-back slide can't move to the right place	X_3	Motion time of the slide was too long
M_2	Set-back slide has difficult in locating	X_4	Extrusion yielding of the holder
X_1	Strength failure of micro-spring	X_5	Tensile yielding of the holder

3.1. Failure Criterion of Set-back Arming Mechanism Unit in Arming Process

Minimal cut sets could be obtained through deduction with structure functions of FTA, the process of deduction was as followed [6].

$$M_1 = X_1 \cup X_2, \quad (1)$$

$$M_2 = X_4 \cup X_5, \quad (2)$$

$$\begin{aligned} T &= M_1 \cup M_2 \cup X_3 \\ &= X_1 \cup X_2 \cup X_3 \cup X_4 \cup X_5 \end{aligned} \quad (3)$$

It could be found from the solving results that there were five minimal cut sets to the failure tree which were $\{X_1\}$, $\{X_2\}$, $\{X_3\}$, $\{X_4\}$, $\{X_5\}$ respectively. All of these were the most weakness of the top event and each of them represents one failure mode of the system. Therefore, all of the five minimal cut sets could become failure criterion of the set-back arming mechanism unit in arming process.

3.2. Mechanical Environment of Arming Process

The unit of set-back arming mechanism mainly used recoil force which caused by launching of project to work, and it was also subjected to centrifugal force, tangential force and friction during the arming process. The curve of set-back (impact) acceleration in barrel was shown in Fig. 4. In this paper, the practical curve (A) is replaced by an approximate curve (B) to simplify the processing. The expression for impact acceleration according to the approximate curve is

$$a = \begin{cases} 8.366\times10^8 t + 50763, t\in[0,0.350]ms \\ -2.552\times10^8 t + 419355, t\in[0.350,1.513]ms \end{cases} \quad (4)$$

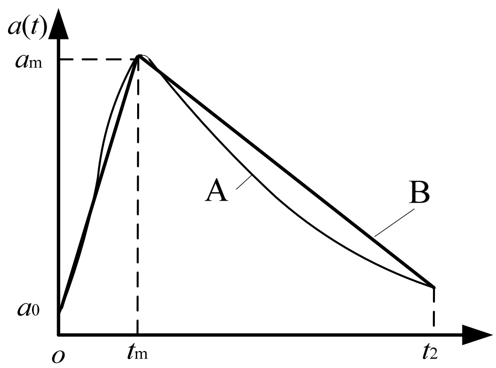


Fig. 4. Curve of the impact acceleration.

To make sure reliable arming of the unit, the inertial safety mechanism must complete arming before the peak of acceleration appears. As a result, calculation of motion characteristics for the unit was mainly concerned with the increased segment of acceleration curve, the time of arming must shorter than 0.35 ms. According to failure criterion of the unit, it should take mainly energy to failure analysis in investigating strength of micro spring and vertical beam of the holder, and exercise time of the set-back slide. With the research results from U. Wanger and Sri Kar, it was indicated that both the maximum stress and the quasi-static theory could be applied to study the failure problem of micro-device of typical dynamic environment the analysis of impact conditions micro-device failure problem [8, 9].

4. Failure Analysis Process

4.1. Strength Analysis of Micro-spring

Mechanical model of one unit of micro-spring of s-type with tensile force F is shown in Fig. 5, and each unit has the same response to tensile force.

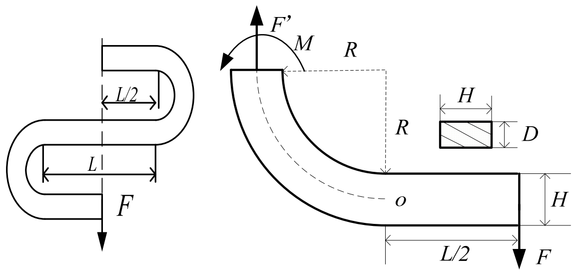


Fig. 5. Model force of one unit of micro-spring.

According to theoretical mechanics, it could be determined that the horizontal section of bending of micro-spring was the most weakness section which was subjected to interaction with tension F and moment M [10]. Edge of Medial of the section was the most dangerous position which beards the maximum tensile stress, and the expression of the maximum stress is:

$$\sigma_{\max} = \frac{M}{W_1} + \frac{F}{S} = \frac{(L+2R+H)\cdot F}{2W_1} + \frac{F}{D\times H}, \quad (5)$$

where R is the radius of medial edge of bending of micro-spring; H is the line-width of beam; L is the length of straight beam of micro-spring; D is the thickness of micro-spring; F is the tensile force to micro-spring and S is the area of cross section of bending respectively and are given by:

$$F=K\Delta y_{\max}, S=H\times D, \quad (6)$$

where K is the elastic coefficient of micro-spring and $\Delta y_{\max}$ is the maximum displacement of micro-spring along y axis, and W_1 is the coefficient of the bending section and is given by:

$$W_1 = DH^2/6, \quad (7)$$

So the maximum stress also cold be expressed as:

$$\sigma_{\max} = \frac{K\Delta y_{\max}\cdot\left[1+\left(3L^3+6L^2R+3L^2H\right)H^2D\right]}{DH} \quad (8)$$

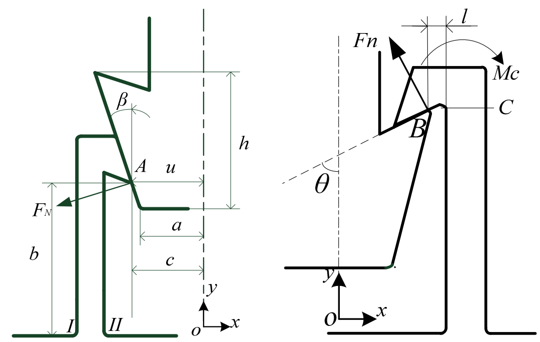
The maximum stress of micro-spring in the process of arming could be obtained according to formula (8) and the result could be used to make judgment of whether strength failure occur [11].

4.2. Strength Analysis of Beam of the Holder

Free body diagram of beam of holder in the process of arming was shown in Fig. 6. The displacement of point A of single vertical beam along x axis with extrusion was:

$$x = u - c, \quad (9)$$

where u is the distance between the medial axis of set-back slide and the contact point A; β is the angle between edge of the chuck and its medial axis; c is the distance between A point and medial axis of the chuck.



(a) (b)

Fig. 6. Model of force of beam to the holder.
(a) Beam of the holder was squeezed by the chuck;
(b) Beam of the holder was tensiled by the chuck.

The maximum displacement of single vertical beam of holder along x axis in the process of arming could be expressed to be:

$$x_{\max} = u_{\max} - c = h\cdot\tan\beta + a - c, \quad (10)$$

where a is the half of horizontal length of apex of the chuck, h is the distance between bottom of the chuck and its apex. According to theoretical mechanics, the deflection of single vertical beam along x axis could be expressed as [10]

$$x=\left(F_n\cos\beta b^3\right)/3EI, \quad (11)$$

where F_n is the extrusion from the chuck; I is the section moment of inertia of the vertical beam; E is the elastic modulus of the material; b is the distance between the bottom of the vertical beam and point A. The extrusion to vertical beam is:

$$F_N = \frac{3EIx}{b^3 \cos\beta} = \frac{3EI}{b^3 \cos\beta}(u - c), \quad (12)$$

Roots of the vertical beams were dangerous position, and I end bearing the maximum compressive stress while II end bearing the maximum tensile stress [11]. The maximum stress could be expressed to be:

$$\sigma_B = \frac{M_n}{W_B} = \frac{3EI(Ltg\beta + a - c)}{W_B \cdot b^2}, \quad (13)$$

where W_B is the coefficient of the bending section of vertical beam, M_n is the moment caused by extrusion and is given by:

$$M_n = F_N \cos\beta b \quad (14)$$

The chuck would make motions ups and downs until its velocity attenuate to zero due to multiple collision with cross beam of the holder. Moment caused by the maximum tensile force $F_{n\max}$ could be deduced with formula (12) and collision theory [12, 13]. The expression of moment is:

$$M_{c\max} = F_{n\max} \cdot \cos\theta \cdot l, \quad (15)$$

where θ is the angle between terminal edge of the chuck and its medial axis, l is the distance between the action point B and root of apex of the vertical beam.

Cross section C of the vertical beam was dangerous position and its medial edge was subjected to interaction with both Fnmax and $M_{c\max}$, the maximum stress of cross section C could be expressed as [11]:

$$\sigma_{c\max} = \frac{F_{n\max} \cdot \cos\theta \left(l \cdot S_1 + W_{B1}\right)}{W_{B1} S_1}, \quad (16)$$

where W_{B1} is the coefficient of bending section of cross section of apex of the beam, and S_1 is the area of cross section C. Values of the maximum tensile stress caused by chuck could be deduced by formula (13) and (16) which would be used for judging failure to the beam.

4.3. Analysis on Motion of Set-back Slider

Schematic force of set-back slide in motion process was shown in Fig. 7. The dynamical model of motion to the set-back slide of motion before it contact with holder could be expressed by differential equation as:

$$m\frac{d^2y}{dt^2} = F_s - F_R - f_c - f_t, \quad (17)$$

where F_S is the recoil force; F_R is the tensile force with micro-spring; F_c is the centrifugal force and F_t is the tangential force; f_c and f_t are the frictions caused by centrifugal force and tangential force respectively and are given by:

$$f_c = F_c\mu, f_t = F_t\mu, \quad (18)$$

where μ is the friction coefficient between set-back slide and substrate.

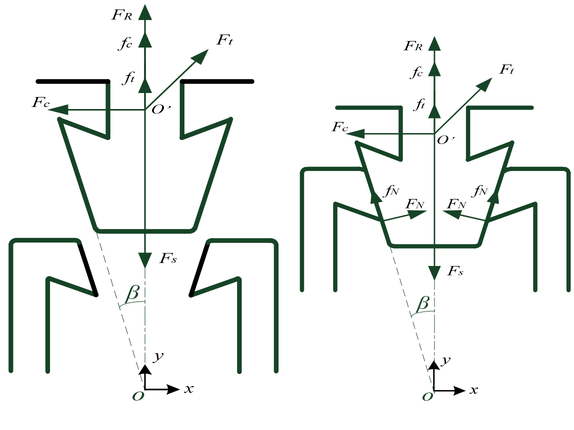


Fig. 7. Schematic diagram of force of the chuck made motion along y axis: (a) the case of before the chuck contact with the holder; (b) the case of after collision appearance.

According to initial conditions, the motion equation of set-back slide before it collided with holder could be derived according to initial conditions which could be expressed as:

$$y = -0.0035\cos(3620.4t) - 349.8972t^2 + 63.8305t + 0.0035 - 0.0176\sin(70474t) \quad (19)$$

The time of motion process is $t_1 \approx 0.1326$ ms and the velocity of slide before collision appearance is Vt1=12.3 m/s which were obtained through solving the equation above with the displacement of slide.

Differential equation of motion to the slide after it collided with holder could be expressed as

$$m\frac{d^2y}{dt^2} = F_s - F_R - f_c - f_t - 2f_N\cos\beta - 2F_N\sin\beta, \quad (20)$$

where F_N is the extrusion reaction of holder, β is the angle between edge of the chuck and its medial axis and f_N is the friction caused by extrusion reaction and is given by:

$$f_N = F_N \mu \,, \tag{21}$$

To enter the holder completely, the displacement of slide along y axis must more than 0.276 mm. t_0 was the time of motion process in which the velocity of set-back slide along y axis reduce to zero from V_{t1}, and it could be obtained by deduction with known conditions all above. The displacement of slide along y axis is y_0=0.320 mm which got by solving equation (8) with t_0. It is found that the chuck could enter the holder completely since y_0>0.276 mm.

The motion equation of set-back slide before it collided with holder could be derived according to initial conditions which could be expressed to be:

$$\begin{aligned} y = &-0.9324t^2 + 0.00017214\sin(70474t) \\ &-0.000029119\cos(70474t) \\ &+0.1685t + 6.8922\times10^{-4} \end{aligned} \tag{22}$$

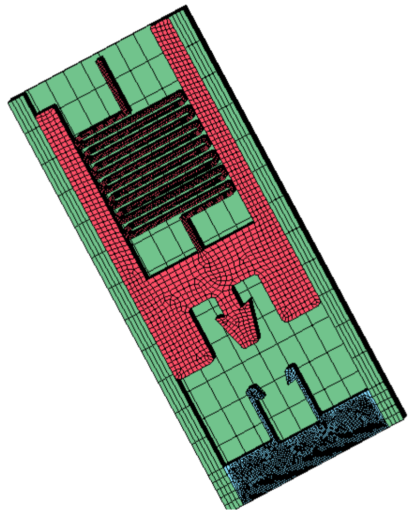
The time of motion process is t_2≈0.1960 ms which is obtained through solving the equation above with the displacement of slide in the process, and the total time of motion for arming of set-back slide is

$$t = t_1 + t_2 \approx 0.3286 \text{ ms} < 0.35 \text{ ms} \,,$$

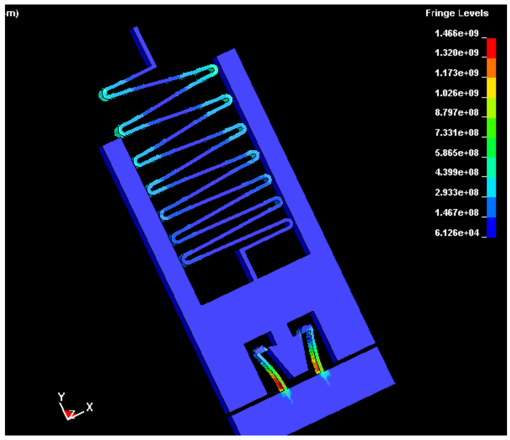
5. Simulation Analysis

Typical MEMS S&A device was made of nickel with the processing technology of UV-LIGA. To facilitate the calculation, there was some simplified processing should be made to model of the set-back arming mechanism unit. Finite element software was employed to build 3-d model of the system and meshed [14, 15], corresponding constraint and impact loading were applied on the model, all of which was shown in Fig. 8(a).

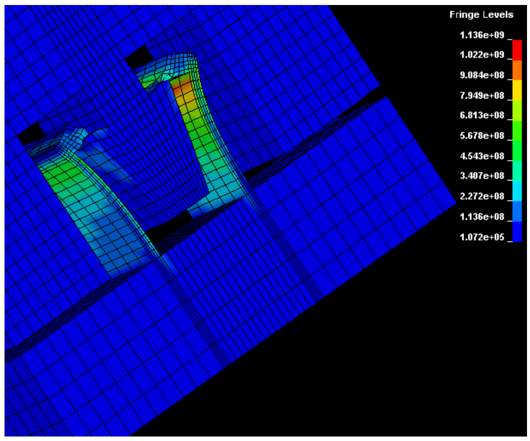
From Fig. 8(b) and Fig. 8(c), it could been found that roots of vertical beam of the holder, the medial edge of bending section of the micro-spring and medial edges of bending section of vertical beam of the holder were the most weakness/dangerous positions in arming process, which were quite similar to the result of theory analysis, and values of the maximum stress could be obtained by post-processing program of simulation analysis. Result of theory analysis and simulation were shown in Table 2 which shown that the error between theory analysis and simulation results were quite small. The yield strength of UV-LIGA nikle is $[\sigma_a]$= 4.2×10^2 MPa, and its tensile strength is $[\sigma_b]$= 8.5×10^2 MPa, $\sigma_{max}<[\sigma_a]$, $\sigma_{Bmax}<[\sigma_b]$, $\sigma_{cmax}<[\sigma_a]$. Strength failure hasn't occurred on both micro-spring and beam of the holder.



(a)



(b)



(c)

Fig. 8. Simulation analysis process: (a) 3-D model of the set-back arming mechanism unit; (b) strength analysis of the model with loads; (c) strength analysis of beam of the holder with tensile force.

Contrast of results between theory analysis and simulation is shown in Table 2.

Table 2. Contrast of results between theory analysis and simulation.

	Theory analysis (MPa)	Simulation result (MPa)	Error
Maximum tensile stress of spring σ_{max}	1.993×10^2	1.989×10^2	0.21 %
Maximum compress stress of the holder σ_{Bmax}	2.752×10^2	2.727×10^2	0.91 %
Maximum tensile stress of the holder σ_{cmax}	2.973×10^2	2.955×10^2	0.61 %

Displacements of the set-back arming mechanism unit in arming process are shown in Fig. 9. It could be found that displacement of the set-back slide along y axis is longer than the distance (d_0=1.1 mm) between its initial position and the place where it is subjected to the maximum compress from the holder, which means that the set-back slide could enter the holder completely. And it also could be found the time of process of arming of set-back slide got from simulation is 0.330 ms which is similar to theory analysis(0.325 ms), and both of them were shorter than t_m(t_m=0.35 ms), so it is certain that the unit could realize function of arming on time.

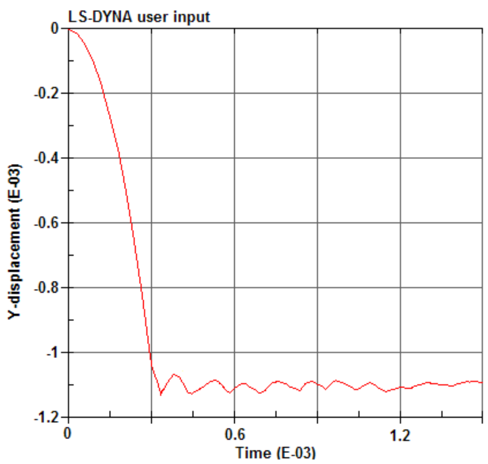


Fig. 9. Graph of displacement & time of the set-back slide along y axis.

From all above, it could be found that there has so little error between the results of theory analysis and simulation results.

6. Conclusions

According to the result of theory computing with the method of analysis, it could be seen that strength failure hadn't occurred on the unit with load, and the unit could implement the function of arming on time in the process of arming; there are no failure occurring in arming process of the unit, and the results of theory analysis is consistent with simulation results which could shown the rationality of the method analysis.

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