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Probit Analysis – a Promising Tool for Evaluation of Explosive's Sensitivity*)

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Abstract: The sensitivity of explosives to various initiating events, in probability of initiation-level of stimulus space, has a shape of sigmoidal curve. In standard sensitivity tests only one point on this curve is sought, most often the 50% initiation probability level. The usual (and most often used) method for its determination is the up-and-down method. The whole sensitivity curve can be obtained by conducting large number of trials at all levels or more effectively by probit analysis. The usage of probit analysis, improvement of the precision of the results and comparison with the results precision of the up-and-down method is demonstrated by the example of determination of sensitivity to friction.

Keywords: probit analysis, sensitivity, sensitiveness, friction, impact

Introduction

The sensitivity of explosives is one of their crucial parameters limiting their usage. Various tests were developed to test the sensitivity to a variety of initiating events (impact, friction, electric spark, bullet impact, etc.). Many of these tests have one thing in common and that is the characteristic sigmoidal curve of sensitivity of explosive *vs.* energy of external stimulus (Figure 1). This curve represents a well-known fact that a single sharp boundary between energy levels causing initiation ('go' level) and not causing initiation ('no go' level) does not exist. Rather there are three intervals: first includes low values of stimulus energy (the sample never reacts), opposite is the region of very high values of stimulus energy (the sample always reacts). The third, most important, interval

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lies between these two extremes and the energy of the impulse causes sample reaction with certain probability. Generally, the low values interval is connected with safety and the high values interval is connected with reliability.

Various methods were developed to evaluate the sensitivity of explosives [1-6]. One of the most widely spread methods is the up-and-down method (staircase, Bruceton staircase) used for determination of the 50% probability level (the level of stimulus where the sample will react with 50% probability). Details of this technique may be found in reference [1]) and therefore it is only briefly described here. In this method equally spaced levels (steps) of explored stimulus are defined first. A serie of 25-30 trials is performed with these steps starting anywhere around expected 50% probability level. If the sample initiates, next trial is performed one step lower, if it does not one step higher. The record of oscillation around the 50% probability level is obtained; the 50% probability level and its standard deviation are calculated.

The up-and-down method has two main disadvantages. The single value reported (50% probability level) as a result is the first disadvantage. This value can be used for rough comparison of various samples; however it does not contain complete information about safety or reliability (steepness of the sensitivity curve). It is only a single point on the sensitivity curve, as displayed in Figure 1. The second disadvantage is the conditioned validity of the result. The determined 50% probability level is valid only in the case of certain ratio of standard deviation and step size. If this condition is not fulfilled, the whole procedure must be repeated with smaller or bigger steps.

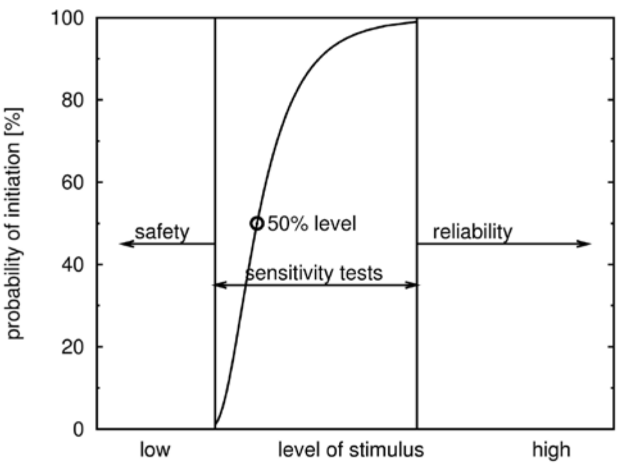

Figure 1. Sensitivity curve.

In order to avoid the problems related to up-and-down method we looked at some alternative methods for results evaluation. In this article we would like to recall attention of explosive community to one old method routinely used in other fields. This method is called 'Probit analysis' [7] and was developed for use in biological sciences and toxicology for determination of LD_{50} (lethal dose). The advantage of this method is its ability to provide researcher with the whole sensitivity curve and not just the 50% probability level often without increasing the number of necessary trials.

Probit analysis

The word probit is an abbreviaton for the 'probability unit'. The principle of this method is the transformation of the sensitivity curve into different coordinates in which the relation becomes linear.

Each value of probability P can be transformed into a probit Pr using the following expression:

$$P[-\infty \leq X \leq \mathrm{Pr}] = \int_{-\infty}^{\mathrm{Pr}} f(x)\mathrm{d}x = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{\mathrm{Pr}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)\mathrm{d}x, \quad (1)$$

where X is a random variable with normal (Gauss) distribution, $f(x)$ is the probability density function with the parameters μ (mean) and σ^2 (variance). From historical reasons, the values $\mu = 5$ and $\sigma^2 = 1$ are used. The probit-probability dependence is tabulated in literature, e.g. [7]. The definition of probits can be easily understood from Figure 2. The filled area bellow the curve corresponds to probability and the x coordinate of the upper boundary corresponds to probit.

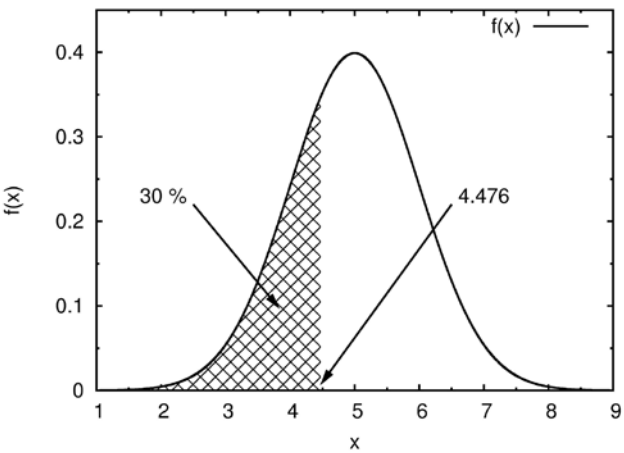

Figure 2. Probit definition.

The plot of logarithmic form of stimuli levels versus probits gives linear dependence. The procedure starts with selection of few levels of explored stimulus and determination of probabilities of ignition on each level. The probabilities are then expressed as probits and plotted against the levels in logarithmic form. Linear regression is performed and the regression line represents the probability vs. stimulus level dependency that can be transformed back into the original coordinates. The whole sensitivity curve can be obtained using this procedure. The confidence intervals can be also expressed.

The usage of the probit method is demonstrated for determination of friction sensitivity of one experimental primary explosive. The up-and-down F_{50} determination is also presented for comparison. The benefits of probit analysis are discussed.

Materials and Methods

The friction sensitivity was determined using LP11b (OZM Research) friction sensitivity tester. It is a modernized version of a standard BAM small-scale friction tester [1, 2, 5]. The ceramic plates were brush hand grooved type.

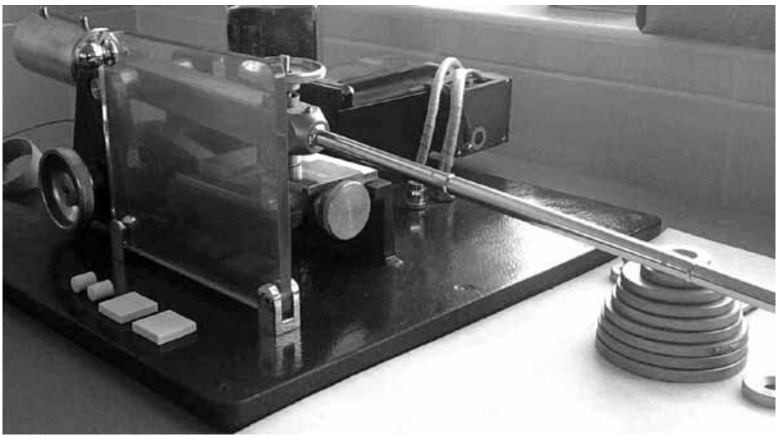

Figure 3. Small scale sensitivity apparatus LP11b (OZM Research).

The methodology is demonstrated on a primary explosive with sensitivity just on the upper range of the machine-operating interval. Primary explosive was selected because the initiation is easily detected (cracking, flame, bang) unlike in the case of some secondary explosives and is therefore less dependent on operator's opinion.

The tests were planned and conducted in a way that allowed us to demonstrate two main issues: (1) comparison with up-and-down method and (2) demonstration of the effect of the number of levels on the precision of obtained results.

The up-and-down method was carried out on 30 samples and the results are summarized in Table 1. The values for the probit method were measured at 4 levels (min. 10 trials at each level). These data were used for comparison with up-and-down. Additional two levels were then measured to demonstrate the effect of the number of levels on the resulting curve. All data for probit analysis are summarized in Table 2.

Results and Discussion

Table 1. Sensitivity data for calculation of F_{50} using up-and-down method

F	outcome of the test, X=failure, O = initiation																
(N)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
15								O		O							
14							X		X		O						
13						X						O				O	
12					X								O		X		O
11		O		X										X			
10	X		X														

cont. Table 1.

F	outcome of the test, X=failure, O = initiation															
(N)	18	19	20	21	22	23	24	25	26	27	28	29	30	n_X	n_O	i
15														0	2	2
14														2	1	3
13					O		O						X	2	4	6
12		O		X		X		O				X		5	4	9
11	X		X						O		X			5	2	7
10										X				3	0	3
													totals			30

Table 2. Sensitivity data for calculation by probit method

F	outcome of the test, X=failure, O = initiation											n_X	n_O	i	P
(N)	1	2	3	4	5	6	7	8	9	10	11	12			
16	X	O	O	O	X	O	O	O	O	X	O		3	8	11	72,7
14	O	X	O	O	O	O	O	X	X	O	X		4	7	11	63,6
12	X	O	O	X	X	O	O	O	X	O			4	6	10	60
10	O	O	X	O	X	X	O	O	X	X	X	X	7	5	12	42
9	X	X	X	O	O	X	X	O	X	O			6	4	10	40
7	X	O	X	X	X	X	X	X	O	X			8	2	10	20

n_X - number of failures; n_O - number of initiations; i - overall number of trials on particular level
P - probability of initiation

The result from the up-and-down method is the 50% probability level determined as F_{50} = 12.3 N with the standard deviation S = 2.6 N. However the ratio of standard deviation and used step S/D = 2.6 is outside the permitted interval ($0.5 < S/D < 2$) [2, 3, 5] and therefore the whole procedure should be repeated again. That means, that in this particular case we have only very crude estimation of F_{50} after performing 30 trials.

The whole sensitivity curve can be obtained from probit analysis. The probability of ignition was determined at the levels of friction force 7, 9, 10 and 12 N. The results are summarized in Table 2. The regression line between logarithms of friction forces and probits is plotted in Figure 4. The 95% confidence intervals are also plotted in this Figure. This regression line (together with the confidence intervals) can be transformed backward into the probability-friction force coordinates. The resulting sigmoidal curve is displayed in Figure 5. The confidence regions have a quite big scatter, mainly in the extrapolated parts of the curve. The 50% probability level was determined as F_{50} = 10.6 N. This value is with 95% probability in the interval ⟨9.7; 12.4⟩.

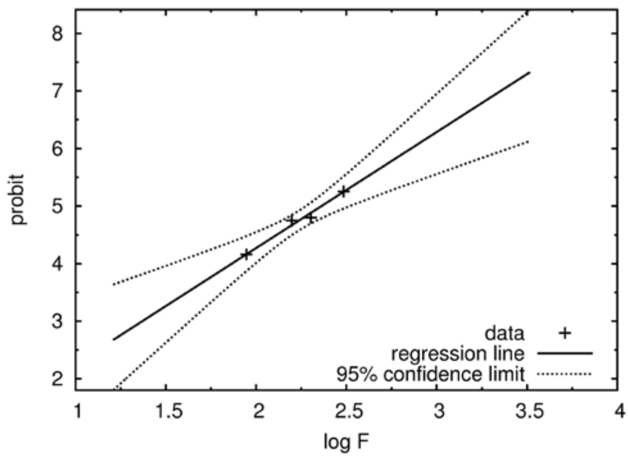

Figure 4. Probit regression line (4 levels).

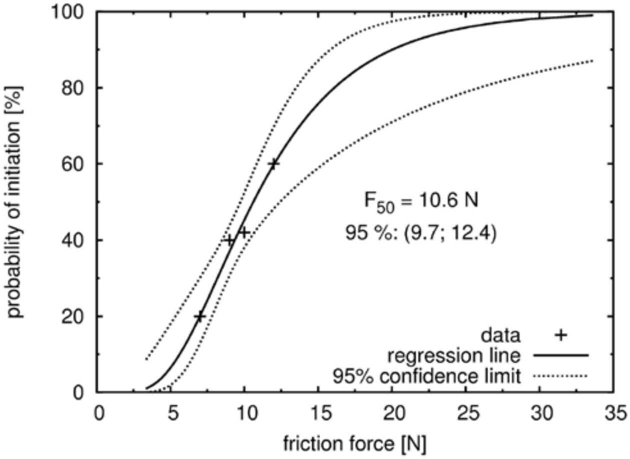

Figure 5. Sensitivity curve (4 levels).

To investigate the improvement of the precision of the whole sensitivity curve, the probability of ignition was determined at two additional levels of friction force (14 and 16 N). The previously obtained probabilities cover the range from 20 to 60%. The higher levels of friction force were selected to get the probabilities of ignition from interval ⟨60%; 100%⟩. The resulting regression line is plotted in Figure 6. The confidence region is narrower than in the previous case (compare with Figure 4). The final sensitivity curve with quite narrow 95% confidence region is plotted in Figure 7. The determined value of 50% probability level is F_{50} = 11.0 N, with the 95% probability interval ⟨10.4; 11.7⟩.

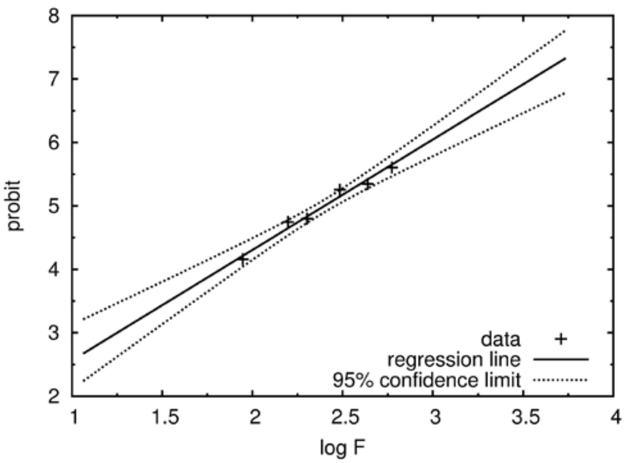

Figure 6. Probit regression line (6 levels).

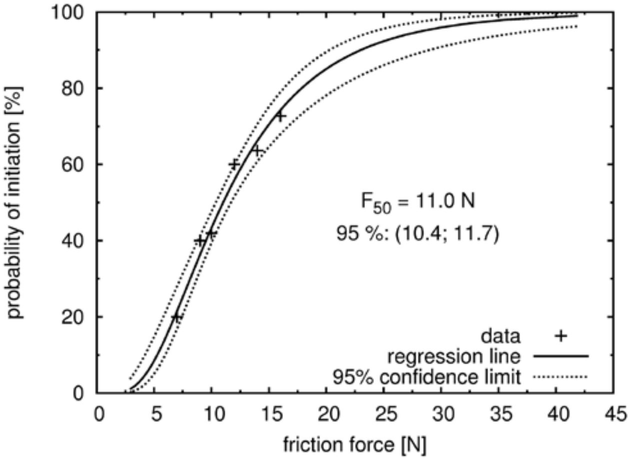

Figure 7. Sensitivity curve (6 levels).

The first round of probit sensitivity test contained 42 trials. The 50% probability level was determined with not so bad precision expressed by 95% confidence interval. The basic idea about the sensitivity curve was obtained. Performing next 22 trials led to much improved precision of the whole curve. On the other hand, from the 30 trials of the up-and-down method only the crude value of F_{50} is obtained which is comparable with the value of F_{50} from the probit analysis of the first series of trials. However in the case of up-and-down method, the additional trials may (but do not have to) lead only to a more precise information about F_{50}. No information is obtained about the whole sensitivity curve.

Conclusion

Probit analysis seems to be a very useful tool in the evaluation of the sensitivity of explosives. Its main benefit in comparison with the standard up-and-down method is obtaining of the whole sensitivity curve from similar number of trials compared to up-and-down method. Furthermore the result of this kind of analysis can be easily improved by performing an additional series of trials.

Acknowledgements

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