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Multivariate analysis applied to a test procedure for determining gun propelling charge weight Part II. Partial least squares analysis

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Abstract

The aim of this study was to find out why several 155 mm gun propelling charge lots produced according to the conventional test procedure for determining gun propelling charge weight had failed to meet the acceptance requirements. Multivariate analysis was applied as an alternative approach to the conventional analysis method to a data set consisting of results connected to 68 test firing occasions. In this paper the results of partial least squares (PLS) modeling applied to the data set are reported. Based on this study the main defects in the conventional analysis method could be identified, the propelling charge lots with safety risks could be traced and the consequences of the change in the procedure parameter could be evaluated.

Keywords: Multivariate analysis; Partial least squares; Internal ballistics; Test firings; Gun propelling charges

1. Introduction

A conventional gun is essentially a heat engine in which the chemical energy of the propellant is transformed into the kinetic energy of the projectile [1]. Nitrocellulose based gun propellants are most commonly used as main propellants in gun propelling charges. The internal ballistic cycle includes all the phenomena taking place during the barrel phases of firing.

In long range firings an essential aim is the maximum muzzle energy. Longer range and greater accuracy are constant objectives when new ammunition is developed. Thus the gun propelling charge has to be determined very precisely in order to ensure precise muzzle velocity value and small muzzle velocity dispersion. According to the firing tables for the 155 mm round combination to be studied, the effect of 1 m/s muzzle velocity deviation on firing distance at range 17.5 km is about 27 m, and correspondingly at range 27.5 km about 47 m. Thus, in the field firing situation wide and uncontrolled discrepancies in the muzzle velocity values between propelling charge lots can have a substantial impact on hit probability.

Unexpected difference in muzzle velocity level has several times been found between the analyzed results of the two test firings (charge establishment and uniformity tests) carried out for each main propellant lot. The gun propelling charge lots produced according to the test procedure for determining gun propelling charge weight used by the Finnish Defence Forces (FDF) had also too often failed to meet the acceptance requirements. The data set consisted of the test firing results for 68 propellant lots of the test procedure for determining gun propelling charge weight of 155 mm full charge, base-bleed ammunition. In the first part of this study [2] principal component analysis (PCA) was applied in order to make a preliminary analysis of the data set.

A mathematical model typically refers to a deterministic and often causal mathematical relationship between the systematic parts of measured variables. The deviations between systematic parts and the data (the residuals) are often explicitly shown in this mathematical relationship [3]. For example, the conventional method used in the initial analysis of the results to be discussed in this paper may well not provide adequate accuracy

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of the correction factors used or take into consideration unexpected changes in procedure parameters. The latter possibility already materialized as a change of the barrel forcing cone construction and in the use of several projectile types [2].

The partial least squares (PLS) method is a modern statistical method combining features from principal component analysis and multivariate regression analysis [4–8]. The PLS method is a representative of the chemometric approach aiming at modeling covariance in data structures as presented by the authentic individual measurements [9]. Thus PLS provides an independent check on the validity of mathematical models. The PLS method has been applied in pattern recognition, classification and discrimination, process monitoring and quality control, modeling and optimization of processes, statistical experiment design, chemical structure – (re)activity modeling of chemicals and multivariate calibration in analytical chemistry. PLS has also earlier been used for process and quality monitoring. However no example of applying PLS in connection to gun propelling charge establishment was found in the literature.

The idea of this study was to repeat the analysis of the data set using an alternative approach to the conventional method of analysis. Using PLS modeling data sets connected to 67 test firings could be studied simultaneously, instead of separate analysis of each test firing carried out with a conventional method of analysis. The aims of this study were to gain further information of possible defects in the procedure studied and to evaluate the usability of the propelling charge lots produced.

2. Experimental

2.1. Test procedure for determining charge weight and the data set

The round studied consisted of the 155 mm full charge with inert projectile and base-bleed unit. The main components of the charge are first a primer igniter of granular porous nitrocellulose propellant, second a primer igniter of tubular porous nitrocellulose propellant and the main propellant of multitubular single base propellant in cloth bags. The propelling charge is ignited with a breech percussion primer. A base-bleed unit is a metal cylindrical body equipped with a propelling charge mounted on the base of the projectile. The base-bleed unit can extend the range of the projectile by as much as 30% [10].

A description of the measurement of variables, data sets and the FDF test procedure has been given in [2]. A schematic presentation of the measuring system is shown in Fig. 1. The variables to be modeled are the temperature of the propelling charge (T_r), the weight of the main propellant (m_r), the relative vivacity of the propellant lot (B_r), the moisture content of the main propellant (H_r), the projectile weight (m_a), the barrel wear (L), the muzzle velocity of the projectile (V_0), the peak chamber pressure by piezo-electric measurement (P_h) and the peak chamber pressure by crusher measurement (P_{cr}).

The main purpose of charge establishment is to determine the weight of the main propellant that will fulfill the defined muzzle velocity requirement within the maximum permissible peak chamber pressures. In addition, it is also ensured that the main propellant lot meets the ballistic requirements given for standard deviations in peak chamber pressure. The maximum permissible peak chamber pressures for each gun, projectile and charge type to be approved for war materiel have to be specified according to defined standards [11] in order to manage the risk of gun and/or ammunition breakage during firing.

The purpose of the uniformity tests is to ensure that the propelling charges produced based on charge establishment fulfill the specified muzzle velocity requirement, and to ensure that the requirements for standard deviations in muzzle velocity and peak chamber pressure and for maximum permissible peak chamber pressures are fulfilled.

In the charge establishment and the uniformity tests technically similar measurements are carried out. In an analytical sense these firings differ, because for each propellant lot three different test charge weights are used in charge establishment, but in the uniformity tests only one charge weight is used.

The initial data set included uncorrected data connected to 2842 rounds fired by a 155 mm test gun on 67 test firing occasions 1999–2003. The number of propellant lots was 68. The data set was formed by collecting data from the test firing database of the FDF and from the propellant procurement documents. Data design has been described in [2]. For each charge establishment or uniformity test there was only one projectile type and one gun barrel. Likewise for all series fired, for each propellant lot, there was only one relative vivacity (B_r) and moisture content (H_r), for each test charge size one main propellant weight (m_r) and for each serial one charge temperature (T_r).

In light of the analysis of the initial data set with 13 variables, some observations were eliminated and the data set was divided on the basis of the barrel forcing cone construction used in the test firings into two parts referred to as cone 1 (1098 observations) and

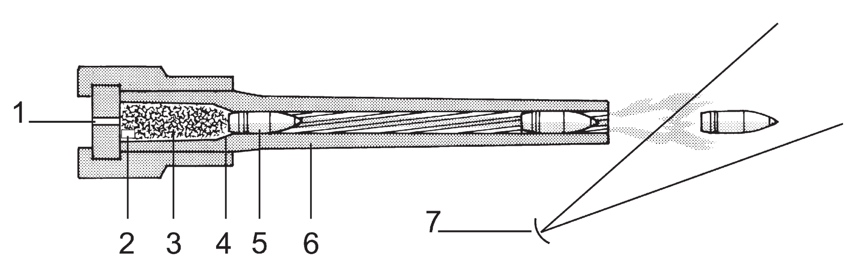

Fig. 1. Measuring system used in test firings. 1. Piezo-electric transducer, 2. Crusher gauge, 3. Gun propelling charge, 4. Barrel forcing cone, 5. Projectile, 6. Barrel, 7. Doppler radar.