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Prediction of Shot Start Pressure for Rifled Gun System

N.V. Sudarsan[#,*], R.B. Sarsar[#], S.K. Das[@], and S.D. Naik[#]

[#]DRDO-Armament Research and Development Establishment, Pune - 411 021, India
[@]DRDO-Defence Institute of Advanced Technology, Pune - 411 025, India
[*]E-mail: nvshemrl@gmail.com

ABSTRACT

Determination of short start pressure (SSP) for gun system has always been of paramount interest for gun designers. In this paper, a generalised model has been developed for theoretical prediction of SSP for rifled gun system using dimensional analysis approach. For this, parameters affecting the SSP of the gun like rifling dimensions, driving band dimensions, material properties of driving band, projectile mass and diameter are taken into consideration. For a particular case of large caliber rifled gun system, the model is established using linear relations among dimensionless groups of parameters. The model has been validated by data available from the open literature.

Keywords: Driving band; Forcing cone angle; Coefficient of friction; Rifled barrel; Dimensional analysis

1. INTRODUCTION

Internal ballistics (IB) deals with the processes that take place inside the gun which is expressed in terms of pressure travel, peak pressure and muzzle velocity as an output. IB study is carried out with either lumped parameter model or gas dynamic model[1-3]. In Lumped parameter model the output is described in terms of its mean properties. This model is employed when the desired results are muzzle velocity and peak chamber pressure of given gun system and is governed by the initial conditions/design parameters from gun, projectile and propellant. Lumped parameter model is inapt for study of flame spread and pressure wave of combustible gases in the gun for which gas dynamic model is used.

SSP is one of the initial parameters of lumped parameter model[4]. When the pressure developed by gases overcomes the initial resistance offered by the loaded projectile, the projectile starts moving inside the barrel. This pressure is called as SSP. The deviation in ballistics performance parameters such as muzzle velocity and peak pressure is due to presumed value of SSP[5]. A marginal deviation in the value of SSP affects on the initial part of P-S curve. Higher SSP results in higher peak pressure and lower SSP favours to lower muzzle velocity[6]. Generally SSP is determined experimentally, which is costly and time consuming process. Particularly for artillery shells, it becomes very difficult to obtain the value of SSP experimentally. A generic theoretical model for prediction of SSP is beneficial to overcome this problem.

Venkatesan[7] and Aggarwal[8] have addressed problem of SSP evaluation and derived an explicit relation between maximum pressure and SSP. The work carried out is applicable only for tubular shaped propellant charge systems. Serebryakov[9] has assumed that SSP is engraving pressure of driving band and its value for normal guns lies between 25 MPa to 40 MPa. The model developed by Schenk[10], *et al*. has described that SSP is an outcome of the resistance, which depends on various properties of driving band like material properties and geometry, as well as its deformation in terms of extrusion and incision processes. Tao[4], *et al*. has defined SSP as a ratio of maximum value of the deformation resistance during the engraving process and the cross sectional area of the gun bore. Siewert[11] has given empirical relations for resistance pressure model for medium and large caliber projectiles where the projectile having a driving band that is interference fitted with both the lands and grooves of the barrel. SSP of projectile is affected by driving band parameters, gun barrel parameters and projectile parameters[12-15]. In the present paper, an effort has been made to develop a generic model for prediction of SSP for rifled barrel gun system. Gun and projectile parameters are used as input parameters and dimensional analysis approach is considered to construct a mathematical model for SSP. The prediction of SSP for large caliber rifled gun system is discussed as a particular case study of the general model.

2. IMPORTANCE OF SSP FOR RIFLED GUN SYSTEM

SSP is one of the input parameters of lumped parameter model, which is determined from dynamic trials/guess value. For different weapon systems, the guess value variation in SSP may result in deviation in muzzle velocity and peak pressure for the same input. To understand effect of SSP on the IB performance parameters, sensitivity analysis of SSP is carried out for rifled gun system using lumped parameter model. Higher SSP has higher peak pressure value as well as higher muzzle velocity. Lower SSP has lower peak pressure value and lower

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muzzle velocity. Here it is demonstrated with 120 mm rifled gun system using three different values of SSP 10 MPa, 30 MPa, and 50 MPa. The respective Pressure – Travel and Velocity-Travel curves are depicted in Fig. 1. It is observed that due to variation of SSP from 10 MPa to 50 MPa, the peak pressure reaches from 430 MPa to 580 MPa and muzzle velocity varies from 1635 m/s to 1720 m/s. Guess value of SSP contributes to the deviation in calculation of the ballistics performance parameters. To reduce such deviations, a theoretical model is required for prediction of SSP. This work proposes one such model using dimensional analysis approach.

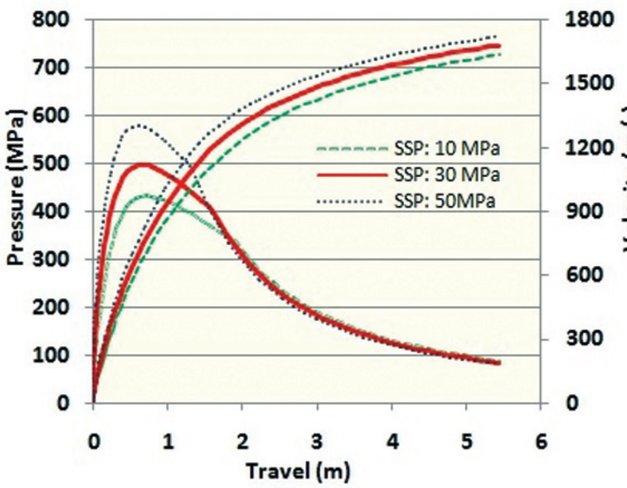

Figure 1. Effect of SSP on IB solution.

3. DIMENSIONAL ANALYSIS METHOD FOR SSP EVALUATION

Dimensional analysis defines a method for reducing complex physical problem to the simplest form prior to obtaining a quantitative solution[16]. For the practical problem, dimensional analysis application is based on the hypothesis. Its solution is a dimensionally homogeneous equation in terms of specified parameters. To model any physical phenomenon of the system with dimensional analysis approach, one has to study all the parameters, which influence the phenomenon defined in the system. Develop dimensionally homogeneous equations using these parameters and solve these equations with the help of algebraic techniques.

For evaluation of SSP, one has to first identify the parameters affecting SSP and using these parameters develop homogeneous equations which can be solved with algebraic techniques.

3.1 Parameters Affecting SSP

The projectile of rifled gun system has driving band which induces spin to the projectile for stability during trajectory. To achieve the SSP for a projectile in a rifled gun system, it has to overcome resistance offered by driving band during engraving process along with initial inertia.

Generally, diameter of the driving band exceeds the rifling groove diameter. It has left and right bevel portions. Before firing the projectile is positioned at its seizing-bore location. After ramming, the driving band is tightly in contact with the inner wall of the barrel as shown in Fig. 2. During burning of the propellant, gas pressure in the chamber rises which increases the pressure at base of the projectile. This base pressure pushes the driving band through the caller diameter of forcing cone hence deformation of driving band takes place. Further driving band is forced into rifling of the barrel and driving band is engraved so that it fits in the rifling of the barrel. The engraving process is divided in three stages namely:

(i) Forcing cone is partially filled with right bevel portion of driving band material
(ii) The forcing cone is totally filled with driving band material
(iii) Diving band material keeps on decreasing in forcing cone till left bevel portion passes through it.

Accordingly the contact area of driving band also changes. The engraving resistance depends on the contact area of driving band with barrel, their properties and geometry[17-21].

SSP of rifled gun system is influenced mainly by driving band parameters, gun barrel parameters and projectile parameters. To evaluate the SSP the parameters taken into consideration along with their dimensions and notations are given in Table 1.

Table 1. Units, symbols and dimensions of parameters affecting SSP

Parameter	Unit	Symbol	Dimensions
Density of driving band	kg/m^3	ρ	$M^1L^{-3}T^0$
Diameter of driving band	m	d_b	$M^0L^1T^0$
Yield strength of band	Pa	σ	$M^1L^{-1}T^{-2}$
Coefficient of friction	----	μ	$M^0L^0T^0$
Contact area	m^2	A	$M^0L^2T^0$
Depth of groove	m	d_g	$M^0L^1T^0$
Width of groove	m	w_g	$M^0L^1T^0$
Width of land	m	w_l	$M^0L^1T^0$
Mass of projectile	kg	m_s	$M^1L^0T^0$
Diameter of projectile	m	d	$M^0L^1T^0$

3.2 General Model for SSP

The general form of SSP (P_0) using all the affecting parameters is defined as:

$$P_0 = f\left(\sigma, \mu, \rho, d_b, A, m_s, d, d_g, w_g, w_l\right) \tag{1}$$

In the present study, Buckingham's Π-theorem is used to collect all affecting parameters of SSP in dimensionless

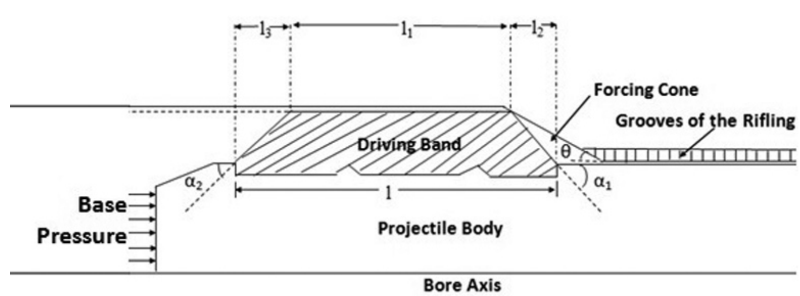

Figure 2. Initial position of driving band in the rifled gun system.

products (π)[22]. The required algebraic equations in terms of π are determined with respect to the individual parameters. Then a dimensional matrix is prepared as shown in Table 2. Using fundamental dimensions the dependent as well as independent parameters are defined. Here x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, and x_{11} are indices of the parameters P_0, σ, μ, ρ, d_b, A, m_s, d, d_g, w_g, and w_l, respectively. For application of Π-theorem, first it is necessary to select the replicate and non-replicate parameter. Based on the following situations five parameters are selected as replicate parameters.

Table 2. Fundamental dimensional matrix of the model

Dimensions	Model parameters										
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}
	P_0	σ	μ	d_b	ρ	A	m_s	d	d_g	w_g	w_l
M (Mass)	1	1	0	0	1	0	1	0	0	0	0
L (Length)	-1	-1	0	1	-3	2	0	1	1	1	1
T (Time)	-2	-2	0	0	0	0	0	0	0	0	0

(a) The dependent parameter (SSP) is not the replicate parameter
(b) The replicating parameters are of different properties
(c) Replicating parameters do not form a dimensionless group
(d) Replicating parameters together contain the same number of fundamental dimensions
(e) No two replicating parameters should have the same dimensions.

Thus, coefficient of friction, depth of grooves along with width of groove and lands are selected as the non-replicating parameters. The dependent parameter, SSP, is also selected as non-replicating parameter. Remaining parameters (projectile diameter, yield strength of driving band, driving band density, projectile mass and contact area) are chosen as the replicating parameters.

The dimensional formula for the relation in Eqn (1) is:

$$\left[ML^{-1}T^{-2}\right]^{x_1} = \left[ML^{-1}T^{-2}\right]^{x_2}\left[M^0L^0T^0\right]^{x_3}\left[L\right]^{x_4}\left[ML^{-3}\right]^{x_5}\left[L^2\right]^{x_6}\left[M\right]^{x_7}\left[L\right]^{x_8}\left[L\right]^{x_9}\left[L\right]^{x_{10}}\left[L\right]^{x_{11}} \tag{2}$$

A set of simultaneous equations are formed by equating the powers of the fundamental dimensions on both sides of Eqn (2). Further the magnitude of these constants is obtained from the solution of simultaneous equations. Then the five dimensionless products are determined by solving for the x's. The final results of dimensional analysis are given in Table 3.

From the results the following complete set of dimensionless products is obtained:

$$\pi_0 = \left[\frac{P_0}{\sigma}\right], \pi_1 = \left[\frac{d_g}{d}\right], \pi_2 = \left[\frac{md_b}{\rho d^4}\right],$$

$$\pi_3 = \left[\frac{A}{d^2}\right], \pi_4 = \left[\frac{w_g}{w_l}\right] \tag{3}$$

Table 3. Results of dimensional analysis

Index	π_0	π_1	π_2	π_3	π_4
x_1	1	0	0	0	0
x_2	-1	0	0	0	0
x_4	0	0	1	0	0
x_5	0	0	-1	0	0
x_6	0	0	0	1	0
x_7	0	0	1	0	0
x_8	0	-1	-4	-2	0
x_9	0	1	0	0	0
x_{10}	0	0	0	0	-1
x_{11}	0	0	0	0	1

Coefficient of friction (μ) is dimensionless quantity and it is directly proportional to SSP. Without loss of generality Eqn (1) can also be written as

$$\pi_0 = \mu\, g(\pi_1, \pi_2, \pi_3, \pi_4) \tag{4}$$

Thus the general model of SSP for rifled gun system is:

$$P_0 = \sigma\mu\, g(\pi_1, \pi_2, \pi_3, \pi_4) \tag{5}$$

g is the function of non dimensional quantities $\pi_1, \pi_2, \pi_3, \pi_4$ which is different for different gun systems and can be linear or non linear.

4. CASE STUDY - SSP FOR LARGE CALIBER RIFLED GUN SYSTEM

A case study is carried out by using this model to predict the SSP of large caliber rifled gun system. To reduce the complexity of mathematical calculations, the following assumptions are made to simplify the model.

(i) Engraving of the driving band is instantaneous and the projectile will not move until the pressure in the bore reaches its maximum engraving pressure.
(ii) After ramming, the forcing cone is filled completely with the initial part of the driving band material, remaining part of the driving band travel through forcing cone during engraving process.
(iii) Relation among dimensional products is linear.

Using Eqn (5) and the above assumptions, the SSP for large caliber rifled gun system can be written as:

$$P_0 = \sigma\mu\,(k_1\pi_1 + k_2\pi_2 + k_3\pi_3 + k_4\pi_4 + k_5) \tag{6}$$

where k_1, …, k_5 are constants and dimensionless products are

$$\pi_1 = \left[\frac{d_g}{d}\right], \pi_2 = \left[\frac{md_b}{\rho d^4}\right], \pi_3 = \left[\frac{A}{d^2}\right], \pi_4 = \left[\frac{w_l}{w_g}\right] \tag{7}$$

Here the contact area between driving band and gun barrel (A) is computed using geometry of driving band from Fig. 2 and law of sines as given in Eqn (8).

$$A = \pi d_b\left[l_1 + lm_2 + (l - l_1)m_1\right] \tag{8}$$

where $l_1 = l - (d_b - d)\cot\alpha_1$

$$m_1 = \frac{\cos\alpha_1 \sin\theta}{\sin(\alpha_1 - \theta)}$$

$$m_2 = \frac{\cos\alpha_2 \sin\theta}{\sin(\alpha_2 - \theta)}$$

Here l - length of driving band; l_1- length of driving band at top; α_1 α_2 - right and left bevel angle; θ - forcing cone angle.

For estimation of five constants (k_1, …, k_5) in Eqn (6), five sets of data associated with 105mm and 155mm rifled barrel gun systems are selected randomly from available data, which is depicted in Table 4[4,6,23].

A set of simultaneous linear equations in k's has been established using data from Table 4. The matrix form of this linear system is shown in Eqn (7) and the solution of this system is obtained using Gauss elimination method.

$$\begin{bmatrix} 0.0115083 & 8.1300476 & 0.4548798 & 1.568 & 1 \\ 0.0115142 & 1.5661444 & 0.5482337 & 1.400 & 1 \\ 0.0083618 & 7.4883969 & 0.5166038 & 1.568 & 1 \\ 0.0083617 & 1.4310342 & 0.6511491 & 1.468 & 1 \\ 0.0106860 & 1.4541480 & 0.3191242 & 1.400 & 1 \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \\ k_5 \end{bmatrix} = \begin{bmatrix} 1.6933333 \\ 2.5998804 \\ 1.7733333 \\ 2.2619617 \\ 1.67763158 \end{bmatrix} \tag{9}$$

The solution of Eqn (9) is k_1= 14.3047; k_2= 0.1697; k_3= 3.8974; k_4= -9.8641; k_5= 13.8450.

k values are marginally varying with selected data set.

Thus, the model for SSP of large caliber rifled gun system is:

$$P_0 = \mu\sigma \left\{14.3047\left[\frac{d_g}{d}\right] + 0.1697\left[\frac{md_b}{\rho d^4}\right] + 3.8974\left[\frac{A}{d^2}\right] - 9.8641\left[\frac{w_g}{w_l}\right] + 13.8450\right\} \tag{10}$$

5. RESULTS AND DISCUSSIONS

The validation of SSP model is done by applying this model for different types of large caliber gun systems. The calculated values are compared with reported values. A total of five test cases namely Case A, Case B, Case C, Case D, and Case E are considered from different types of gun systems: 105 mm, 120 mm, 130 mm, 155 mm, and 175 mm, respectively. The required input parameters for each test case are obtained from PROjectile Design/Analysis System (PRODAS®) commercial software and available data in literature are provided in Table 5. The output of SSP model for each test case and its comparison with available literature data[4,6,21,23] are depicted in Table 6, it shows that the error is less than 3 per cent.

Table 6. Comparison of test cases results with reported values

	SSP (MPa)		
	Reported	Calculated	Error
A	35.1	34.5	0.6
B	29.0	28.6	0.4
C	12.0	11.3	0.7
D	12.0	12.4	0.4
E	39.0	37.9	1.1

Table 4. Data for large caliber rifled gun system

Parameters	Units	I	II	III	IV	V
Projectile diameter	m	0.10505	0.105	0.15499	0.15499	0.1545
Driving band density	kg/m^3	1661	8430	1661	8304	8330
Driving band length	m	0.015	0.01815	0.025	0.03175	0.01587
Driving band diameter	m	0.1078	0.1072	0.1595	0.15748	0.1585
Depth of groove	m	0.001209	0.001209	0.001296	0.001296	0.001651
Forcing cone half angle	deg	3	3	5.742	2.87	2.5
Coefficient of friction	-	0.15	0.22	0.15	0.22	0.22
Yield strength of band	MPa	40	76	40	76	76
Projectile mass	kg	16	14.97	45	43.545	43.545
Ratio of width of land and groove	-	1.568	1.4	1.568	1.468	1.4
Contact area	m^2	0.00502	0.006044	0.01241	0.015642	0.007618
SSP	MPa	10.16	43.47	10.64	37.82	28.05

Table 5. Input parameters of test cases

Parameters	Units	Case A	Case B	Case C	Case D	Case E
Bore diameter	m	0.105	0.12	0.13	0.155	0.175
Driving band density	kg/m3	8430	1661	1661	1661	8940
Driving band length	m	0.015	0.0395	0.035	0.0285	0.025
Driving band dia	m	0.108	0.1235	0.135	0.1595	0.179
Depth of groove	m	0.0012	0.0012	0.0013	0.0013	0.0016
Forcing cone half angle	deg	3	3.704	5	5.74	5.5
Coefficient of friction	-	0.22	0.15	0.15	0.15	0.22
Yield strength of band	mPa	76	40	40	40	76
Projectile mass	kg	16	6.9	33	45	79
Projectile diameter	m	0.105	0.12	0.13	0.155	0.175
Ratio of width of land and groove	-	1.40	1.38	1.57	1.56	1.40

Sensitivity analysis of depending parameters of SSP is carried out for 155 mm rifled gun system. SSP is estimated for each case by changing nominal value of one parameter and keeping remaining parameters the same. The results are depicted in Table 7. The variation in driving band length, projectile diameter and ratio of width of groove and land affect the SSP significantly. Density of driving band, driving band diameter, depth of grooves, forcing cone half angle and mass of projectile marginally influence the value of SSP.

Table 7. Sensitivity analysis for SSP with depending parameters

Parameter	Units	Nominal value	Deviation (%)	Variation in SSP (%)
Driving band density	kg/m3	8303.97	10	1.0
Driving band length	m	0.03175	1	1.6
Driving band dia	m	0.15748	5	1.0
Depth of groove	m	0.001296	10	1.0
Forcing cone half angle	deg	2.87	10	0.1
Coefficient of friction	-	0.22	1	1.0
Yield strength of band	mPa	76	1	1.0
Projectile mass	kg	43.545	10	1.0
Projectile diameter	m	0.15499	1	1.3
Ratio of width of land and groove	-	1.468	1	6.0

6. CONCLUSIONS

A generalised model has been developed for rifled gun system using dimensional analysis approach. A case study for large caliber rifled gun system with linear relations is established and validated. The results are well corroborated with the reported values with a maximum deviation of 3 per cent. The major depending parameters affecting SSP are ratio of width of groove and land, driving band length and projectile diameter. The model employed in this study is useful for determination of SSP theoretically for large caliber rifled gun systems.

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CONTRIBUTORS

Mr N.V. Sudarsan received his MSc (Statistics) and MSc (Mathematics) from Osmania University, in 2007 and 2009 respectively. Presently working as Scientist 'C' in ARDE, Pune. His areas of interest are : Internal and external ballistics of guns.
Contribution in the current study, he helped in literature survey, simulation work, data generation, model the SSP and formulated to large caliber rifled gun. Author for correspondent.

Dr R.B. Sarsar obtained his PhD from the DIAT, Pune, in 2014. Presently is working as Scientist 'D' in ARDE, Pune. His areas of research are : Flight dynamics and internal ballistics.
Contribution in the current study, model the SSP, simulated data generation using PRODAS and organising the manuscript.

Dr Samir Kumar Das is working as Professor at Department of Applied Mathematics, DIAT, Pune. He has 25 years of teaching and research experience. He has published more than 100 papers in national/international journals.
Contribution in the current study, he has reviewed the manuscript.

Dr (Mrs) Smita D. Naik obtained her PhD from the University of Poona, Pune in 1988. Presently she is working as Scientist 'G' in ARDE, Pune. Her areas of research are flight dynamics and stability analysis. She has published 55 papers in national/ international journals.
Contribution in the current study, she helped in concept and idea to formulate SSP model and has reviewed the manuscript.