Defence Science Journal, Vol 47, No 4, October 1997, pp. 455-465

Reliability Assessment Based on Design & Manufacturing Tolerances for Control Burst Mechanism of Small Arms

S.K. Basu* & D.R. Sonawane**

and

A.M. Datar

Armament Research & Development Establishment, Pune-411 021

ABSTRACT

Very often specified tolerance is made greater than process tolerance, depending upon (i) the manufacturing process capability, and (ii) the 'aspiration level' of the designer in effecting a specified tolerance. This applies to multiple components merging into an assembly. In assembly tolerance, errors due to mating are inherent. Common errors arise due to clearance, misalignment in planes and distortion that may cause side stack. Such errors affect the functional performance of the subsystem and consequently become the main cause of failure. Probability distribution of the assembly tolerance and probability distribution of stacked up tolerance of the components in actual practice leave a common zone of interaction, based on which the in-built reliability changes. From the designer's tolerance, one may have an idea about the 'aspiration level' of assembly tolerance stacking error. Assuming both these parameters, viz., actual stacking error and designer's aspiration level of stacking error to follow the normal probability distribution, it is possible to get the reliability of the product assembly.

The paper presents a real life case study for assessing the reliability of sub-assembly at the initial stages of development for control burst mechanism (CBM) of rifle.

1. INTRODUCTION

A designer, while designing any mechanism, generally tends to restrict the tolerance level in a narrow band to achieve successful functioning of the mechanism. However, due to practical constraints and limitations of the manufacturing process, as well as requirement of manufacture on a large scale, specific tolerances are needed on these parts. The tolerance levels are thus most important for a designer to decide upon. This is more important for the assembly tolerance, individual components and their dimensional relationship with each other.

Assessing reliability, in such models, is some-what difficult. Moreover, the designer and the manufacturer are interested in achieving the optimum level of tolerance, and the effect of deviations in tolerance on reliability of the

Received 25 June 1997

* 9, Buena Monte, Pashan, Pune-411 008.
** 633/5, Swami Vivekanand Hsg Society, Navi Sangavi, Pune-411 027.

assembly must be assessed before finalising the design. There are several techniques for assessing reliability. In the present study, the authors have attempted to assess reliability based on tolerances and carried out actual work on control burst mechanism (CBM) of a rifle.

1.1 Tolerances & Reliability

The assembly tolerance is dependent on the tolerances of various important dimensions of the components. It can be found out after identifying the dimensional chains. There are three cases which must be considered.

Case(i): When there are linear dimensions, the overall tolerances may be obtained as algebraic sum.

Case(ii): When individual dimensions are related by a trigonometrical or nonlinear relationship, we may have to use 'partial derivative method' to add up the assembly tolerances.

Case(iii): When each dimension has tolerance randomly distributed, we may use random number simulation to obtain the assembly tolerance.

However, very often, we need to have tolerances based on optimisation principle, such as linear programming, when the situation of dimensional chain is similar to case(i). To put it in the programming form,[1] (maximise or minimise)

$$\Phi(z) = w_1 T_1 + w_2 T_2 + \ldots + w_K T_K$$

Subject to constraints $T_i \leq a_i$

and/or $\Sigma T_i \leq b_i$

and non-negativity $T_{1,2,\ldots K} > 0$

where T denotes tolerance, w_K is the weightage given on dimensional tolerance T_K, depending upon the relative importance of T_K on the assembly, and a_i and b_i are some predefined constants.

This will warrant the precise values of the compromised dimensional tolerances, which will consequently help achieve the precision assembly.

Depending on whether $\Phi(z)$ and constraints are linear or nonlinear, linear programming or non linear programming can be used.

In assembly, tolerance stacking errors due to mating are inherent. Common errors arise due to clearance, misalignment in planes and distortion that may cause side shake. Such errors affect the functional performance of the subsystem and consequently become the main cause of failure. Hence, the tolerance stacking error in assembling the subsystem should be included in the fault-tree diagram, as a basic fault event.

Taking a number of observations (say 30), the actual assembly tolerance stacking error can be found out. We also have from the designer's tolerance, an idea about the 'aspiration level' of stacking error of assembly tolerance. Assuming these two parameters, viz., actual stacking error and designer's aspiration level of stacking error to follow the normal probability distribution, it is possible to get the reliability of the subsystem assembly.

It is also possible to relocate tolerance on individual components of the assembly by providing the factor of importance to each, as in AGREE[2] method. This will help augment reliability of the subsystem.

The study carried out on CBM of a rifle is described below.

2. METHODOLOGY

An attempt has been made to quantify the complex nonlinear relationship by some mathematical law. The systematic methodology to be followed is given below:

(a) Define the sequence of important matings of the components based on functional requirements,

(b) Find the mathematical relationship between the related dimensions in the mating sequence,

(c) Determine variation in system tolerance, considering the permissible variation in dimensions by the designer,

(d) Write a computer program to do all the calculations for a given dimension,

(e) Find the statistical distributions of each and every important dimension based on the data provided, from sample observations,

(f) Simulate the functioning of CBM unit for, say 1000 (K) times, using random numbers, and using the above computer program,

(g) If the entire mating sequence is followed by the simulated dimensions, the firing is successful; otherwise it is a failure, and

(h) If there are f number of failures, then reliability may be found using values of f and K.

3. CONFIGURATION OF CONTROL BURST MECHANISM

3. Firing Mechanism of a Rifle

The firing mechanism of the rifle consists of a hammer, a trigger, a sear, a safety sear, a change lever and springs for hammer, etc. This arrangement is shown in Fig. 1. The safety sear provides mechanical safety, so that a round is not fired even accidentally. The change lever enables the soldier to choose the type of firing—repeat or control burst—apart from the safe position wherein the firing mechanism is locked. Each time a round is fired by pressing the trigger, the action of gas on the piston initiates rearward motion of the moving components, namely, piston extension. As it strikes the hammer, it starts swinging backwards against a spring, and is held in 'cocked' position by the sear, and this combination by safety sear. In the forward motion of piston extension, it rides over the combination of hammer and sear since they are spring-loaded and locked by safety sear. At a particular distance during forward motion of piston extension, it depresses the safety sear, releasing the combination of hammer and sear. If the sear is held in this position, it results in firing a single round at a time, whereas if it is depressed with respect to the hammer, it results in full automatic firing. To achieve control burst, a linkage mechanism is to be provided to link hammer, trigger and sear.

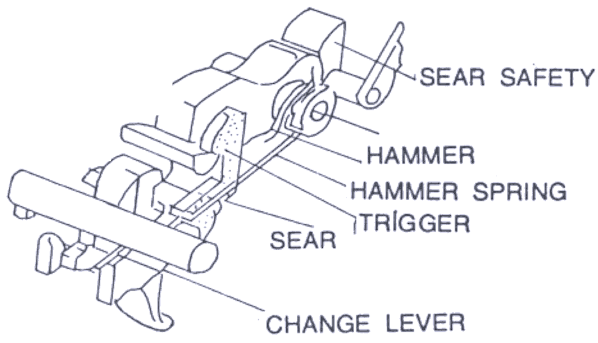
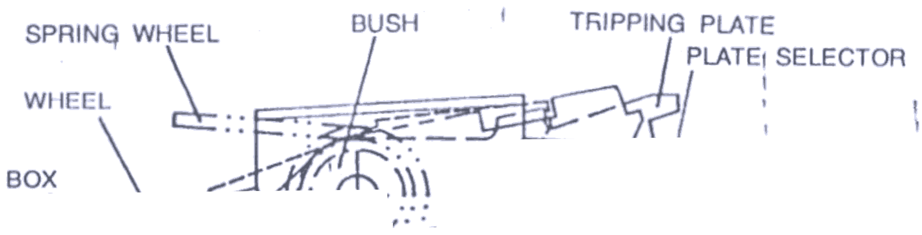


Figure 1. Firing mechanism

3.2 Control Burst Mechanism

The control burst mechanism has been integrated into the main firing mechanism as a compact and replaceable module. It is placed between the hammer and the change lever. The CBM consists of a box, which contains a spring-loaded wheel, a tripping plate, and a plate selector. The assembly of CBM is shown in Fig. 2. The hammer is fitted with a spring-loaded pawl. These components are made in sheet metal by press work and thus have a very small thickness (0.7-1.5 mm). The wheel has a peculiar shape, having dissimilar teeth at front and rear ends. There are three teeth at the front end and two at the rear. The shapes of the teeth are peculiar, as the functions to be performed by front and rear teeth are different. The shapes of the tripping plate and the plate selector are so designed as to occupy less space, yet provide effective linkage to carry out the required functioning with adequate strength. These components basically link the wheel to the sear in the third round firing position and the change lever to the wheel in control brust position respectively. The components are shown in Fig. 3. Thus, the CBM becomes a special case of rack-pinion mechanism. The engagement of pawl and wheel is controlled in such a way that after the third round is fired, they are disengaged automatically and further action can take place only after release and re-pulling of the trigger.



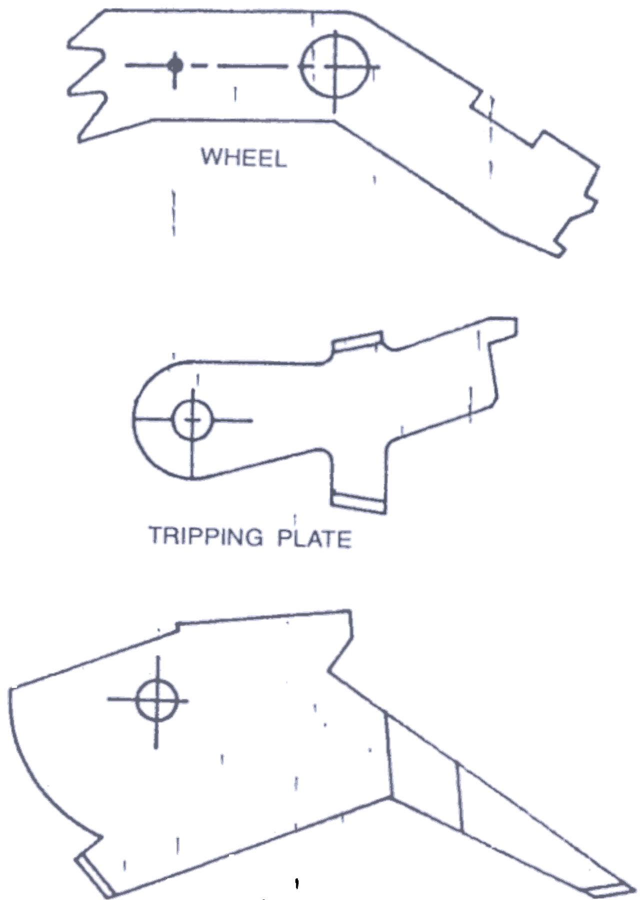


Figure 3. Components of control burst mechanism

3.3 Functioning of Control Burst Mechanism

The functioning and sequence of control burst firing are illustrated in Fig. 4 and are explained as: (i) When the change lever is set at the control burst firing position, its lug pushes the plate selector down, which, in turn, pushes the wheel up, bringing it in the circular path of the pawl. The hammer in this position is held by the trigger and is now ready to fire (Fig. 4(a)). (ii) When the trigger is pulled, the hammer gets released and swings forward. The pawl engages the front first tooth of the wheel during this action. The sear is, in turn, engaged with the rear first tooth of the wheel and is kept clear of the path of the hammer (Fig. 4(b)). After the round is fired under recoiling action, as explained earlier, the hammer swings back and the pawl being spring-loaded, slips down. When the rearward motion is complete and the forward motion starts, the hammer is also free to swing forward, as the sear has been kept away from its path. During this period, the pawl engages the second tooth at front and the sear gets engaged to the second rear tooth, again keeping it out of the path of the hammer. By completing its forward swing, the second round is fired. (iii) Again, under the action of gas, the hammer starts swinging back and the pawl slips down. When the backward swing is over, under spring load, the hammer starts its forward swing, as the sear is out of path. The pawl engages the front third tooth of the wheel. The wheel now engages the tripping plate, which presses the sear so as to keep it away from the path

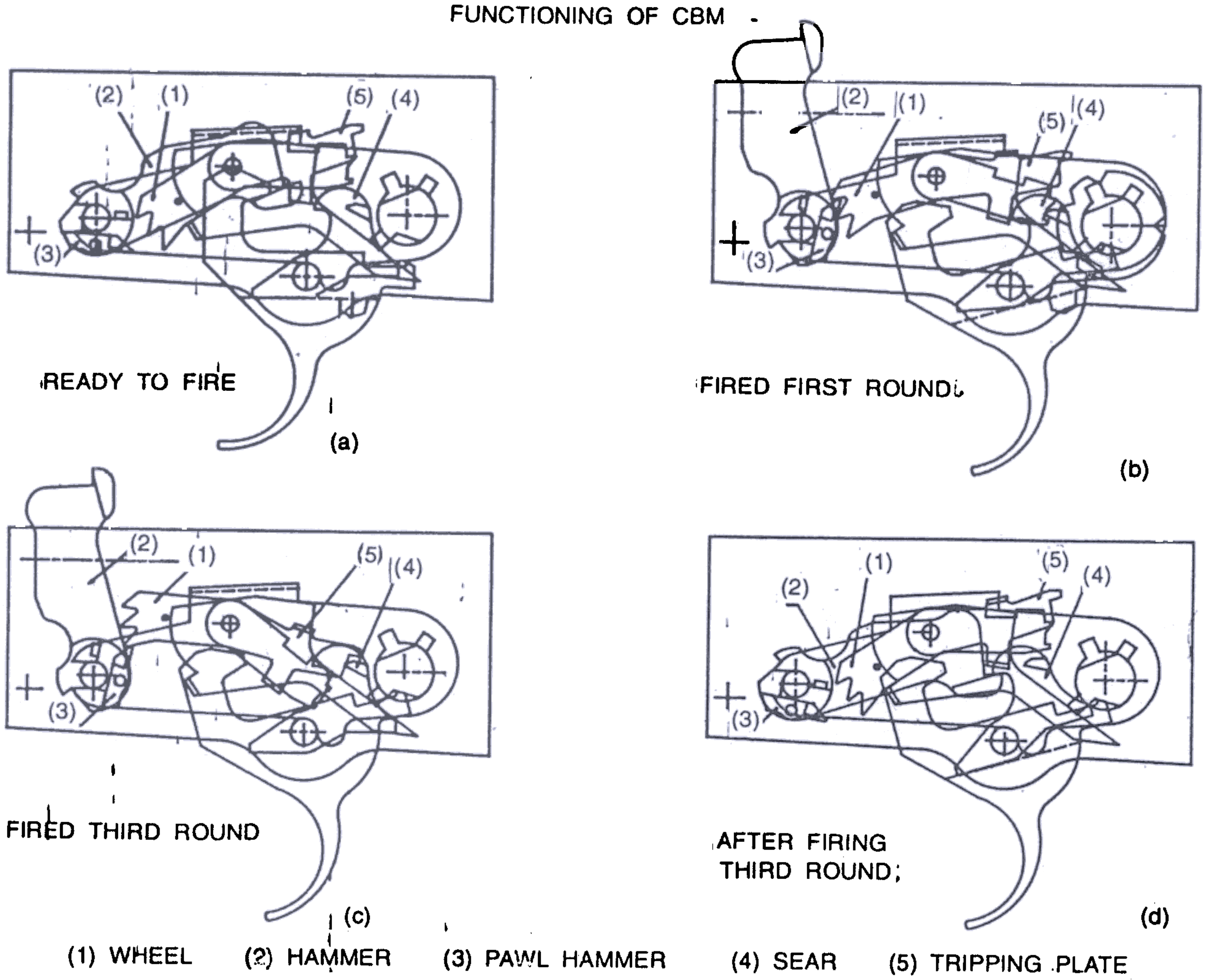


Figure 4. Sequence of operation of control burst mechanism

of the hammer. The third round is then fired (Fig. 4(c)). (iv) During its backward swing after firing the third round, the pawl slips down. Since the wheel is now not engaged with the sear at the rear end, it comes to its original position under spring load. This results in movement of the tripping plate as well, which releases the sear. Thus, when the hammer swings back fully, it gets arrested by the sear. After this, the hammer is no more free to swing forward. As such, moving masses do complete their motions, feeding the next round into the chamber. However, since the hammer is held back, firing stops (Fig. 4(d)). (v) Further firing can be effected only after release of the trigger and then pulling it again to start the action.

3.4 Action Set: Sequence of Important Mating Parts

Action	Rotation of plate selector along with the lug,
Action 2	First tooth of wheel and pawl mating,
Action 3	Protrusion of auxiliary sear and rear end of wheel,
Action 4	Second tooth of wheel and pawl mating,
Action 5	Protrusion on sear and rear end of wheel,
Action 6:	Pawl touches at the lower portion of the wheel at front end,
Action 7	Protrusion on sear and tripping plate mating,
Action 8	Wheel disengaged from the sear, and

Action 9 Hammer is held by the scar

4. RELIABILITY OF CONTROL BURST MECHANISM

Proper functioning of the CBM can be assured if it works under variable conditions of changes in rate of firing, which depends on the amount of gas controlled by the gas regulator, variation in spring characteristics, leakages of gas at various positions, etc. Further, the design being of modular concept, interchangeability of the CBM unit is the main requirement. As such, the dimensional accuracies of various components, assembly of CBM and variation in assembly into the main firing mechanism play crucial roles. Since production accuracy requirements are very stringent, the reliability assume considerable importance.

To study the total reliability of the CBM, the total functioning can be divided into various action sets. Each set comprises certain actions played by a combination of various components. A general idea of such action sets and the components involved is given in Section 3.4. These action sets have been analysed for their mutual interdependent functioning. Geometric equations have been formulated for each of the action sets. Maximum and minimum conditions of various parameters are taken into account to find out the possible output of the action set. All the combinations, which fall within the desired limits, contribute to reliability. The overall reliability can then be found using the equation

$$Ro = R1 * R2 * \quad * Rn$$

where Ro is the overall reliability and $R1$, $R2$ are reliabilities of individual action sets.

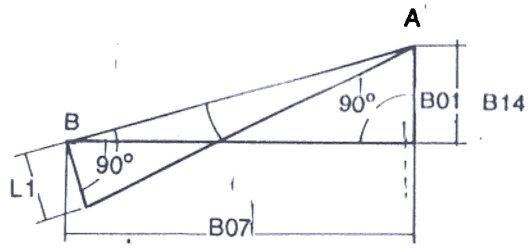
The malfunctioning modes considered for the study are[3]

(a) Non engagement of pawl and wheel

(b) Firing single shot only

(c) Firing two shots only

(d) Firing full automatic mode



5(a) A - WHEEL CENTRE
B - LOG CENTRE

Figure 5(a). Rotation of plate selector

Each action set relates to one of the modes of malfunctioning. Such combinations have been studied by solving the equation for each action set and finding probability of error/malfunctioning.

5. MATING SEQUENCE

Refer to Figs 5 (a), (b), (c) wherein $B01$, $B02$, ... : dimensions on box, numbered as 1, 2, etc. and $W01$, $W02$, ... dimensions on wheel, numbered as 1, 2, etc.

5.1 Action (1): Rotation of Plate Selector

The distance between centre of plate selector and centre of lug is

$$D1 = \sqrt{(B01 - B14)^2 + B07^2} \tag{1}$$

Radius of the outer circle of the lug = $L1$

Actual rotation of the plate obtained by subtracting the offset 01 will be

$$D2 = (L1 - O1) \tag{2}$$

From this, we get,

$$D3 = \sqrt{(D1^2 + D2^2)} \tag{3}$$

and the angle of rotation is thus given by

$$\theta 1 = \cos^{-1}(D1/D3) \tag{4}$$

Using Eqns (1) to (4), the plate rotation angle has been calculated. Refer to Fig. 5(a).

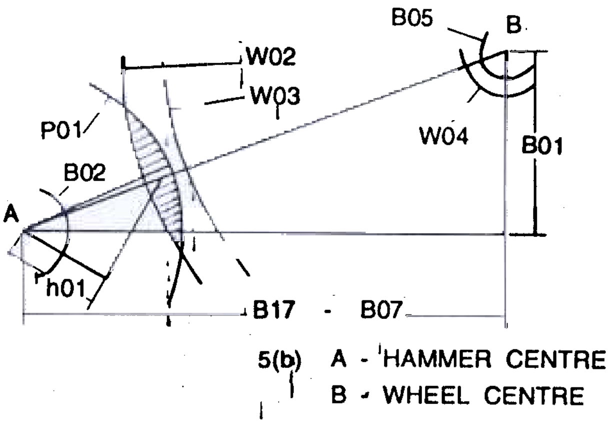


Figure 5(b). Dimensions in pawl and wheel mating

5.2 Action (2): Basic Interference between Wheel & Pawl

The dimensional chain may be drawn as follows:

W02 <------------------> $\sqrt{p01^2 + h01^2}$ <------------------------------------>

<----------------------------------> $\sqrt{B01^2 + (B17 - B07)^2}$ <--------------------------> Interference

Basic interference =

$$W2 + \sqrt{p01^2 + h01^2} - \sqrt{B01^2 + (B17 - B07)^2} \quad (5)$$

where $p01$ is the related dimension on pawl and $h01$ is related dimension on hammer.

The range of interference between pawl and wheel is shown in Fig. 5(b).

5.3 Action (3): Protrusion on Sear & Wheel Mating

Sear and wheel mating criterion defined as the angle of rotation of the wheel should be greater than the angle of protrusion on sear.($\theta 7 > \varepsilon$).

Refer to Fig. 4.1(c), in which the interference zone is shown. All the dimensions are related in nonlinear way. So, simulation will be a better solution for seeing the dimensional chain.

Referring to Fig. 5(c), to find ε,

$$R1 = \sqrt{(B01+B15)^2 + (B07 - B17 + B16)^2} \quad (6)$$

$$\theta 2 = \cos^{-1}((B07 - B17 + B16)/R1) \quad (7)$$

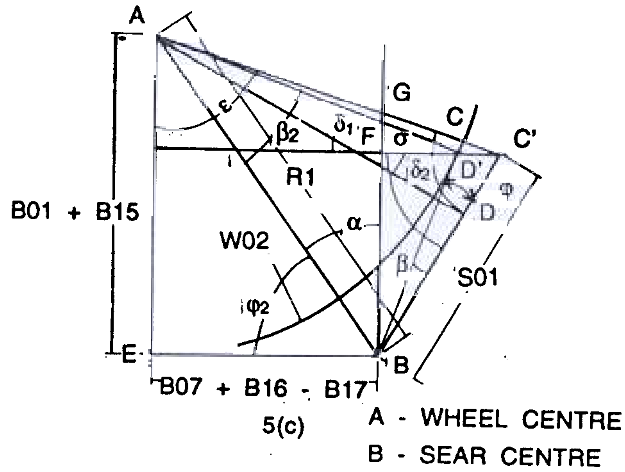


Figure 5(c). Wheel and protrusion on sear mating

$$\alpha = 90 - \theta 2 \quad (8)$$

Also, r * θ is the offset provided on the sear

Thus, $\beta = 24 + \Phi$ and $\delta = 90 - \theta 2$

$l(BD) = R1 * \sin(\alpha + \beta)$

and $l(AD) = R1 * \cos(\alpha + \beta)$

$$\sigma = \tan^{-1}(DC'/AD) \quad (9)$$

where $l(DC') = l(BC') - l(BD)$ (10)

$$\beta 2 = 180 - \beta - \alpha - \delta 2 \quad (11)$$

$\delta = 90 - \beta$

Thus, $\varepsilon = \delta 2 - \delta$ (13)

The wheel rotation angle is found from Eqn. (2) and

$$L2 = \sqrt{(B01 - B14)^2 + B07^2} \quad (14)$$

$$L3 = \sqrt{L2^2 + D2^2}$$

and $\theta 3 = \cos^{-1}(L2/L3)$ (15)

Let $L4 = B17 - B07 - \sqrt{(h01^2 + p01^2)}$, and

$L5 = \sqrt{(B01^2 + (B17 - B07)} - \sqrt{(h01^2 + p01^2)}$

so, $\theta 4 = \cos^{-1}(L4/L5)$

Therefore, $\theta5 = \theta4 - (40.76 - \theta3)$ (18)

An important criterion is that $\theta5$ should be greater than zero. Now let $\theta6$ be the angle by which the wheel swings up. The corresponding angle at the rear end of wheel is then given by

$$r1 * \theta5 = r2 * \theta6 \quad (19)$$

Then the wheel rotation angle is

$$\theta7 = \theta4 - 5.16 + \theta5 + \theta6 \quad (20)$$

(The wheel rotation angle at the rear end should be greater than the above angle; otherwise it is failure. i.e., $\theta7 > \varepsilon$)

The above three action sets model firing of the first round in a control burst. A similar formulation has been done to model firing of the second and third rounds.

5.4 Simulation of Mechanism for Firing Three Rounds

Using the formulae as above, a computer program is written to simulate the mechanism for firing three rounds. A specified set of dimensions and designer's specified tolerances were considered. This program is interactive, so that the user may change the dimensions and the tolerances and then simulate the mechanism for, say, *n* number of times. The designer's base values and tolerances have been considered for the simulation run, wherein normal distributions have been assumed. The program gives the result for every firing whether it is successful or unsuccessful. It also gives how many times the mechanism is successful during the run. The program also gives the set of dimensions which have caused failure. The above listed formulae may be used to find the mean and variance of the $\theta7$, ε etc. which are critical for successful functioning. Thereafter, using these parameters, reliability can be found assuming normal or some other distribution.

5.5 Simulation Run

Using the program, a simulation run for values with σ, $2*\sigma$ and $3*\sigma$ was carried out. The results of the simulation run are given in Table 1 (each run consists of 1000 rounds and *R* indicates the values of reliability).

Table 1. Results of simulation run

Run No.	Multiplier of σ	Success	Failure	Reliability[+]
1	$1*\sigma$	984	16	0.972
2	$2*\sigma$	972	28	0.963
3	$3*\sigma$	950	50	0.948

[+] Demonstrated reliability, using binomial sampling method

6 VALIDATION OF SIMULATION PROGRAM

To find the pattern of variation in the dimensions, data were collected on 10 sets of CBM mechanism. Using this data, histograms were plotted (Fig. 6(a)). Also, an attempt has been made to fit some statistical distributions to these data sets (Table 2). It is observed that the variation is not necessarily normal, but may sometimes be skewed (Fig. 6(b)).

Table 2 showing *t* value with 8 degree-of-freedom and 0.05 level of significance = 2.306. Calculated *t* value for normal distribution is less than table *t* value. So, the dimensional variation pattern is well explained by normal distribution.

After commencement of mass manufacture, during a period when it was considered that the production had stabilised, 10 sets of CBM subassembly were selected at random from the production run. They were mismatched for dimensional data and all relevant dimensions were noted. They were assembled again and put for firing test from two rifles. The actual firing values are given in Table 3. A total of 60 rounds, i.e. 20 burst, were fired and burst either less than three or more than three were recorded as unsatisfactory performance.

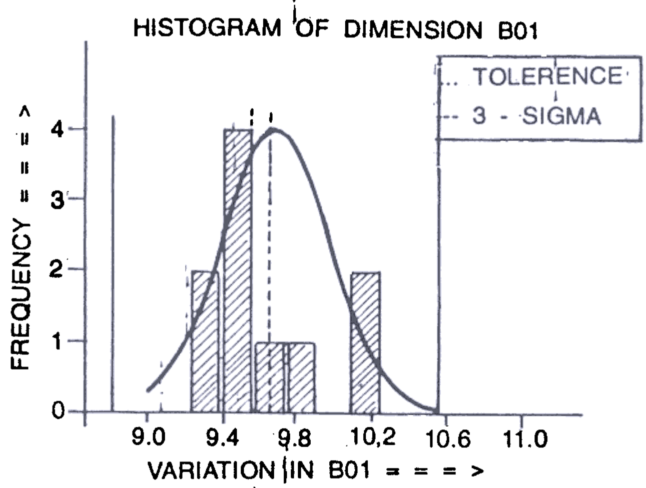


Figure 6(a). Normal variation pattern

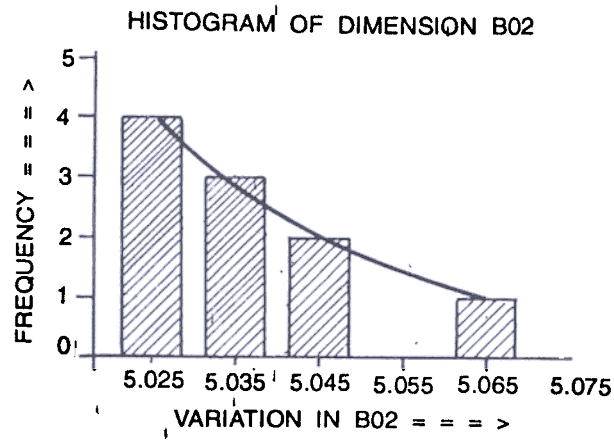


Figure 6(b). Non-normal variation pattern

7. ANALYSIS OF SIMULATION RUN DATA

Based on the data for 10 sample sets wherein actual measurements of related dimensions were made, a simulation run was carried out.

(a) Analysis of Action 1 shows variations found in the rotational angle using the actual dimensional data matched with the variation using tolerances allowed by the designers. The range of the rotational angle is 10.947 ° to 11.081°. Based on the analysis, it is found that the angle varies from 10.8485 ° to 10.9814 °. Thus, there are cases in which the angle is lower than the minimum angle required.

(b) Analysis of Action 2 shows that the actual range of interface based on dimensional data is much wider as compared to the designer specified limits. The upper limit is well matching. However, the lower limit is well below the specified limit.

(c) Analysis of Action 3 shows that the actual range of tolerance stacking matches well with designer specifications.

(d) The cumulative simulation run of the complete action set predicts reliability of 95 per cent with the present set of dimensions. This is

Table 2. Statistical analysis of dimensional data

(a) Dimension B01

Distribution	Parameters	*t* value
Normal	μ = 9.688; σ = 0.28893	1.6355
Beta	m = 38.62; n = 4.216	3928.74
Exponential	θ = 0.10322	185.6655
Gamma	α = 1.999 × 10-5 θ = 484424.1	14823.628
Weibull	$p1$ = 4.32; σ = 16744.88	14823.628
Log Normal	$m1$ = 9.68419; $s1$ = 0.0081	724.3326

(b) Dimension W04

Distribution	Parameters	*t* value
Normal	μ = 5.012; σ = 0.0074	1.1683
Beta	m = 31.21; n = 6.436	1361745.3
Exponential	θ = 0.19952	150.6289
Gamma	α = 1.999x10-5 θ = 250612.5	2.5910
Weibull	$p1$=6.196; σ = 19611.37	5099083.5
Log Normal	$m1$ = 5.011; $s1$ = 0.0001	724.3326

Table 3. Firing data from field trial (s - sucess; f - failure)

Set No.	Rifle No. 1		Rifle No. 2	
1	9s	1f	10s	0f
2	9s	1f	10s	0f
3	9s	1f	10s	0f
4	10s	0f	9s	1f
5	10s	0f	9s	1f
6	8s	2f	9s	1f
7	7s	3f	10s	0f
8	10s	0f	10s	0f
9	10s	0f	10s	0f
10	10s	0f	10s	0f

in good agreement with the real figures found by actual firing. It is also found that the variation in the dimensions in the actual components was greater than specified tolerances. However, in actual functioning, the results were found satisfactory. Such cases, though vary few in number, may be due to complex nonlinear relationships which we have simplified for the purpose of the present study.

From the dimensional analysis, it is found that the variations in dimensions are not always normally distributed, as shown in Fig. 6(b). Here, most of the dimensions were within the designer's limit. So, this non-normal distribution has not affected the function of the weapon.

From the simulation run, it was found that even if the tolerances of some dimensions are released, it does not affect the reliability. Accordingly, designers have released the tolerances to ease manufacture. On the contrary, two dimensions were most sensitive for any change. The tolerances were tighter in this case.

From the results of simulation, it is clear that the reliability of the CBM unit comes near about 95 per cent for a given set of basic dimensions and tolerance values.

The 5 per cent drop in reliability may be due to the limitations of process capabilities to produce the components within the specified tolerances[3]

8. CONCLUSION

The model was extremely useful in establishing the reliable functioning of CBM of a rifle. The rifle is presently under mass manufacture and is being used by the Indian Army.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the help and guidance provided by Dr S.K. Salwan, Director, Armament Research & Development Establishment (ARDE), Pune and Shri P. K. Roy, Jt Director, ARDE during the course of this work and the permission accorded to publish this paper.

REFERENCES

Nagoi, B.K.A. & Tan, K.C.K. Tolerance stack analysis for assembly. *Proc. Instn. Mech. Engrs.* 1996, **210**(B2), 279-89.

2 Rao, S.S. Reliability-based design, McGraw-Hill, Inc, 1992.

3. Datar, Anil & Roy, P.K. Control burst mechanism for rifle. Proceedings of National Conference on Mechanics and Mechanisms (NACOMM 95), Jan. 1996. p. A6-A11.

Contributors

Prof SK Basu is Professor Emeritus at Government College of Engineering, Pune. During 1959-61, he worked in the Machine Tools Research Institute (ENIMS), Moscow, as UNESCO fellow and visited a large number of scientific and research institutions in USA and Germany under NSF and DAD scientists exchange scheme. He has about 150 technical papers to his credit published in international/national journals and has guided 20 PhD students in the areas of tribology and machine tools. He is a winner of four prestigious awards of the Institution of Engineers, (India), for the best papers published. He won *AIMTDR* awards in 1982 and 1984 conferences and *NRDC* awards in 1976, 1977 and 1986. He has written five engineering textbooks and has a number of patents to his credit.

Mr DR Sonawane did his MSc (Statistics). For the past three years, he has been associated with assignments in reliability engineering from various defence laboratories. He is working mainly on mechanical systems, including hydraulic systems. He is also responsible for software development in related fields. He has published several technical papers.

Mr AM Datar is presently Dy Director, Aeronautical Research & Development Establishment (ARDE), Pune. He has done his BE from College of Engineering, Pune and MSc (Gun System Design) from Royal Military College of Science (RMCS), Cranfield University, UK, where he also won trophy for his performance. He has also obtained Master's Diploma in Business Administration. For the past 10 years, he has been working in the field of weapon design and has specialised in the area of small arms. He is Chartered Engineer and a member of Institution of Mechanical Engineers (India).