Practical Methods of Optimizing the Maximum Range for Rockets

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Abstract: - Range extension for artillery projectiles, rockets, and missiles is a problem of trajectory optimization based on a set of constraints aimed at maximizing the range as a measure of performance. Solid Rocket Motors (SRM) are rocket motors that use solid propellants. For higher engine efficiency and cost minimization, optimization of the engine is necessary, which implies a modification of the schematics of the engine. SRM optimization is currently a key topic in aerospace engineering research.

Because some input data remain constant, others can be considered as variables, and their influence on the performance parameters of the rockets was investigated. In some investigations, the time until impact is an important performance parameter; in others, the range can be considered as the performance parameter to be optimized.

In this study, pulsed solid propellant rocket motor technology was considered to demonstrate a feasible method for range extension.

For the targeted optimization problem, the influence of the thrust profile along the launching angles was studied, and the results from the performed calculations were analyzed and discussed.

Key-Words: - Optimization design, rocket range extended, multi-pulsed solid rocket motor, rocket efficacity

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1 Introduction

Solid Rocket Motors (SRM) are rocket motors that use solid propellants. SRM is very important in the modern field of aerospace propulsion systems and will be a core part of it for the foreseeable future. Compared to other types of rocket propulsion systems, the SRM option is preferred because of its simpler manufacturing technology, long-lifetime storage, short time required for launch preparation, ease of operation and handling, and large potential amount of chemical energy concentrated in a relatively small volume. In addition, lower costs are preferred compared to other types of rocket motors. Even with the advent of reusable rocket boosters, SRM and its development will be essential in ballistic technology. In counterbalance to the advantages mentioned above, there are a number of disadvantages, the main one being reduced control over thrust and therefore over the energy profile developed by the motor. Optimization of the SRM constitutes the core part of the research in this field, with the aim of minimizing cost and maximizing engine efficiency for specific situations, payloads, and vehicles [1]. The modern era demands increasingly complex optimization processes with new variable profiles that need to be monitored using new multidisciplinary optimization methodologies.

Because many products from artillery, projectiles, rockets, and missiles currently use SRM, the problem of optimizing the method of managing the energy produced by the engine is essential [2].

The distance traveled horizontally from the launch position to the ground impact position is known as the range. The problem of range extension for projectiles, guided or unguided missiles, has been intensively studied and discussed in the past, and still represents a permanent preoccupation in this domain. Because optimization methods permit better use of the available energy, many methods have been developed over time [3], [4].

Several methods of range extension can be approached from different perspectives:

- Optimizing the aerodynamic configuration to minimize drag. This method involves a new geometric shape for the wings, body, nose, or the entire assembly. Sometimes, new materials are required to maintain mass balance for stability.

- Optimization of the design configuration by staging. This method involves major changes in configuration and technology [5].
- Optimizing solid propellant rocket motors (SRM) [6], [7] using:
    - Grain composition with a higher specific impulse (Isp) propellant for higher efficiency – requires replacement of grains and nozzle redesign;
    - Grain design for optimizing the burning surface – reshaped grains, if possible;
    - Geometric design of the motor (optimization of the burning chamber and especially the nozzle, including fixed or variable geometry).

In addition to those listed above, pulsed SRM technology is a method for optimizing SRM and can be a simple way of extending the range [8], [9]. A pulsed rocket motor is typically defined as a multiple-pulse solid-fuel rocket motor. Typically, an SRM cannot be easily shut down and reignited. The pulse rocket motor allows the motor to burn in segments (or pulses) until the completion of that segment. The next segment can be ignited on command either by an onboard device/algorithm or in a pre-planned sequence. All the segments are contained in a single rocket motor case, as opposed to staged rocket motors [10]. This concept allows energy management for the same amount of propellant used in conventional SRM.

The benefit of the pulsed rocket motor is that near-optimal energy management of the propellant burn can be accomplished by the on-command ignition of the subsequent pulses. Each pulse can have a different thrust level and burn time and can achieve a different specific impulse depending on the type of propellant used, its burn rate, its grain design, and the current nozzle throat diameter [11].

This technology is already in use, and an example is the anti-hail rocket, which will be used as the computational model in this study.

2 Problem Formulation

2.1 Model Description

The existing RAG-96 anti-hail rocket, which represents the analysis model in this study, has a two-pulsed SRM created by splitting the grain into two segments [12]. Between the two segments a pyrotechnic delay device is placed to ensure the continuity of burning and simultaneously prevent the other segment from burning until ignition (Fig.1). The lag devices are small components of the rocket that contain a pyrotechnic composition with a slow burning rate and almost no thrust.

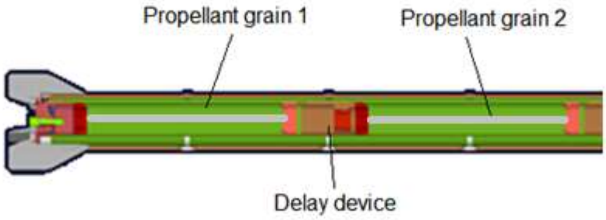

Fig. 1 Two-pulsed rocket motor

The delay device produces a lag time Δt that practically divides the thrust into two sequences (Fig.2). The delay time can be adjusted using this device (by varying the composition or geometric design) to obtain an optimized trajectory of the missile. Depending on the delay time Δt, the profiles of the thrust diagrams will differ. The first pulse determined the same thrust sequence for all cases, and the only difference was the starting time of the second thrust sequence.

The total energy produced by the rocket motor is almost the same, but the profile of its use over time is different and produces different results for the flight parameters and implicitly, for the trajectory of the rocket.

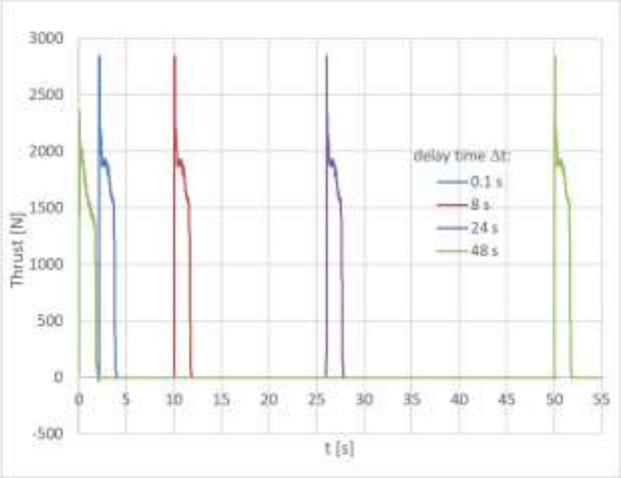

Fig. 2 Thrust diagrams for different delay times Δt

The scope of this study is to analyze the lag time Δt (delay time) between the sequences of Thrust 1 and Thrust 2 in order to obtain a maximum range for the rocket trajectory.

For the first approximation of the trajectory, a 3 degrees of freedom (3-DOF) mathematical model was used.

The forces acting on the rocket are: thrust, gravitational force, and aerodynamic forces (lift and drag).

By modifying the delay time (Fig.2), a new thrust distribution is practically involved in the motion equations, and implicitly results in a new flight path. As a result, the trajectory depends on the lag time. The obtained effect is that the trajectory of the rocket is more flattened and elongated, which is advantageous in some cases (guided projectiles or missiles, hail combat).

The rocket used as an example for performing the calculations evolved in the supersonic regime. It is well known that the transient regime from subsonic to supersonic is a very important energy consumer because the drag increases at speeds around Mach 1. This technology was used in a practical way to optimize the trajectories of the anti-hail rocket, except that for this type of rocket, optimization was performed to flatten and lengthen the trajectory. However, the same method can be used to optimize the maximum range for a number of ballistic products that use SRM.

2.2 Input Data

We propose to study the influence of the delay time Δt on the trajectory path using the input data of a certain anti-hail rocket currently in production and use. All input data related to mass and aerodynamic configuration, as well as SRM are provided in [12].

The investigations carried out in this study were performed by varying the delay time from 0.1 s to 48 s.

In addition to the influence of thrust variation with time, the trajectory is also influenced by the variation of rocket mass with time (Fig. 3). The rocket has a variable mass during its evolution, primarily owing to propellant consumption.

Pyrotechnic devices are connected together to form pyrotechnic chains, thus enabling the generation and propagation of pyrotechnic signals. A pyrotechnic chain consists of a succession of devices distributed according to a dedicated architecture designed to be as safe and reliable as possible.

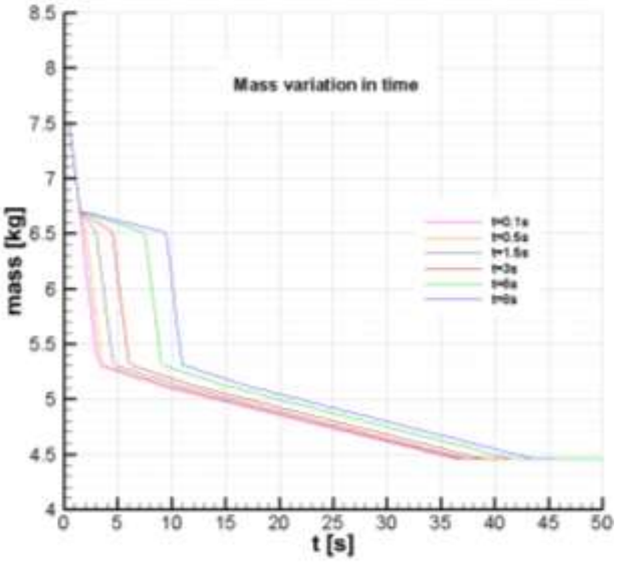

Fig. 3 Mass variation over time
for different delay times Δt

Starting from the same initial mass for all cases, a linear mass variation was considered for each sequence of operation corresponding to the devices involved in the pyrotechnic chain, which involves mass consumption.

3 Numerical Results

The time and position parameters specific to the evolution of the rocket were obtained by integrating the motion equations, starting from the initial data and conditions.

The trajectories were calculated starting from sea level (H=0m), under ideal conditions (without considering the influence of the wind, mass, geometric, or thrust deviations).

The trajectories can be analyzed on the basis of different launching angles combined with different delay times as input data.

The range of the missile depends on the initial launch conditions, the most important of which is the launching angle. Fig. 4 expresses clearly the trajectories for different launching angles from 30^0 to 60^0. They were calculated for the particular case when Δt=0.1s as a reference base for subsequent calculations.

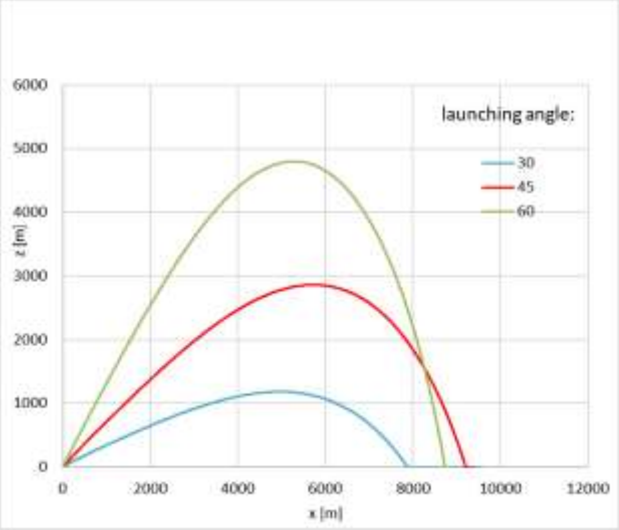

Fig. 4 Trajectories for different launching angles for delay time Δt=0.1s

It is well known that for a ballistic trajectory, the maximum range is obtained when the launch angle is approximately 45^0. Therefore, this particular launch angle was chosen as the input data for most of the calculations and analyses performed in this study. The influence of the delay time on the trajectory, especially on the maximum range, is clearly shown in Fig. 5 for 45^0 launching angles.

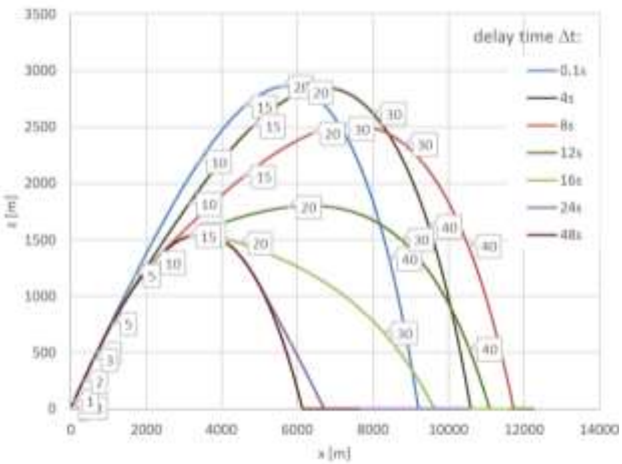

Fig. 5 Influence of Δt on trajectories for 45^0 launching angles

The increase of Δt results in a continuous decrease of the maximum height of the trajectory, as can be observed from Fig. 5. This is explained by the engine's division of energy, which enables the missile to evolve in ballistic motion between two simultaneous pulses. During this ballistic evolution, the thrust is zero and the gravitational effect prevails. In other words, a trajectory flattening is obtained. After the first thrust pulse, the rocket is allowed to evolve freely in the gravitational field, the energy developed in the second pulse being less used for an ascending evolution, but rather horizontal, increasing the range.

Without this delay device, it can be seen that the maximum range is slightly over 9 km. Another observation from Fig. 5 is that the range initially has an increase with Δt, followed by a decrease. This means that there is an optimum value of Δt for obtaining the maximum range for a certain value of launch angle. On the same diagram, there are the moments of time associated with the rocket's evolution. The influence of the parameter Δt on the position of the rocket at a particular moment in time is evident. The different evolution of the rocket leads to different moments of impact.

Fig. 6 illustrates the influence of Δt on the impact moment of the rocket for 45^0 launching angles. As we can see there are two extrema for this function: a maximum and a minimum value.

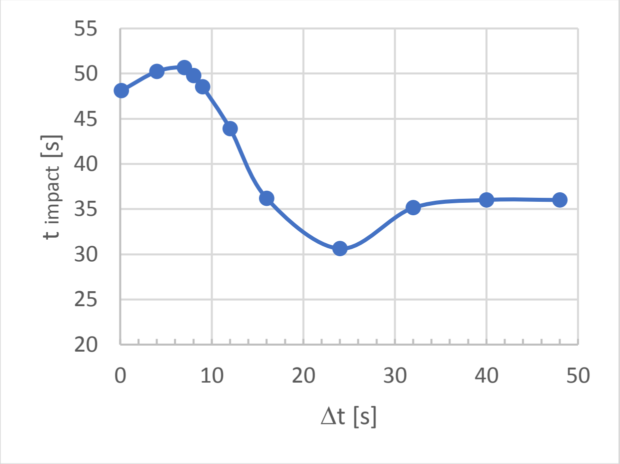

Fig. 6 Dependency on Δt of the impact moment of the rocket for 45^0 launching angles

Starting to increase Δt from 0s, the impact time will rise to a maximum which corresponds to the maximum range.

After a certain moment of time, when the rocket reaches the downward part of the trajectory, any increase in thrust will have the effect of shortening the range and reaching the ground faster, i.e. reducing the impact time till a minimum is reached.

Continuing to increase the Δt, the impact time will rise again and then will remain constant because the moment for the start of the second pulse becomes higher than the impact time.

The conclusion is that the increasing maximum range is obtained by paying the price of increasing the time of impact.

Representing the range dependency of Δt (Fig. 7) for different launching angles, we can see that there is an optimum Δt for each launching angle that maximizes the range.

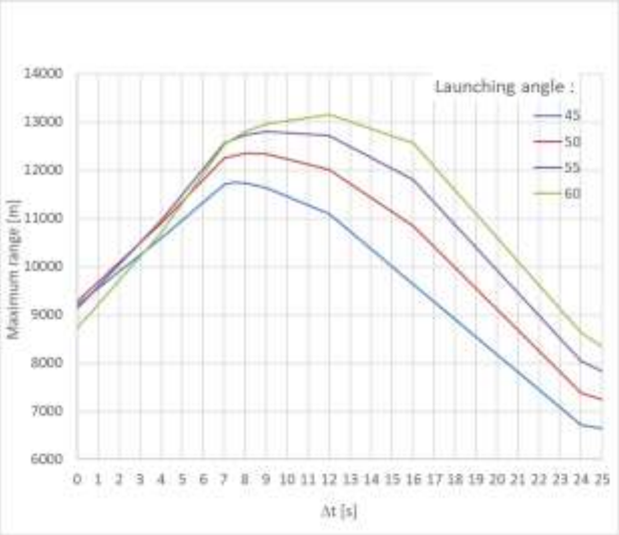

Fig. 7 Maximum range dependence on Δt

From Fig. 7 it can be seen, with certain limitations, that the same range can be obtained for different launch angles by calibrating the time interval Δt of the delay device.

Otherwise, we can represent the optimum values of the maximum range dependence on Δt in Fig. 8. This means that by calibrating good values for Δt and using higher elevations for launching, the maximum range could be increased by more than 20% for this particular rocket.

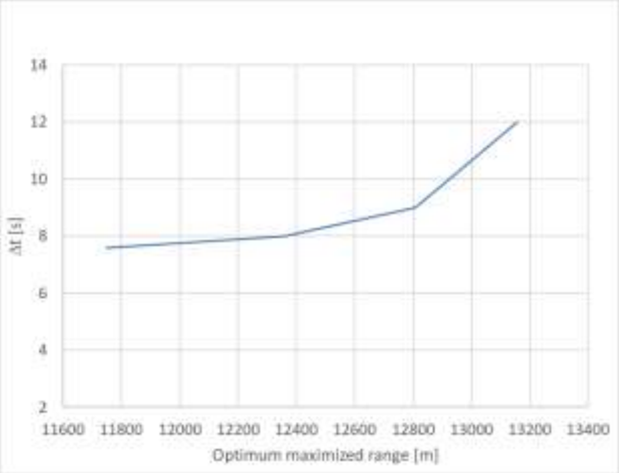

Fig. 8 Optimization of the maximum range

If we analyze the influence of the delaying time Δt on the velocity profile (Fig. 9) computed only for 45^0 launching angles, it is obvious that the maximum velocity of the rocket depends on Δt.

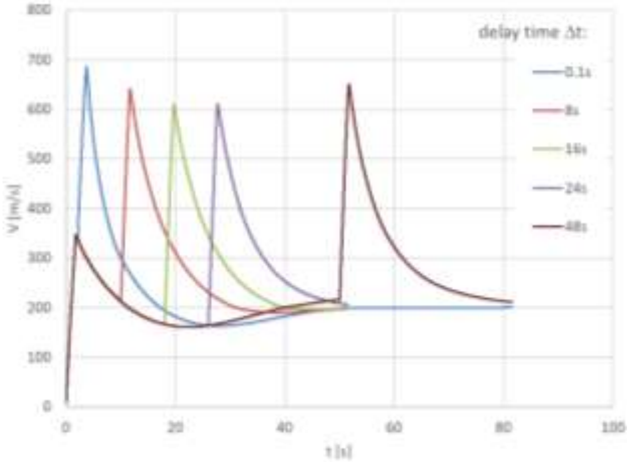

Fig. 9 Velocity dependence on Δt for 45^0 launching angles

For the present case, the rocket has a supersonic evolution (Fig. 9), regardless of the Δt value. For other products the transonic regime could be avoided by optimal engine energy management, keeping the rocket in subsonic regime. The results obtained could be even more spectacular because the high energy loss around Mach=1 could be avoided.

The study could be extended in the same manner for other values of launching angles.

4 Conclusion

The first conclusion is that the delay time offers, in a limited way, a useful instrument for controlling the trajectory profile. The fragmentation of the grain propellant into several segments separated by delay devices allows a more efficient management of the energy produced by the rocket motor in order to increase the maximum range.

A second obvious conclusion of the study is that for each launching angle, there is an optimum delaying time Δt that ensures a maximum range for the same thrust input.

Existing pyrotechnic devices are reliable and robust, but are also complex in manufacturing technology. Furthermore, their installation is relatively costly because of their hazardous characteristics. Importantly, they also have to be regularly checked or replaced to ensure high reliability level requirements.

In the case of using pyrotechnic delay devices, they have by construction a defined delay time, and cannot be easily adjusted for each launching angle. For the case of optimizing the maximum range, the disadvantage of using this technology consists in the direct dependence of the delay time on the launch angle. This disadvantage could be avoided in the future by using electronic ignition devices, such as, for example, in the case of a pyro-numerical architecture that can initiate combustion at a predetermined moment of time. A pyro-numeric architecture was designed and patented by Dassault-Aviation in 2010. This lies in the use of digital bus for the command distribution instead of pyrotechnic communication solutions. Digital orders are transmitted through classical electric wires from the numerical bus to each smart initiator which are designed to receive, decode, and interpret the digital messages. Smart initiators are directly settled on pyrotechnic terminal functions and keep the same mechanical interface as the European Standard Initiator actually used on ESA's launchers. In this way, pyrrolines, multi-ways relays, and time delays are replaced by electric wires and digital clocks [13].

The main conclusion is that this study definitely showed an increase in the maximum range. For 45^0 launching angles, the maximum range could be extended by almost 28% for Δt=7.6s.

It should not be overlooked that the maximum range is achieved at the cost of increasing the time to impact. For the same example (45^0) the time to impact increased by 4.3%.

In the present work, the effects of using dual pulse SRM applicable to anti-hail rocket RAG-96 were studied. Using this technology for the operation of SRM, the possibility of extending the maximum range was practically demonstrated. The numerical results were validated by experimental measurements. In the future, the research may continue with multi-pulse SRM studies, which will enable a much more efficient management of the energy produced by the engine.

The practical applicability being already demonstrated, the technology presented and the method for optimizing the maximum range can be extended in the future to other ballistic products using SRM. Some of the engines currently used by ballistic products can be modified relatively easily and at low cost to obtain an extension of the range through the presented method. However, the method is strongly influenced by the input data and the constraints specific to each ballistic product. Therefore, for the optimization of other projectiles or missiles, it is necessary to study the technological implications and the costs involved vis-à-vis the possible benefits.

In the context of the increasingly extensive use of AI in almost all fields, new directions of its use can be analyzed in the future for the optimization problems discussed in this study.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Cristina Mihailescu formulated the problem, prepared the mathematical model, provided the requirements, and the input data, carried out the simulation and interpretation of results, and extracted the conclusion.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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