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DYNAMIC ANALYSIS OF THE MULSTISTAGE PARACHUTE-STORE SYSTEM

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Abstract: *The three dimensional motion of a rigid parachute and payload system is studied. The system consists of a symmetric parachute rigidly connected to a payload. The general nonlinear equations of motion of the payload are put in a form that is convenient for the analysis of the various intermediary stages (with/without parachute) in flight. Unsteady fluid effects for the parachute are represented by scalar values of apparent mass. Unsteady fluid effects for the payload are ignored.*
The study case consists of determination the times of the flight and specification of the respective parachutes to stabilize a statically unstable payload. The 3 degrees of freedom, planar motion of a released store is simulated. The released store has geometric form of the bomb. While airborne, the released store has three main flight segments: 1) with drogue chute attached (9 sec); 2) after drogue chute is released by a pyrotechnic device (3 sec), and 3) segment with the main parachute (drag chute) opened, which is the remaining part of the flight. The main chute helps to stabilize the unstable bomb. The paper shows and discusses the results of the system motion simulation and tests.

Keywords: Parachute deployment, Ballistic parachute, SIRAC

1. Introduction

This paper describes a model of experiment designed to investigate the dynamic of flight of the rescue system based in rocket. The system is designed for quick deployment to enable the rescue of store launch from the lowest possible height. In traditional systems the parachute is gradually pulled out from the top, exposing the length of the material to distortion by air currents and damage by contact with airframe or detached parts thereof. In the system proposed, the canopy is kept contained in a harness until the suspension ropes are fully extended at security distance above the store, where it is then extracted for safe inflation. This design minimizes the danger of damage to the fabric and suspension ropes during deployment. Inflation of the canopy starts in 0.4 to 0.7 seconds from activation of the system. The system is designed with reserve capacity to work even under extreme conditions.

In order to investigate the sequence of events of a recuperation system based in rocket, it was designed an experiment, which comprises of two separate parachutes: a drogue parachute and a main parachute. While airborne, the released store has three main flight stages: 1) with drogue chute attached (9 sec); 2) after drogue chute is released by a pyrotechnic device (3 sec), and 3) stage with the main parachute (drag chute) opened, which is the remaining part of the flight. In this stage, the system is activated electrically. The firing switch is displaced and a striker fires igniter, which ignite the powder load. These combustion products ignite the solid fuel of the rocket engine. The rocket engine accelerates out of the rocket tube, punches through the protective covers, pulling out the inner container with the rescue parachute above the store. During launch there is minimal recoil. The flame in the launching tube is not thrown forward, but is freely released through the rear into the exhaust tube.

The present study consists of development the tools for determination the times of the flight and specification of the respective parachutes to stabilize a statically unstable payload. Much of the progress reported in the present body of work was performed at SIRAC (Sistema de Recuperação Aérea de Carga) project (2003). The paper shows and discusses the results of the system motion simulation and tests.

2. Mathematical Formulation

The mathematical model includes three parts. The first part is to model the dynamic of parachute-store system. Newton's Second Law of Motion governs the motion of system. Balancing the forces of acceleration, gravity, and air resistance yields the second-order initial value problem. The second part is to model the instantaneous drag area. In this context, based on the work by Yavuz and Oler (1993) and Koldaev and Silva (1999), the unsteady fluid effects for the parachute are represented by scalar values of apparent mass. This formulation uses typical wind tunnel tests results for represent the time dependent variation of the drag area for a parachute wind-tunnel speed. Finally, the third part is to model the influence of the thrust pyrotechnic that perturb the system in the stages of released of the pilot chute and start parachute rocket rescue system.

2.1 Spatial Motion

Figure 1 illustrates the trajectory coordinates for the system being considered. The store is assumed to be a point mass, which develops negligible aerodynamic forces. The store and parachute are assumed to possess a common axis of symmetry and to follow the same ballistic path. The assumption required to make both the store and parachute follow the same ballistic path is that in the trajectory angle equation they both possess the same tangential velocity, taken here to be the store velocity. In this way, considering the forces in the direction of the symmetry axis, the equation of the motion for the parachute and store is given as:

$$\left(m_s + m_p\right)\frac{dV}{dt} = T\,\mathrm{Cos}\delta - F_s - F_p - \left(W_s + W_p\right)\mathrm{Sin}\theta\,, \tag{1}$$

$$m_s\,\frac{V^2}{R} = -\,W_s\mathrm{Cos}\theta - T\,\mathrm{Sin}\delta\,, \tag{2}$$

$$\frac{dH}{dt} = V\,\mathrm{Sin}\theta\,. \tag{3}$$

where m is defined as mass, F is the aerodynamic force, T is the thrust, W is the weight and V is the trajectory velocity. The angle θ is the trajectory angle from the horizontal plane and δ is the angle of application of T in relation to body axis. The subscripts s and p are referents to store and parachute, respectively. The variable R indicates the radius of trajectory, $R = \frac{V\,dt}{d\theta}$, and H is the altitude of motion.

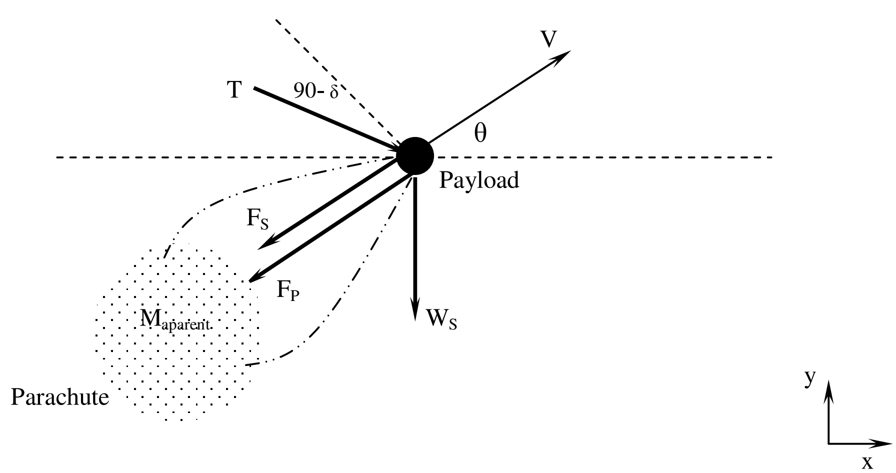

Figure 1. Parachute-store system motion in space.

The coupling between the parachute-store system and fluid motion occurs through the drag force. The drag of the store depends on the drag area of the vehicle, $(C_d S)_S$, and on the instantaneous dynamic pressure, $\frac{1}{2}\rho V^2$, which changes during the opening process of the parachute. Mathematically, can be formulated:

$$F_S = \frac{1}{2}(C_d S)_S \rho V^2 . \tag{4}$$

In the simplest case, it is assumed that the parachute stays aligned with the trajectory. The aerodynamic force along the axis of symmetry of the parachute is typically expressed by:

$$F_p = \frac{1}{2}(C_d S)_p \rho V^2 + \frac{d(m_a V)}{dt} . \tag{5}$$

where ρ is the fluid density, $(C_d S)_p$ is the drag area of the parachute, m_a is the added mass associated with the fluid. Note that the instantaneous drag area varies during the opening process, and it is a function of the parachute characteristics, the initial conditions, and parachute-store masses, Oler (1989). In section 2.2, the model for $(C_d S)_p$ is considered.

The apparent or added mass term, m_a, is defined as follows, Knacke (1992):

$$m_a = k_{11}\, \rho\, \vartheta , \tag{6}$$

where k_{11} is the added mass coefficient that depends on the parachute particular. The variable ϑ is the representative volume defined as:

$$\vartheta = \frac{\pi D^3}{8} . \tag{7}$$

As the diameter of the canopy, D, varies during the opening process, the representative volume of the canopy is considered to be proportional to the instantaneous drag area of the canopy. Using the Equations 6 and 7, and some manipulation, we obtain:

$$m_a = k_{11}\, Rm\, (S^*)^{3/2} , \tag{8}$$

where the parachute mass ratio Rm is defined by $Rm = \rho\, (C_d S)_p^{3/2}$. The dimensionless variable S^* is the parachute area ratio. It represents the relationship between the resultant parachute drag forces and that recovery system parameters specified. In this way, can be formulated:

$$S^* = \frac{(C_d S)_p}{(C_d S)_0} , \tag{9}$$

Note that the parachute drag area, $(C_d S)_p$, increase from close to zero at line stretch to $(C_d S)_0$ with full open canopy. In order to facilitate a parametric study, all equations are reduced to a dimensionless form. Using as reference parameters: store mass, critical velocity, density in altitude of launch, it is possible rewrites the equations 1 to 3 in form:

$$\left(1 + \frac{m_a}{m_S + m_p}\right)\frac{dV}{dt} = -\,\mathit{factor}\left(S^* V^{*2} + \mathrm{Sin}\theta - \frac{T\,\mathrm{Cos}\delta}{m_S + m_p}\right), \tag{10}$$

$$\frac{d\theta}{dt} = - \mathit{factor} \frac{(\mathrm{Cos}\theta + \mathrm{T}\,\mathrm{Sin}\delta)}{|\mathrm{V}|} \,, \tag{11}$$

$$\frac{dH}{dt} = \mathit{factor}(\mathrm{V}\,\mathrm{Sin}\theta) \,. \tag{12}$$

Comes to all attention that the variable time, t, is dimensionless by $\frac{V_{crf}}{g}$, where V_{crf} is the terminal velocity of the system in the last stage of the recuperation process and g is the gravity acceleration. The parameter *factor* is defined by $\frac{V_{crf}}{V_{cr}}$. It is arising from of different forms of dimensionless the time and velocity.

2.2 Drag Area

There is a considerable database for determining appropriate value for modeling the change in S^*. These databases consider a large number of geometric properties of the parachute, including basic constructive shapes, reefing, and porosity, as well as variables associated altitude, dynamic conditions at line snatch, and terminal velocity. In this work, it is assumed that the variation of the instantaneous drag area with the time for a particular parachute is dependent on parachute filling time, t_f, and of constants of parachute filling process A and B. This being so:

$$S^* = A\tau^B + (1 - A)\tau^2 \,, \tag{13}$$

where τ is defined by $\tau = \frac{t}{t_f}$. By their simplicity, empirically based axial momentum methods for obtaining gross design loads and timing sequences during inflation are broadly utilized because of their ease of use, Strickland (1996). However, t_f had to be specified along with assumptions concerning the variation of S^* during the fill time. Koldaev and Silva (1999) derived:

$$\tau = \frac{t\, V_{cr} V_0}{g\, C \sqrt{S}} \,, \tag{14}$$

where C is the dimensionless constant of parachute filling, S is the area of parachute canopy (m^2) and V_0 is the velocity of system at the beginning of filling (m/s). For real parachutes with ratio of projected diameter to nominal diameter of canopy, D_p = 0.62 – 0.94, we have k_{11} varies between 0.6 and 0.8. Depending on the characteristics of parachute in wind tunnel tests (reefed, non-reefed, desreefed), it is possible determines the correct value of C.

2.3 Pyrotechnic Thrust Recoil

The body pilot parachute is ejected by powder charge. The ignition of this charge is controlled by a pre-programmed timer (timer #1), which command the ignition process at 9 seconds after the launch of the payload. The same timer activates the rocket of main parachute rescue system at 3 seconds after the timer #1. Once that the rocket is deployed, it will be less than two seconds before of the payload fell the impact produced by two forces. The first force is produced by stretching of the complete system – that is the rocket, suspension lines, inner container with chute, chute lines – this stretch force then pulls the inner container off the packed parachute (*snatch force*). The second force follows after the canopy has inflated (*opening shock*). Consequently, it has been waited that the payload swings in a pendulum manner until it stabilizes directly below the canopy. In order to include this effect in the dynamic of separation of the pilot parachute and start parachute rocket rescue system, the term thrust T must be modeled in equations 10 and 11. A step function was used to model the ejector forces, with the time-averaged load applied for the length of time that would be needed for the actual piston to reach its end-of-stroke position.

3. Results and Discussion

3.1 Configuration of Simulation

The results are presented in terms of the parameters shown in Tables 1 and 2. The stages of flight designed for test are shown in Table 3.

The various phases of a parachute drop generally consist of three principle stages: deployment, inflation, and steady state. The deployment phase begins with the ejection of the payload from the aircraft and ends when the suspension lines and folded canopy have been fully extracted from the deployment bag. During the subsequent filling, or inflation phase, the elongated parachute transforms from a closed tube to an open canopy, ultimately increasing the aerodynamic drag and decelerating the payload. In this work, the sequence of deployment and inflation was modeled by different parameters of the filling ascribed to functional relation for instantaneous drag area, S^*. The terminal velocity was used as constraints of project. The respective parameters are summarized in Table 4.

Experimental launches at the development of SIRAC system had being initiated at 1500 ft of altitude and 41.15 m/s. In Tab. 5 is depicted the standard initial conditions. Should be note that the one of objectives of this method is determines the minimum firing height. So, various initial conditions and times of flight will be necessary for simulation.

Table 1. Payload.

Mass [kg]	**Area** [m^2]	**Cd**
70	0.037	0.2

Table 2. Parachutes.

Parachute	**Mass** [kg]	**Area** [m^2]	**Cd**
Pilot	0.5	2.26	0.5
Drag	3.6	40.5	0.75

Table 3. Stages of Flight.

Stage	**Components**	**Time** [s]	**Rescue**
I	Pilot + Drag + Store	8	Traditional
II	Drag + Store	3	–
III	Drag + Store	ground	Rocket

Table 4. Filling parameters.

Parachute	**K**	**A**	**B**	**C**	**Terminal Velocity** [m/s]
Pilot	0.3	1	2	5	25.75
Drag	0.66	1	3	2	5.12

Table 5. Standard Initial Conditions.

Altitude [ft]	**Velocity** [m/s]	**Trajectory Angle** [deg]
1500	41.15	0.

3.2 Results

The instantaneous drag area varies during the opening process. It is a function of the parachute characteristics, the initial conditions, and parachute/payload masses. The functional relation contained in Eq. (13) can be determined by considering a series of wind tunnel tests of parachute. In this work, it is assumed that the tests results for the drag parachute can be collapsed to a single curve through of the filling parameters A = 1 , B = 3 and **C = 2**. The model of flight dynamic was integrated simultaneously to determine the instantaneous parachutes position, velocity and opening state.

The typical function of a parachute is to decelerate a payload from an initially high velocity to a final velocity that is low enough to allow ground contact without damage to the payload. Fundamentals questions to be addressed in the analysis of the problem, for example: What are the terminal velocities of the different stages of the process of recuperation? What is the latest time that the parachute can be opened while keeping impact velocity below a specified threshold? For the present work, any theses questions can be answered with assistance of the Figure 2. It can be seen clearly the stages of deployment and the respective instantaneous velocities. The tendency of the swings in a pendulum manner was captured, Figure 3. Note that the variation in θ does not change significantly the trajectory of system. It is interesting that the technique adopted, though very simple, display a lot of the features of dynamic of flight of the CG of parachute/payload system. However, it should be pointed out that these results are rather qualitative and no attempt has been made, at this time, to investigate the finer details of the ballistic trajectory. The simulations of the trajectory of the center of gravity fail when the relative motion between the parachute and the store needs to be considered. These results can be used only for pre-specify the velocity, parachute area and altitude of launch.

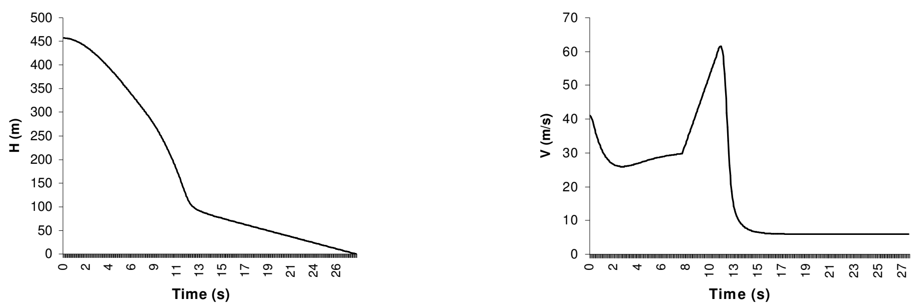

Figure 2. Ballistic Trajectory of payload/parachute system.

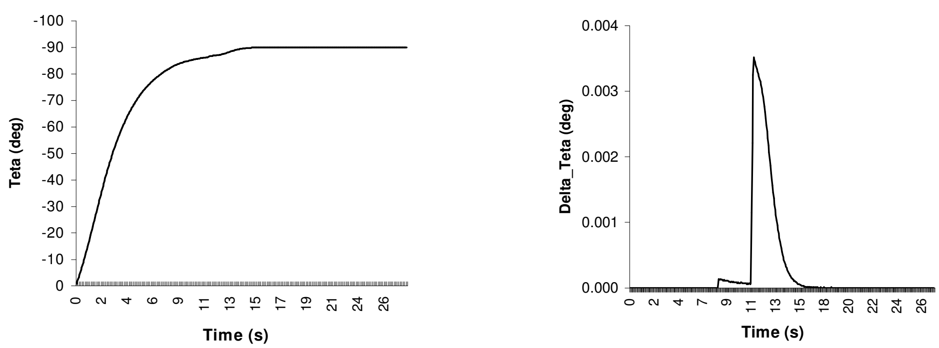

Figure 3. Variation in trajectory angle (θ).

The Fig. 4 presents the landing velocity and time of flight for drag parachute/payload system, resulting of simulation of recuperation process (three stages) for various altitude of launch. Comes to all attention that, in all cases, the payload was rescue with the drag parachute. The parachute rocket rescue system is designed for rescue from the lowest possible height but it is still a compromise. The faster the parachute is opened the greater the impact on the store. The more this impact is reduced, the more height is needed to open the chute. So, for configuration depict in Tables 1 to 5, the landing velocities of payload are inside of constraints of this problem.

Finally, since the idea is to stay on the safe side, two questions must be solved: to specify the dimensions of field of the landing, horizontal range, and opening shock. The opening shock, or jerk, is the shock produced while the parachute deploys. Mathematically, the jerk is the time derivative of the acceleration. In all simulations, the dimensionless parachute average force was small than 6000. This value is very small than nominal value of drag parachute used. Figure 4 shows the horizontal range for the standard initial conditions. In this context, can be conclude, through of the results above mentioned, that it is possible to execute the experiment with the standard conditions specified in item 3.2.

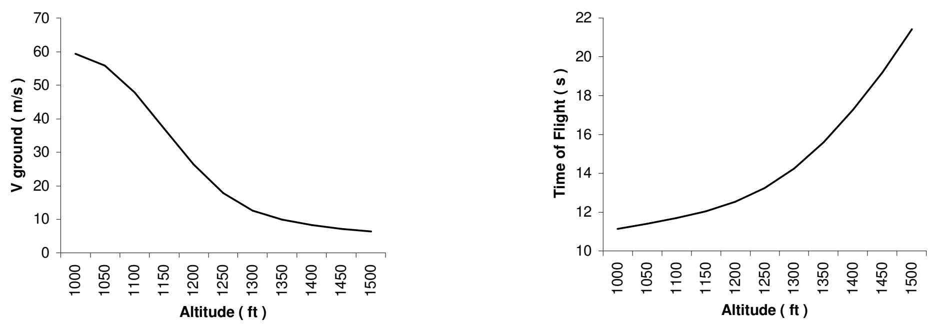

Figure 4. Landing Velocity and Time of Flight in recuperation process with three stages.

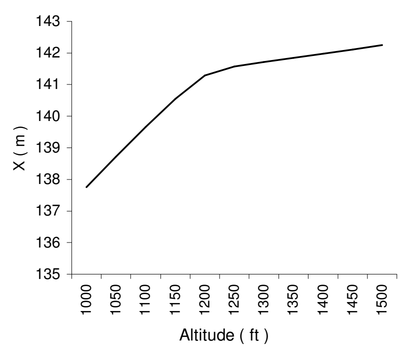

Figure 5. Horizontal range for standard initial conditions.

3.3 Experimental Test

The payload designed for use in rescue system is depicted in Figure 6. Essentially, this store is constituted of three parts: The pilot chute, drag parachute and rocket compartments. The belt of the join is opened with a pyrotechnic device and, in this moment, the compartment of pilot parachute is released. After 3 s of the free fall, the rocket of extraction of drag parachute is firing by electronic commander. The solid rocket is depicted in Figure 7. Further insight into the project may be obtained in reference SIRAC (2003). In this moment of the development, the payload was launched three times. The acquisition data system failed in all experiments. Nevertheless, it was possible to estimate the horizontal range and the time of flight. Based on comparisons between the limited set of simulations and the even more limited set of associated experimental data, it appears that the methodology holds reasonable promise for development into an aero-prediction code for dynamic analysis of ballistic rescue system.

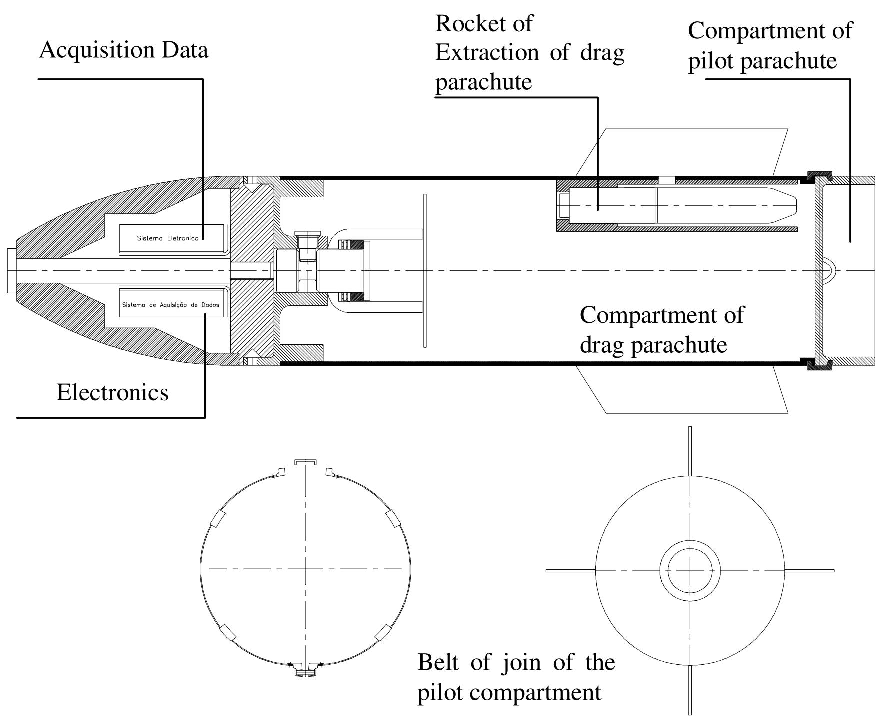

Figure 6. Payload.

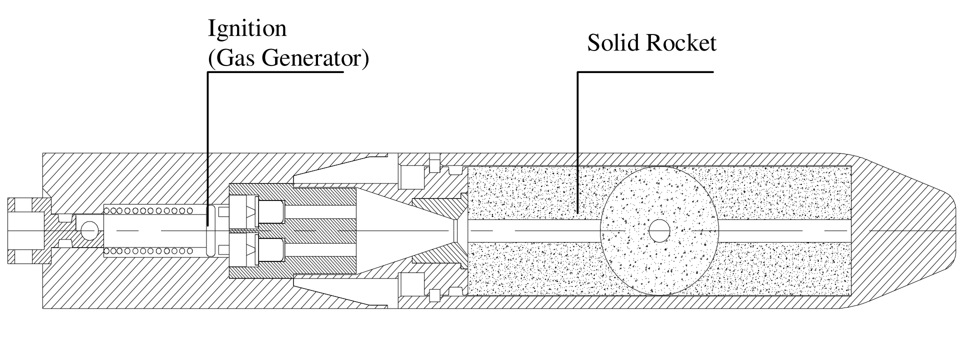

Figure 7. Solid rocket.

4. Conclusions

This paper describes a model of experiment designed to investigate the dynamic of flight of the rescue system based in rocket. The launch conditions has been specified through of the simulation of certain number of launchings in different flight conditions in order to estimate design parameters, which as, horizontal range, opening shock, terminal velocity, time of flight and variation in angle of trajectory. The shortcoming of these initial estimates is the point-mass approximation. The simulations of the trajectory of the center of gravity fail when the relative motion between the parachute and the store needs to be considered. However, the technique adopted display a lot of the features of dynamic of flight of the CG of parachute/payload system that can be used for pre-specify the velocity, parachute area and altitude of launch.

Ballistic Parachute implies there is a rocket that launches the parachute through the skin of the aircraft to where the chute can deploy. The force of this device is approximately the same as a military RPG (rocket propelled grenade) and it can cause similar damage if anyone were to get in the path of one. In this context, further work on the method's ability numerically predict and experimentally investigate the use of this system is of fundamental importance.

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