Dynamic Modeling and Performance Analysis of a Pneumatic UAV Launch System

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***Abstract* – A dynamic mathematical model was developed to analyze the performance of a portable pneumatic launcher for UAVs, designed to accelerate an aircraft of up to 30 kg to 20 m/s using compressed air. The formulation is a coupled system of ordinary differential equations describing the mechanical dynamics of the moving assembly together with the evolution of the pneumatic variables in the tank and cylinder, including the compressible mass flow through the control valve. The model was implemented numerically in MATLAB, yielding the time evolution of position, velocity, acceleration, pressures and mass flow during the launch sequence. A parametric analysis then evaluated the influence of initial tank pressure, storage volume, piston diameter, effective valve area, total moving mass and rail length on the exit velocity. Performance depends significantly on the interaction between the available pneumatic energy, the flow capacity and the geometry of the launcher, and the model constitutes a useful tool for preliminary sizing and for the comparative evaluation of design alternatives.**

***Keywords*— UAV, pneumatic launcher, dynamic modeling, compressed air, parametric analysis.**

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) are currently used widely in fields such as aerial surveillance, environmental monitoring, infrastructure inspection, and logistics [1], [2]. In many operational scenarios, especially in remote environments or areas with limited space, traditional takeoff methods, such as runways or vertical takeoff systems, may not be feasible [1], [2]. As a result, alternative launch mechanisms capable of accelerating UAVs to their required takeoff speed within a limited distance have attracted growing interest [1], [2], [3], [4].

Catapult-based launch systems represent a practical solution for these applications [1], [3], [4], [5], [6]. By converting stored mechanical or pneumatic energy into kinetic energy, catapults allow UAVs to reach the speed necessary for takeoff without the need for long runways. Various types of launch mechanisms have been explored, including elastic, hydraulic, mechanical, and pneumatic systems. Among these alternatives, pneumatic launchers have gained attention due to their ability to generate high forces over short time intervals, their relatively simple design, and their compatibility with commercially available components.

Within this line of research, several complementary contributions have been reported. Kondratiuk and Ambroziak [4] analysed the dynamics of kinetic launchers and related the energy stored in the launching device to the exit velocity attainable over a finite guide length, while Cheng et al. [6] designed and tested a hydraulic catapult. Jastrzębski [7] showed that the opening time of the main valve governs the pressure losses occurring during take-off, making valve behavior a first-order design variable rather than a secondary effect. For pneumatic systems specifically, Siddiqui et al. [1] and Hammad-ur-Rehman et al. [8], [9] reported the modelling, fabrication and testing of UAV catapults, and Khrulev [3] analyzed catapult parameters as a function of the characteristics of the UAV to be launched. These works confirm the maturity of the concept, but they also show that the coupling between tank thermodynamics, compressible flow through the valve and the inertia of the moving assembly is often treated partially: the supply pressure is held constant, the valve transient is neglected, or the two subsystems are analyzed separately. This limits their usefulness for exploring design alternatives, since the trade-offs that dominate the sizing of a launcher arise precisely from that coupling.



Fig. 1. WS No. 1 pneumatic launcher, Air Force Institute of Technology, Warszawa, Poland.

Nevertheless, the design of pneumatic launch systems depends on the interaction between compressed air expansion, piston motion, structural inertia, and the mass of the UAV being launched. Accurately predicting the launch velocity and system loads requires a detailed understanding of these coupled physical processes [1], [3], [7], [10].

In practice, pneumatic components such as tanks, cylinders and valves are commonly sized using simplified energy balances or empirical rules, which are useful for preliminary component selection [3], [7], [10].

However, rapid actuation at high acceleration requires a more detailed understanding of the transient behaviour of pneumatic actuators, whose response depends on air

compressibility, pressure evolution, valve flow characteristics and the inertia of the moving components. Dynamic models have therefore become an important tool for predicting the performance of pneumatic actuation systems.

This limitation acquires a specific meaning when the launcher is approached from a Design Thinking perspective. Design Thinking organizes engineering work as an iterative cycle in which a need is framed, a broad space of alternatives is generated, and candidate solutions are prototyped and tested so that the resulting evidence reformulates the problem itself [11], [12]. The difficulty here is that the natural prototyping medium, a physical launcher, is expensive, slow to modify and potentially hazardous, which in practice collapses the ideation stage to the one or two configurations a team can afford to build. A dynamic model that reproduces the dominant physics of the launch therefore acts as a low-cost prototyping medium: it allows dozens of configurations to be evaluated in the time a single hardware iteration would require, it makes the trade-offs between tank pressure, storage volume, piston diameter, valve area, rail length and moving mass explicit before any component is purchased, and it turns a target requirement such as 20 m/s for a 30 kg UAV into a bounded region of the design space rather than a single point solution. The model is thus not only an analysis tool but an instrument for exploring, evaluating and iterating alternatives, which is the function prototyping performs within the Design Thinking cycle.

Accordingly, the objective of this work is to develop and numerically solve a coupled dynamic model of a portable pneumatic UAV launch system and to use it to characterize the influence of the main design parameters on the exit velocity. The contributions are threefold: a lumped-parameter formulation that couples tank discharge, compressible flow through the control valve and carriage motion in a single system of ordinary differential equations; its numerical implementation and verification in MATLAB for a launcher specified to accelerate a 30 kg UAV to 20 m/s over a 5 m rail; and a parametric study that identifies the dominant parameters and the non-monotonic behaviors constraining the design space.

The paper is organized as follows. Section II describes the launcher, the modelling hypotheses, the governing equations and the numerical implementation. Section III reports the base case and the parametric analysis. Section IV discusses the results and states the verification status and limitations of the model. Section V presents the conclusions.

II. Methodology

The proposed model considers the pressure evolution within the pneumatic cylinder, the mass flow through the valve, and the resulting motion of the launch carriage carrying the UAV [1], [3], [13], [14]. The governing equations of the system are implemented and solved in MATLAB. This approach allows key performance parameters to be evaluated, such as launch velocity, pressure evolution, and the mechanical loads generated during the launch process [1], [8], [15].

A. Launch System Description

From a physical standpoint, the launcher converts the energy stored in a compressed air tank into kinetic energy of the moving assembly [1], [3], [7]. Air flows from the tank into a pneumatic cylinder through a valve; the resulting pressure acts on the piston and produces a thrust force that accelerates the carriage and, with it, the UAV along the guide rail. The operating scheme is shown in Fig. 2. The process therefore couples phenomena of two natures: tank discharge, compressible flow and pressure variation in the cylinder on the pneumatic side, and displacement, velocity and acceleration of the moving system on the mechanical side.

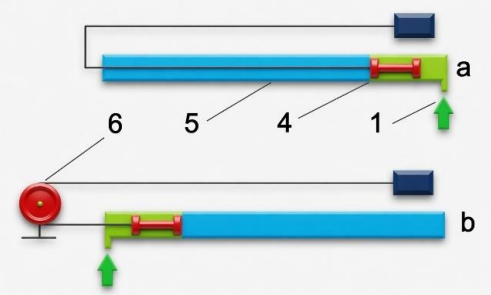


Fig. 2. Launcher layout: 1 - compressed air inlet, 2 - carriage with payload, 3 - cable, 4 - piston, 5 - cylinder, 6 - fixed pulley, 7 - moving pulley.

B. Pneumatic System Components

The launcher can be decomposed into five main elements [1], [7]: the compressed air storage tank, which holds the energy of the system at a pressure above atmospheric; the control valve, which regulates the passage of air into the cylinder and therefore governs the mass flow rate available for acceleration; the pneumatic cylinder, in whose active chamber the pressure generates the force transmitted to the carriage; the launch carriage, guided on rails that restrict motion to a single direction and ensure a linear trajectory; and the UAV, coupled to the carriage so that both are represented dynamically as a single moving assembly of equivalent mass.

A damping mechanism is incorporated at the end of the travel. Although it does not contribute to the thrust force, it limits the loads arising when the carriage reaches the end of the guide and preserves the structural integrity of the launcher [7], [9], [14].

Under this configuration the model represents the coupled behavior of these subsystems through a lumped-parameter

description in which each is characterized by global variables such as pressure, volume, position and velocity [1], [3], [10]. The tank and cylinder are modelled as pneumatic volumes with variable pressure, the valve as a compressible flow restriction, and the carriage together with the UAV as a moving mass subjected to the pneumatic force and to equivalent mechanical losses, so that the energy stored in the compressed air is transformed into force on the piston and then into the exit velocity of the UAV.

C. General assumptions

The motion of the carriage and UAV is taken as one-dimensional along the rail, and both are represented as a single equivalent mass. Compressed air is modelled as an ideal gas at constant temperature, with uniform pressure in the tank and in the cylinder at each instant, and the system is described through lumped parameters. The flow through the valve is treated as compressible, quasi-steady and one-dimensional, and may operate in either the choked or the unchoked regime depending on the pressure ratio. The cylinder volume varies only with piston displacement, mechanical losses are represented through an equivalent viscous friction, and the launcher structure is considered rigid during launch. The launch terminates when the carriage reaches the useful length of the rail, and the exit velocity is defined at that instant.

D. State variables and parameters

The state variables describe the temporal evolution of the system during launch, while the parameters characterise its geometric, mechanical and pneumatic properties; together they constitute the basis of the system of differential equations used in the simulation.

The state variables of the model are defined in Table I, while the geometric, mechanical and pneumatic parameters of the base case are summarized in Table II.

TABLE I
STATE VARIABLES

Variable	Description	Unit
$x(t)$	Launch carriage position	m
$v(t)$	Launch carriage velocity	m/s
$P_c(t)$	Pressure in the cylinder chamber	Pa
$P_t(t)$	Pressure in the storage tank	Pa

TABLE II
MODEL PARAMETERS

Parameter	Description	Value	Unit
R	Specific gas constant of air	287	J/(kg·K)
γ	Heat capacity ratio of air	1.4	-
T	Air temperature	293.15	K
P_{atm}	Atmospheric pressure	101325	Pa
m_{uav}	UAV mass	30	kg
v_{target}	Target launch velocity	20	mm/s
L	Useful rail length	5.0	mm
D_p	Piston diameter	0.086	mm
$stroke$	Cylinder stroke	5.0	mm
V_{c0}	Initial dead volume of the cylinder	$2x10^{-4}$0.0002	m^3m³
P_{t0}	Initial absolute pressure of the tank	$9x10^5$1400000	Pa
P_{c0}	Initial pressure of the cylinder	101325	Pa
V_t	Tank volume	0.03	m^3m³
C_d	Valve discharge coefficient	0.8	-
A_v	Effective valve area	$1.5x10^{-4}$0.00015	m^2m²
$m_{carriage}$	Estimated carriage mass	15	kg
m	Total moving mass ($m_{carriage} + m_{uav}$)	45	kg
c	Equivalent viscous friction coefficient	40	N·s/m
A_p	Piston area	0.005809	m^2m²

The formulation of the mathematical model adopted in this work is based on criteria widely used in previous studies on pneumatic launchers and pneumatic actuation systems for UAVs, where compressed air is represented as an ideal gas, the system is described through lumped parameters, the flow through valves and restrictions is modeled as compressible with transition between choked and unchoked regime, and the overall response is expressed through coupled differential equations between the pneumatic and mechanical parts [1], [3], [10].

The initial tank pressure was selected within the order of magnitude reported for real pneumatic launchers, where receiver pressure is one of the main variables used to adjust performance. The discharge coefficient was adopted to represent the non-ideal nature of the flow through the valve, consistent with the use of flow coefficients in pneumatic components and with models that employ a non-ideal valve explicitly. The loss coefficient was introduced as a first-order equivalent parameter grouping friction and mechanical resistances of the moving system, following criteria that consider losses at the carriage and pulley and evidence that friction and leakage directly influence launch velocity [1], [3], [10], [16].

On this basis a first-order formulation was adopted for the evolution of pressure in the tank and cylinder and for the motion of the moving assembly. The constant temperature hypothesis is a simplification of the base model, while leakage and additional losses are left for later refinement.

E. Equation of motion

The dynamics of the moving assembly, composed of the launch carriage and the UAV, were formulated by applying

Newton's second law in the longitudinal direction of the rail. Under the adopted hypotheses, the driving force of the system corresponds to the pneumatic force generated in the cylinder, while mechanical losses are represented through an equivalent resistive force. In this way, the equation of motion can be expressed as:

$$m\frac{dv}{dt} = F_p - F_f \quad (1)$$

Where m is the total moving mass, F_p is the pneumatic force exerted by the cylinder, and F_f is the equivalent resistive force.

The pneumatic force is calculated from the difference between the pressure in the cylinder chamber and atmospheric pressure, acting on the effective area of the piston, that is:

$$F_p = A_p(P_C - P_{atm}) \quad (2)$$

On the other hand, the resistive force is modeled at this stage through viscous friction proportional to velocity, such that:

$$F_f = c \cdot v \quad (3)$$

Where c is the equivalent viscous friction coefficient. Substituting these expressions into the equation of motion, we obtain:

$$m\frac{dv}{dt} = A_p(P_C - P_{atm}) - c \cdot v \quad (4)$$

Furthermore, the kinematic relationship between position and velocity is given by:

$$\frac{dx}{dt} = v \quad (5)$$

Together, these expressions describe the mechanical response of the system during the acceleration phase on the rail.

F. Pressure dynamics in the cylinder

The evolution of pressure in the cylinder chamber was obtained from the ideal gas equation of state applied to the air contained in said control volume. Considering that the mass of air in the cylinder varies due to the flow from the tank and that the chamber volume changes with piston displacement, we have:

$$P_cV_C = m_cRT \quad (6)$$

Where P_c is the pressure in the cylinder, V_c the instantaneous volume of the chamber, m_c the mass of air contained in it, R the specific gas constant of air and T the absolute temperature.

Upon deriving this expression with respect to time and adopting, in the base model, the hypothesis of constant temperature, we obtain:

$$\frac{dP_c}{dt} = \frac{RT}{V_c}\dot{m} - \frac{P_c}{V_c}\frac{dV_c}{dt} \quad (7)$$

Where $\dot{m}$ represents the mass flow rate of air entering the cylinder. The second term of the equation reflects the pressure decrease associated with the increase in internal volume as the piston advances.

Since the volume of the cylinder depends on the position of the moving assembly, it is defined as:

$$V_c = V_{c0} + A_px \quad (8)$$

Where V_{c0} is the initial dead volume of the cylinder, A is the effective area of the piston and x is the position of the carriage. Consequently, the temporal variation of the volume is given by:

$$\frac{dV_c}{dt} = A_p \cdot v \quad (9)$$

Where v is the velocity of the moving assembly. Substituting this relationship into the previous expression, the pressure dynamics in the cylinder are finally written as:

$$\frac{dP_c}{dt} = \frac{RT}{V_c}\dot{m} - \frac{P_c \cdot A_p}{V_c}v \quad (10)$$

This equation represents the coupling between the pneumatic and mechanical parts of the system, since the pressure in the cylinder depends on both the air flow entering from the tank and the volume change induced by the piston motion.

G. Pressure Dynamics in the Tank

The evolution of pressure in the storage tank was modeled based on the ideal gas equation of state, considering that compressed air constitutes the energy source of the system and that its pressure decreases as the fluid is transferred to the cylinder during launch [1], [3], [7]. This approach is consistent with formulations previously used in modeling pneumatic catapults for UAVs and compressed air tank discharge systems.

$$P_tV_t = m_tRT \quad (11)$$

Where P_t is the pressure in the tank, V_t is the internal volume, m_t the mass of air stored, R the specific gas constant of air and T the absolute temperature. Assuming in the base model that the tank volume remains constant and that the temperature does not vary during the process, we obtain:

$$\frac{dP_t}{dt} = \frac{RT}{V_t}\frac{dm_t}{dt} \tag{12}$$

Defining $\dot{m}$ as the mass flow rate of air leaving the tank and entering the cylinder, the variation of mass in the tank can be written as:

$$\frac{dm_t}{dt} = -\dot{m} \tag{13}$$

so the pressure dynamics in the tank are finally expressed as:

$$\frac{dP_t}{dt} = -\frac{RT}{V_t}\dot{m} \tag{14}$$

This equation indicates that the tank pressure decreases as the compressed air is discharged, and constitutes the link between the stored pneumatic energy and the dynamic response of the system during the launch phase.

H. Mass Flow model through the valve

The air flow from the tank to the cylinder was modelled as compressible flow through a restriction, following the approach commonly adopted for pneumatic launch systems, in which the flow rate depends on the pressure ratio between supply and receiver volumes and may occur in the choked or unchoked regime [1], [7], [10]. Defining the pressure ratio as:

$$r = \frac{P_c}{P_t} \tag{15}$$

and the critical pressure ratio as:

$$r_{crit} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{16}$$

When the pressure ratio satisfies the condition:

$$r \le r_{crit} \tag{17}$$

the flow is considered choked, so the mass flow rate reaches its maximum value and can be written as:

$$\dot{m} = C_d A_v P_t \sqrt{\frac{\gamma}{RT}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \tag{18}$$

On the other hand, when:

$$r > r_{crit} \tag{19}$$

The flow is unchoked and the mass flow rate is expressed as:

$$\dot{m} = C_d A_v P_t \sqrt{\frac{2\gamma}{RT(\gamma-1)}\left[\left(\frac{P_c}{P_t}\right)^{\frac{2}{\gamma}} - \left(\frac{P_c}{P_t}\right)^{\frac{(\gamma+1)}{\gamma}}\right]} \tag{20}$$

Where C_d is the valve discharge coefficient, A_v is the effective flow area, R is the specific gas constant of air, T is the absolute temperature and γ is the ratio of specific heats. In this formulation, the discharge coefficient allows to represent in a simplified manner the losses associated with the actual geometry of the valve and the non-ideal effects of the flow. In this way, the distinction between critical and subcritical regime is physically coherent with experimental observations reported in the literature for pneumatic components used in UAV launchers.

I. System of Differential Equations

Based on the expressions obtained for the mechanical dynamics of the moving assembly, the evolution of pressure in the cylinder, the tank discharge, and the mass flow through the valve, the behavior of the launcher can be represented through a coupled system of ordinary differential equations. In terms of the state variables defined previously, the complete model is given by:

$$\boldsymbol{y}(t) = \begin{bmatrix} x(t) \\ v(t) \\ P_c(t) \\ P_t(t) \end{bmatrix} \tag{21}$$

Deriving the state variables:

$$\frac{dx}{dt} = v \tag{22}$$

$$\frac{dv}{dt} = \frac{1}{m}\left[A_p(P_C - P_{atm}) - c \cdot v\right] \tag{23}$$

$$\frac{dP_c}{dt} = \frac{RT}{V_c}\dot{m} - \frac{P_c \cdot A_p}{V_c}v \tag{24}$$

$$\frac{dP_t}{dt} = -\frac{RT}{V_t}\dot{m} \tag{25}$$

Considering an instantaneous volume of the chamber of:

$$V_c = V_{c0} + A_{px} \tag{26}$$

We have:

$$\dot{\boldsymbol{v}}(t) = \begin{bmatrix} v \\ \frac{1}{m}\left[A_p(P_C - P_{atm}) - c \cdot v\right] \\ \frac{RT}{V_c}\dot{m} - \frac{P_c \cdot A_p}{V_c}v \\ \frac{RT}{V_t}\dot{m} \end{bmatrix} \tag{27}$$

This system constitutes the complete mathematical formulation of the problem and allows the simultaneous description of the interaction between compressed air expansion and the acceleration of the moving assembly during launch. Its numerical resolution provides the temporal

evolution of position, velocity, and system pressures, as well as the exit velocity achieved at the end of the rail.

J. Numerical Implementation

The system of differential equations obtained was solved numerically in MATLAB, following a time-domain simulation approach widely used in previous studies on pneumatic catapults for UAVs, where the first-principles formulation is integrated through numerical calculation and dynamic simulation tools [1], [8].

The implementation was modular, separating parameter definition, mass-flow calculation, evaluation of the dynamic system and the launch termination condition. Time integration used the ode45 solver, suitable for the coupled system describing position, velocity and pressures, and the simulation returned the exit velocity, launch time and maximum acceleration together with the complete time history of the launch.

The initial conditions employed for the launch simulation were:

$$x(0) = 0\ , v(0) = 0\ , P_c(0) = P_{c0}\ , P_t(0) = P_{t0} \qquad (28)$$

Where P_{c0} corresponds to the initial pressure in the cylinder and P_{t0} corresponds to the initial pressure in the tank.

The simulation stopped when the carriage reached the useful length of the rail, that is, when:

$$x = L \qquad (29)$$

In this way, the exit velocity was defined as:

$$v_{sal} = v(t)\ para\ x = L \qquad (30)$$

which constitutes the most important performance variable of the system, given that it allows verifying whether the launcher meets the requirement of reaching 20 m/s for a UAV of up to 30 kg.

The model is therefore a preliminary design tool: it captures the dominant phenomena of pneumatic launch and allows the effect of geometry, loading pressure, tank size, valve area and moving mass to be analyzed before hardware is committed.

K. Parametric Analysis

In order to evaluate the influence of the main design parameters on the launcher's performance, a parametric analysis was carried out based on the previously developed numerical model. This type of approach has been used in works such as those by Khrulev, Siddiqui, and Hammad-ur-Rehman for system sizing, optimization, and sensitivity analysis, through systematic variation of its main parameters and observation of their effect on the dynamic response [1], [3], [9].

In the present study, the analysis was conducted by varying one parameter at a time with respect to the base case, while the others were kept constant, with the purpose of isolating its effect on the UAV's exit velocity. The selected parameters were the initial tank pressure, the tank volume, the piston diameter, and the effective valve area. For each configuration, the system of differential equations was solved numerically until the carriage reached the end of the rail, obtaining as variables of interest the exit velocity, launch time, and maximum acceleration. In this way, the parametric analysis allowed identifying which parameters exert the greatest influence on the launcher's performance and, consequently, establishing criteria for its preliminary sizing.

III. RESULTS

The dynamic response of the system under the base design condition was obtained by simulating the launch with the parameters defined above. The temporal evolution of position, velocity, cylinder and tank pressures, acceleration and mass flow through the valve is presented in Figs. 3 to 7.

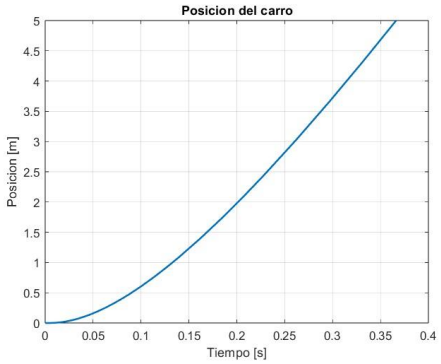


Fig. 3. Position of the moving assembly versus time.

Figure 3 shows the temporal evolution of the carriage position during launch. The displacement increases continuously from rest until the useful rail length of 5.0 m is reached, in approximately 0.36 s. The increasing slope of the curve indicates that the carriage advances progressively faster, confirming that the moving assembly completes the whole acceleration path.

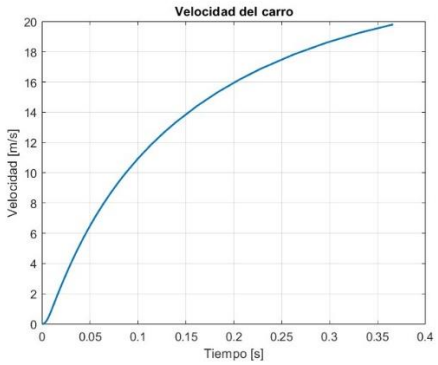


Fig. 4. Velocity of the moving assembly versus time.

Figure 4 shows the temporal evolution of the carriage velocity during launch. It is observed that the velocity increases continuously from the initial condition of rest until reaching a value close to 20 m/s at the end of the path, in an approximate time of 0.36 s. The graph shows a more pronounced velocity gain in the initial stage and a progressively smaller increase as the process advances, which is consistent with the gradual decrease in acceleration as the system discharges and the carriage approaches the end of the rail.

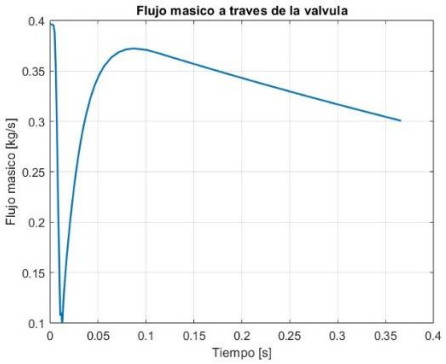


Fig. 5. Mass flow rate through the valve versus time.

Figure 5 presents the mass flow through the valve. An initial transient is observed, with a high value at the beginning of the process followed by an abrupt drop associated with the rapid pressurization of the cylinder chamber, whose initial volume is small. The flow then partially recovers and decreases progressively as the piston advances and the tank pressure falls, reflecting the strongly transient nature of the mass exchange between tank and cylinder.

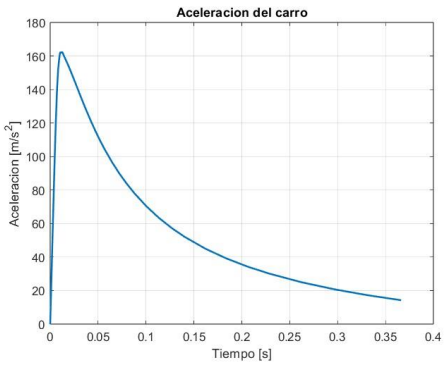


Fig. 6. Acceleration of the moving assembly versus time.

Figure 6 shows the temporal evolution of the carriage acceleration during launch. An initial high peak is observed, associated with the rapid pressurization of the cylinder and the instantaneous generation of considerable pneumatic force on the moving assembly. Subsequently, the acceleration decreases continuously as the cylinder volume increases, the internal pressure drops, and the system gradually loses thrust capacity. Although the maximum value constitutes a short-duration transient, its magnitude confirms that maximum acceleration represents a critical parameter from the structural and system sizing perspectives.

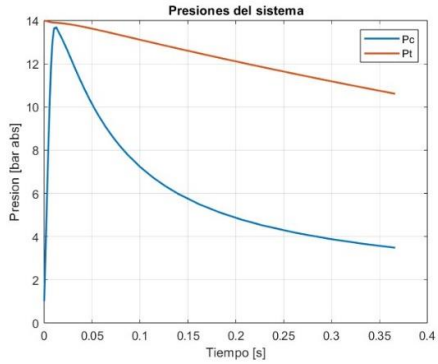


Fig. 7. Tank and cylinder pressures versus time.

Figure 7 presents the pressures in cylinder and tank. The cylinder pressurizes rapidly at the beginning of the process, approaching the tank pressure within a very short interval, and then decreases progressively as the internal volume grows with piston displacement. The tank pressure falls more smoothly, consistent with its greater storage capacity, which explains the variation observed in the mass flow through the valve.

The results of the parametric analysis are presented below. For each parameter, the exit velocity obtained at the end of the rail is reported as the performance indicator.

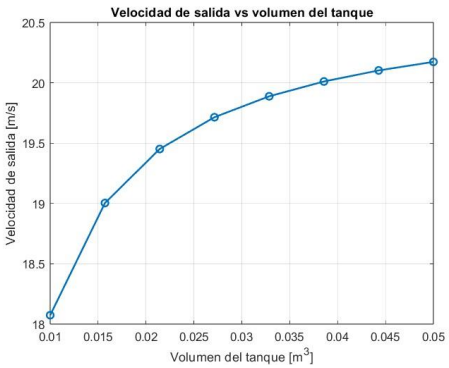


Fig. 8. Exit velocity versus tank volume.

Figure 8 presents the exit velocity as a function of tank volume. The launch velocity increases continuously with storage volume but with a progressively smaller slope, from about 18.1 m/s at 0.01 m³ to 20.2 m/s at 0.05 m³. Increasing the tank volume improves performance, with an effect that moderates for larger volumes.

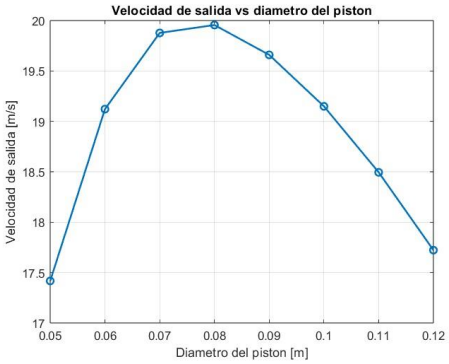


Fig. 9. Exit velocity versus piston diameter.

Figure 9 presents the exit velocity as a function of piston diameter. Within the analyzed range the velocity first increases with diameter, reaching a maximum close to 20 m/s around 0.08 m, and then decreases gradually, indicating an optimal intermediate diameter for which the system performs best.

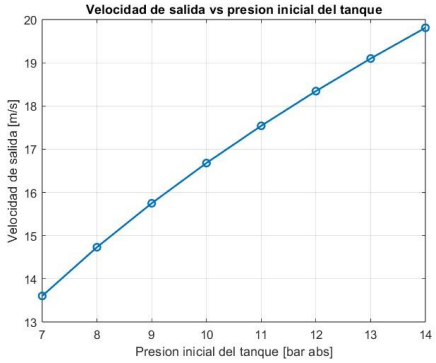


Fig. 10. Exit velocity versus initial tank pressure.

Figure 10 shows the exit velocity as a function of initial tank pressure. The trend is practically monotonic across the analysed range: the velocity rises from about 13.6 m/s at 7 bar abs to close to 19.8 m/s at 14 bar abs, which makes the initial tank pressure one of the most influential parameters on system performance within the interval considered.

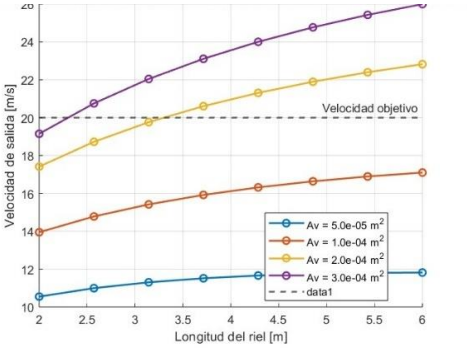


Fig. 11. Exit velocity versus rail length for different effective valve areas.

Figure 11 presents the exit velocity as a function of rail length for different effective valve areas. For every area the velocity grows continuously with rail length, though at a progressively lower rate, and for a given rail length a larger valve area yields higher velocities. Only the larger areas allow the 20 m/s target to be exceeded, which highlights the combined influence of flow capacity and available acceleration distance.

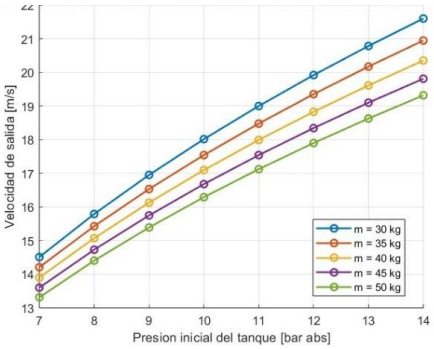


Fig. 12. Exit velocity versus initial tank pressure for different total moving masses.

Figure 12 presents the exit velocity as a function of initial tank pressure for different total moving masses. For all masses the exit velocity increases almost linearly with pressure, and for a given pressure it decreases as the moving mass grows, displacing the curves towards lower velocities. Initial tank pressure and total moving mass are therefore both highly influential, since they determine respectively the available pneumatic energy and the inertia to be accelerated.

Figure 13 presents the exit velocity as a function of piston diameter for different initial tank pressures. For every pressure the velocity rises to a maximum near 0.08 m and then falls, and for a given diameter higher initial pressures yield higher exit velocities. Both parameters therefore influence performance significantly, with an intermediate diameter maximizing the launch velocity.

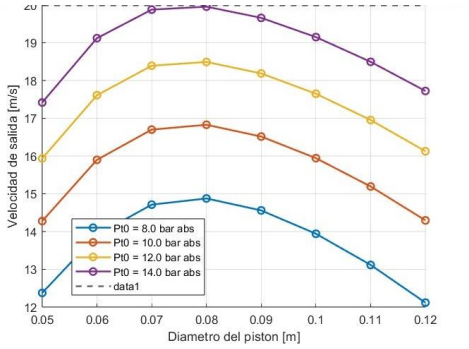


Fig. 13. Exit velocity versus piston diameter for different initial tank pressures.

IV. Discussion

The results obtained show that pneumatic launch constitutes a markedly transient process, in which the majority of energy transfer occurs within a few tenths of a second. In the base case, the system allowed traversing the 5.0 m rail and reaching an exit velocity of 19.81 m/s, which corresponds to 99.04% compliance with the goal of 20 m/s. This behavior is consistent with what Khrulev [3] reports, who notes that dynamic models of pneumatic catapults allow capturing the interaction between motion, pressure, and gas-dynamic parameters in a more realistic way than simplified methods based solely on force balance. Similarly, Siddiqui et al. [1] show that tank discharge and actuator dynamics must be analyzed in a coupled manner, since the system response depends simultaneously on pressure evolution, flow rate, and movement of the moving assembly.

The temporal evolution of acceleration, pressure and mass flow confirms this transient nature. The calculated maximum acceleration was 161.56 m/s², about 16.5 g, indicating a severe but short-lived initial thrust. This must be interpreted carefully from a structural standpoint: although not a sustained load, it is a critical condition for the carriage, the attachment mechanism and the interface with the UAV. Jastrzębski [7] shows that pressure losses and the useful energy available during launch depend strongly on valve dynamics, and Szczepaniak and Jóźko [10] highlight that the flow characteristics of pneumatic distributors are determining factors in launcher circuits. This supports the interpretation that the peak mass flow obtained here, 0.3966 kg/s, and the rapid initial pressurization of the cylinder are governed by the discharge capacity of the pneumatic system and by the behavior of its control elements.

The parametric analysis also showed that initial tank pressure is one of the most influential factors on exit velocity, with a variation range between 13.60 m/s and 19.81 m/s within the studied interval. This result is again consistent with the observations of Khrulev [3], who notes that regulation of receiver pressure constitutes one of the most effective means for adapting the launcher's performance to different mass conditions and operation. Likewise, tank volume produced a velocity increase between 18.07 m/s and 20.17 m/s, although with progressively smaller gains for higher volumes, suggesting diminishing benefits from continuing to increase storage capacity.

Piston diameter presented a non-monotonic behavior, with velocities between 17.42 m/s and 19.96 m/s and a maximum around 0.08 m, indicating an optimal intermediate value. Khrulev [3] likewise shows that increasing cylinder diameter can extend the operational range of a launcher, although its selection should respond to design criteria rather than to geometric oversizing. The combined studies further show that rail length and effective valve area must be analyzed jointly, since higher velocities are reached only when sufficient travel distance and sufficient flow capacity are available at the same time. Launcher design is therefore a problem of balance between available pressure, mass to be accelerated, flow capacity and geometry, rather than the isolated optimization of a single parameter.

Read from the perspective of the design process, these results are the outcome of a rapid iteration cycle. The non-monotonic response of exit velocity to piston diameter is a case in point: discovering it through physical prototyping would require building and instrumenting several cylinders, yet it emerges directly from the model and invalidates the intuitive assumption that a larger cylinder always produces a faster launch. Likewise, the combined analysis of rail length and valve area shows that the 20 m/s requirement is met not by tuning one parameter but by a family of admissible combinations, allowing the design team to choose among them on secondary criteria such as portability, component availability or cost. The model thus supports the convergent phase of the design cycle, narrowing a broad space of alternatives to a justified subset before resources are committed to hardware.

It is important to distinguish between the verification and the validation of the model presented. Verification concerns whether the mathematical formulation has been solved correctly, whereas validation concerns whether it represents the physical system with sufficient fidelity for its intended use [17]. The work reported here comprises verification activities only. Tightening the solver tolerances from 10^{-3} and 10^{-6} to 10^{-11} and 10^{-14}, which raises the number of integration steps from 57 to 1453, changes the exit velocity by 1.9×10^{-3} % and the launch duration by 3.1×10^{-3} %, so the reported performance is converged; the peak acceleration, a much sharper feature, varies by 0.26 % and is quoted at its converged value. The mass-flow

law was checked at the critical pressure ratio r* = 0.5283, where the choked and unchoked branches agree to machine precision, and the simulated pressure ratio spans 0.072 to 0.979, so that transition is genuinely traversed. The computed response also reproduces the expected qualitative limits: the tank pressure decreases monotonically, the cylinder pressure remains bounded above by the instantaneous tank pressure, and lowering the initial tank pressure reduces the exit velocity until, below about 2 bar absolute, the carriage no longer reaches the end of the rail.

No experimental validation was performed. The model has not been contrasted against measurements taken on a physical launcher, so the absolute values reported here, an exit velocity of 19.81 m/s, a peak acceleration of 161.56 m/s² and a launch duration of 0.36 s, must be read as model predictions under the stated hypotheses rather than as verified performance of a built system. Two simplifications bound their reliability in a known direction: the isothermal hypothesis neglects the temperature drop accompanying expansion and therefore overestimates the pressure available in the cylinder, and the representation of all mechanical losses through a single assumed viscous coefficient acts the same way, so the predicted exit velocity should be regarded as an upper bound. The contribution of this work consequently rests on the relative trends and on the identification of dominant parameters, which are far less sensitive to these simplifications than the absolute magnitudes are. Validation on an instrumented test bench, with pressure transducers in the tank and cylinder and optical measurement of carriage velocity, is the necessary next step before the model is used for detailed design or for structural certification.

V. Conclusions

Pneumatic launch is a strongly transient process, characterized by rapid initial pressurization of the cylinder, a gradual drop in tank pressure, time-varying mass flow and high acceleration at the beginning of the travel. The model showed that performance depends not only on the energy initially stored but on the dynamic interaction between available pressure, cylinder volume expansion and the inertia of the moving assembly. Initial tank pressure, total moving mass, piston diameter, effective valve area and rail length proved to be highly influential on exit velocity, while tank volume contributes positively with diminishing returns.

It was identified that some parameters present non-monotonic behaviors, such as piston diameter, for which there is an intermediate value that maximizes exit velocity within the studied range. Similarly, combined analyses showed that meeting the target velocity does not depend on a single isolated parameter, but on the proper balance between flow capacity, pneumatic storage, acceleration length, and system inertia. This confirms that preliminary launcher design should be approached as a problem of compromise between kinematic performance and structural requirements, especially due to the presence of significant acceleration peaks during the initial stage of launch.

The developed model constitutes a useful tool for the preliminary sizing and comparative evaluation of pneumatic launcher configurations for UAVs, and, by making the design space explorable at negligible cost, it supports the iterative generation and evaluation of alternatives that characterizes design-driven innovation. Its present status should nevertheless be stated precisely: the numerical implementation has been verified, but the model has not been validated experimentally, so its predictions are to be used comparatively rather than as certified absolute performance. Future work should incorporate a non-isothermal formulation, leakage and additional pneumatic losses and, above all, contrast the predictions against measurements obtained on an instrumented prototype, in order to refine the accuracy of the model and extend its validity to advanced design stages.

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