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Modeling and testing of a tube-in-tube separation mechanism of bodies in space

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ABSTRACT

A tube-in-tube concept for separation of bodies in space was investigated theoretically and experimentally. The separation system is based on generation of high pressure gas by combustion of solid propellant and restricting the expansion of the gas only by ejecting the two bodies in opposite directions, in such a fashion that maximizes generated impulse. An interior ballistics model was developed in order to investigate the potential benefits of the separation system for a large range of space body masses and for different design parameters such as geometry and propellant. The model takes into account solid propellant combustion, heat losses, and gas phase chemical reactions. The model shows that for large bodies (above 100 kg) and typical separation velocities of 5 m/s, the proposed separation mechanism may be characterized by a specific impulse of 25,000 s, two order of magnitude larger than that of conventional solid rockets. It means that the proposed separation system requires only 1% of the propellant mass that would be needed for a conventional rocket for the same mission. Since many existing launch vehicles obtain such separation velocities by using conventional solid rocket motors (retro-rockets), the implementation of the new separation system design can reduce dramatically the mass of the separation system and increase safety. A dedicated experimental setup was built in order to demonstrate the concept and validate the model. The experimental results revealed specific impulse values of up to 27,000 s and showed good correspondence with the model.

1. Introduction

Separation of bodies in space, for example rocket stages and satellites, is a critical stage of any space mission and requires a dedicated separation system. A survey of separation mechanism is given by Kolesnikov et al. [1] and Mitchell [2]. Most commonly used impulse separation mechanisms consist of springs, gas operated pistons (hot or cold gas), or auxiliary rockets (retro-rockets). The main considerations for selection of a separation mechanism are reliability, weight, separation shocks, contamination (from combustion products), and the generation of angular velocity on the vehicles. Retro-rockets were used in the strap-on separation for the space shuttle solid rocket boosters and the Delta IV strap-on liquid propellant boosters (Stockinger et al.[3]), whereas pneumatic pistons were selected for the separation between the first and second stages of the Delta IV. An example of tradeoff between different separation thrusters for the AERS 1 launch vehicle was given by Mayers et al. [4], which resulted in selection of retro-rockets for separation between the first and second stages due to the advantage over gas operated pistons in weight, safety, and cost. For the separation of the ARES I rocket and the ORION multi-purpose crew vehicle a tradeoff study between springs and pneumatic thruster (cold gas operated pushers) was conducted (Konno et al. [5]). Retro rockets were less favorable due to the requirement of relatively low separation forces, therefore the larger specific force and impulse they provide was of lesser importance. Jeyakumar et al. [6] presented stage separation analysis using retro-rockets in a multistage launch vehicle. They discussed a common scenario in which the control of the lower stage is obtained with thrust vector control, thus the retro-rockets are required to provide sufficient thrust in order to allow separation before the pressure in the first stage drops to such a low value that does not allow effective control. The timing of firing of the retro-rockets is also critical, since a late firing will cause loss of control due to non-effective vector control from the first stage, whereas an early firing of the retro-rockets could result in collusion of the two stages due to the acceleration of the spent motor.

From surveying current separation systems, it appears that springs are used for the payload separation (for example see Dowen et al. [7]) where relatively small and very accurate forces are required, whereas retro rockets are used when large forces are required. Gas operated pistons fill in the intermediate thrust requirement region and some-

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Nomenclature

a	Burning rate coefficient [m/s Pa^n]
A_t	Tube cross-section area [m^2]
c_v	Specific heat at constant volume [J/kg K]
c_p	Specific heat at constant pressure [J/kg K]
d_t	Tube diameter [m]
e	Specific internal energy [J/kg]
E_K	Kinetic energy [J]
e_k	Specific kinetic energy [J/kg]
F_{THRUST}	Thrust force [N]
$F_{friction}$	Friction force [N]
g_0	Standard gravitational acceleration 9.806 [m/s^2]
h_{prop}	Propellant combustion products enthalpy [J/kg]
h_{conv}	Convective heat transfer coeff. [W/(m^2 K]
h	Specific enthalpy [J/kg]
I	Impulse [N m]
I_{sp}	Specific impulse [s]
k_t	Tube heat loss coefficient [–]
L_{tube}	Ejection tube length [m]
L_0	Initial combustion chamber length [m]
m	Mass [kg]
M	Mass of separated body [kg]
M_W	Gas molecular weight [kg/mol]
n	Burning rate exponent [–]
Nu	Nusselt number [–]
P	Pressure [Pa]
Pr	Prandtl number [–]
Q	Heat transferred to the gas [J]
r	Burning front progress [m]
R	Specific constant [J/kmol K]
R_0	Universal gas constant =8315 [J/kmol K]
Re	Reynolds number [–]
S_{ip}	Surface area of a solid particle [m^2]
t	Time [s]
T	Temperature [K]
V	Volume [m^3]
V_0	Initial combustion chamber volume [m^3]
V_f	Volume of the chamber and the tube [m^3]
V_{ip}	Volume of a solid particle [m^3]
W_{gas}	Work done by the gas [J]
x	Location of along the tube axis [m]
x_{12}	Distance between the bodies [m]
Y_i	Mass fraction of chemical species i [–]
$Y_{prop,i}$	Mass fraction of gas from propellant i [–]
Z	Fraction of the propellant burned [–]

Greek symbols

γ	Specific heat ratio [–]
η	Gas co-volume constant [–]
λ	Thermal conductivity [J/(m K s)]
μ	Gas viscosity [kg/(m s)]
ρ	Density [kg/m^3]
Δh_f	Heat of formation [J/kg]

Subscripts

a	Ambient
A	Average
c	Chamber
g	Gas phase
p	Solid propellant grains
t	Tube
0	Initial condition

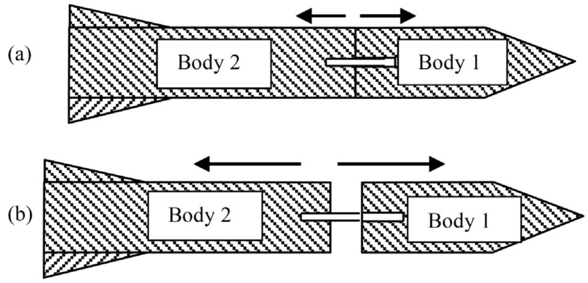

Fig. 1. A tube-in-tube mechanism for rocket stages separation. (a) Before separation. (b) After separation.

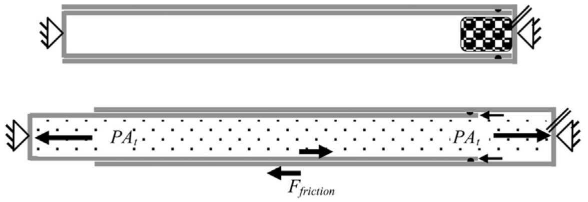

Fig. 2. Detailed look at the tube-inside-tube mechanism before (above) and after (bottom) separation. The propellant charge is also shown in the drawing before separation. The friction from the sealing O-ring counters the overall pressure forces on both tubes, which is PA_t. A_t is the inner diameter of the outer tube, which is equal to the outer diameter of the inner tube.

times make the best tradeoff.

This research presents an experimental and theoretical study of a new kind of separation system of bodies in space. The new separation mechanism can generate separation velocities similar to those obtained with retro rockets, but with only a fraction of the propellant. By maximizing the generated impulse and thrust from the propellant, the proposed separation system offers the opportunity to minimize the required propellant mass and therefore increasing the safety and reliability while reducing the system mass.

This new separation mechanism configuration stems from an idea filed as a patent by Gany and Michaels [8] and further presented by Michaels and Gany [9,10] of obtaining larger impulses from a certain propellant in comparison to the conventional rocket motor configuration, by ejecting a weight from a combustion chamber through an ejection tube. The separation system studied here is essentially implementation of that idea by making use of each separated body as the ejected weight of the other body. The efficiency and effectiveness of this concept increase with the increase of the ejected weights; therefore it is very efficient when large separated bodies are considered. A schematic drawing of the suggested separation mechanism of a tube-in-tube is shown in Fig. 1.

The separation system is composed of two nested tubes which each tube is attached to another body. A small amount of propellant is placed inside the inner tube, which can also be referred to as the initial combustion chamber. Once the propellant is ignited, the gas pressure within the chamber imparts force on each body in an opposite direction and causes the separation. In this paper it is shown both theoretically and experimentally that separation velocities of a few meters per second can be obtained with less than one percent of the propellant mass which would be needed in order to perform the same task with a rocket motor. The need of such a small amount of propellant for separation between large bodies reduces the separation system weight and increases safety. Additional possible advantages of this idea are the circumvention of residual angular velocities as the ejection tube guides