# DYNAMICS OF ION-BEAM-PROPELLED SPACE DEBRIS

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***Abstract:*** *The article studies the dynamics and control problem of the recently proposed Ion Beam Shepherd concept (IBS) for active debris removal in low Earth orbit. After introducing the concept and its main features the fundamental aspects of the interaction between a quasineutral plasma beam and an orbiting body are investigated based on fluid models presented in the literature. The relative dynamics and control problem of the IBS-debris system is then investigated for a quasi-circular inward spiralling orbit. Results show that stable close proximity formation flying is possible even under the disturbance induced by the ion beam as long as proper relative position and velocity measurement systems are available.*

***Keywords:*** *Space Debris, Electric Propulsion, Ion Engine, Formation Flying*

## 1 Introduction

Active debris removal (ADR), i.e. the process of displacing space debris from crowded orbits using a dedicated orbiting and/or ground based facility, has been advocated as a necessary step to guarantee the survival of space activities in Earth orbit[1].

ADR is, however, a costly and complex operation. Firstly, the momentum required to deorbit (or reorbit) a large amount of debris mass implies the need for a large hardware and/or fuel mass in order to physically generate the required force. The use of high specific impulse thrusters or propellantless systems is key to reduce such mass to reasonable levels. Secondly, the complexity related to the transfer of momentum from the debris remover to a typically uncontrolled non-cooperating object makes such operation particularly risky. Performing a rendezvous and docking maneuver, the most obvious way to allow physical transmission of momentum to a target debris, is a formidable technological challenge possibly requiring sophisticated sensors and robotic actuators, especially when one considers spinning or chaotically tumbling objects.

The Ion Beam Shepherd concept (IBS) recently proposed by our team [2] [3] and, independently, by JAXA [4] and CNES[5], promises to makes the momentum transfer problem much simpler by employing a highly collimated, high-velocity ion beam produced on board a shepherd spacecraft and pointed against the target debris to modify its orbit and/or attitude with no need for docking. Active Debris removal is one of the candidate applications for this concept.

Although in principle conceptually simple, the proposed removal approach involves new and interesting challenges from the dynamics and control point of view. The debris shepherd and the space debris should be de-orbited simultaneously in a controlled and reliable way, keeping a safe distance between each other to avoid undesired collisions.

A basic aspect to be investigated is the dynamical interaction between an orbiting body and a plasma beam of a few keV. Such interaction, which needs to be understood in details before the implementation of any possible control strategy, has, to the authors' knowledge, never been studied in the literature. The force and torque transmitted to a target of generic shape and located at a generic position with respect to the thruster nozzle need to be evaluated as a function of the thruster characteristics. Once a sufficiently accurate model is obtained what remains to investigate is the relative dynamics of the orbiting space debris with respect to the shepherd spacecraft and possible control strategies to stabilize the system. The aim of the present article is to address these aspects at a preliminary level.

First, we select a plasma beam model available from the literature and formulate the basic equations for computing the force and torque transmitted by an ion beam to a target object. Next, assuming the debris and the debris shepherd are in circular or quasi-circular orbits we model the relative center of mass dynamics using linearized relative equations of motion to which we add the differential acceleration generated by the ion beam. A custom designed numerical tool, called IBIS (Ion Beam Interaction Software) is employed to simulate the relative position of the IBS with respect to the debris during a deorbiting maneuver and to assess the effectiveness of a simple control strategy in achieving the required stability.

## 2 The Ion Beam Shepherd (IBS)

The Ion Beam Shepherd is a new concept of space propulsion in which a shepherd spacecraft employs a primary propulsion system (e.g. an ion thruster) to produce and direct a collimated quasi-neutral plasma beam towards a target object. As a consequence, the latter undergoes a force $\boldsymbol{F}_D$ originated by the momentum carried by the plasma ions colliding with the target (Figure 1). The force $\boldsymbol{F}_D$ can be related to the reaction force $\boldsymbol{F}_{p1}$ that the primary propulsion system exerts on the shepherd satellite by the equality:

$$\boldsymbol{F}_D = -\eta_B \boldsymbol{F}_{p1}. \tag{1}$$

where $\eta_B$ is the beam momentum transfer efficiency, which depends primarily on the beam-target interaction geometry and will be computed later.

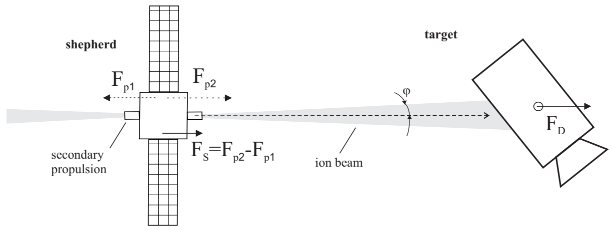


Figure 1: *Schematic of ion beam shepherd satellite deorbiting a space debris*

In order to avoid the IBS to secularily drift away from the target the reaction force $\boldsymbol{F}_{p1}$ needs to be compensated by a secondary propulsion system (e.g. another ion thruster) mounted on the shepherd spacecraft (Figure 1). In addition, the secondary propulsion system can be used for controlling the IBS-debris relative displacement along the orbit normal and along the out of plane direction.

A zero secular variation of the distance bertween the two bodies is obtained when the two orbit semimajor axes $a_D$ and $a_S$ are equal at any instance of time $t$. That means we have:

$$a_D(t) = a_S(t), \tag{2}$$

at all times throughout the deorbiting or reorbiting process.

After performing the derivative and taking into account Gauss variational equation for the semimajor axis we derive the constraint:

$$\frac{v_D F_D}{m_D} = \frac{v_S F_S}{m_S}, \tag{3}$$

where $v$, $F$ , $m$, denote, respectively, the orbit tangential velocity, the resulting tangential force and the mass, while the subscript 'D' and 'S' refer to the target debris and the shepherd spacecraft, respectively. When the two spacecraft are coorbiting at close distance, as it is generally the case for this application, we have $v_S \approx v_D$ and the last equation reduces to:

$$\frac{F_D}{m_D} = \frac{F_S}{m_S}, \tag{4}$$

Note that the spacecraft separation distance is constant only for the case of circular orbit while for elliptic orbits it oscillates with a relative amplitude equal, to first order, to the orbit eccentricity. This makes the IBS concept less suitable for highly eccentric orbits. Fortunately, the great majority of large Low Earth Orbit (LEO) debris has eccentricity less than 0.01 (Figure 2).

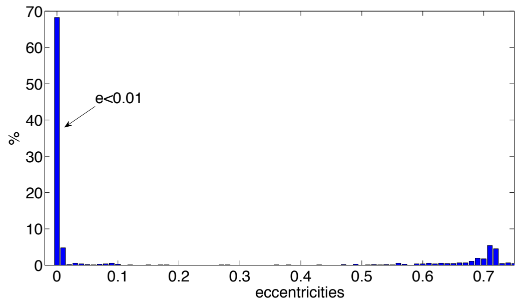


Figure 2: *Eccentricity distribution for LEO space debris larger than 1 tonne*

If we make the assumption that the debris orbit is initially circular and evolves in a quasi-circular manner the orbit radius evolution $r(\tau)$ from its initial value $r_0$ can be approximated fairly accurately by[3]:

$$\frac{r}{r_0} \simeq \frac{1}{(1 \pm \epsilon\tau)^2} = 1 \mp 2\epsilon\tau \pm 3(\epsilon\tau)^2 + o\left[(\epsilon\tau)^2\right],$$

where the + (-) sign indicates a deorbit (reorbit) maneuver, $\tau$ is the non-dimensional time related to the time $t$ through the initial orbit mean motion $\omega_0$:

$$\tau = \omega_0 t = \sqrt{\frac{\mu}{r_0^3}}t,$$

and the small non-dimensional coefficient $\epsilon$ is the ratio between the debris tangential acceleration and the local gravity at the beginning of the deorbit meneuver:

$$\epsilon = \frac{F_D r_0^2}{m_D \mu},$$

where $\mu$ is the gravitational parameter.

The total maneuver time can be written as[3]:

$$\Delta\tau = \pm\frac{\sqrt{r} - \sqrt{r_0}}{\epsilon\sqrt{r_0}},$$

which can be used to show that, for instance, a 2-tonne debris can be deorbited from 1000 to 300 km altitude with 100 mN of continuous thrust ($\epsilon \sim 2.8 \times 10^{-5}$) in about three months.

### 2.1 Ion Beam modelling

The Parks and Katz self-similar model [6] has been selected for the simulations here. The axisymmetric, stationary plume consists of a fully-ionized, collisionless, quasineutral plasma, consisting of singly-charged, highly-supersonic ions and isothermal electrons of temperature $T_e$.

Let us set the origin of a cylindrical coordinate system $\langle r, \theta, z\rangle$ at a point on the plume axis far enough from the optics where local, near-field effects such as beam non-uniformities and residual thruster magnetic fields can be neglected. Since the axial velocity $u_z$ of the ions at the plume initial section is expected highly supersonic, Parks and Katz assume that their variation along the plume can be neglected, so that:

$$u_z(r, z) = u_0. \tag{5}$$

Then, the plasma density and radial ion velocity are described by [6]:

$$n(r, z) = \frac{3n_0}{h(z)^2} \exp\left(\frac{-3r^2}{h(z)^2 R_0^2}\right), \tag{6}$$

$$u_r(r, z) = u_0 r \frac{h'(z)}{h(z)} \tag{7}$$

where: $R_0$ is the plume effective radius at $z = 0$, which accounts for about 95% of the beam flux, $n_0$ is the average density value of the tube $r \leq R_0$ containing the total beam current, and $h(z)$ is the dimensionless function accounting for the self-similar plume radial expansion, which satisfies:

$$\frac{dh}{dz} = \sqrt{\frac{12}{M^2} \ln h + h_0'^2}; \quad h(0) = 1. \tag{8}$$

Here, $M = u_0(m_i/kT_e)^{1/2}$ is the Mach number based on the axial velocity, and $h_0'$ is the tangent of the divergence angle at $z = 0$. Typical Mach numbers for commercially available ion thrusters are between 15 and 20.

The beam total mass flux and momentum are, respectively:

$$\dot{m} = \pi R_0^2 m_i n_0 u_0, \qquad F_0 = \dot{m} u_0. \tag{9}$$

These two magnitudes are conserved along the plume; $F_0$ is the negative thrust on the shepherd. Therefore, the plasma beam emitted by the thruster is characterized by the exhaust velocity (or specific impulse) $u_0$, the mass flow $\dot{m}$, and the plume radius $R_0$. The effective radius of the beam increases downstream according to

$$R_B(z) = R_0 h(z) \tag{10}$$

and $h(z)$ depends on $M$ and $h_0'$.

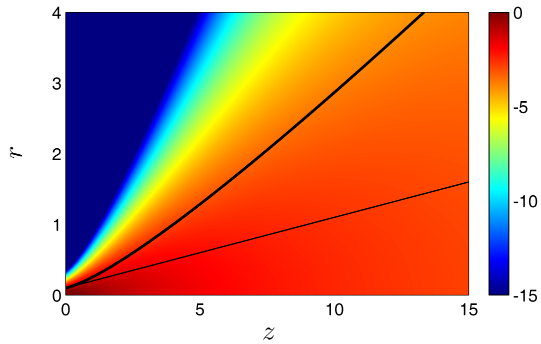


Figure 3: *Density contour of the plasma beam considering an initial divergence angle of 5.7 deg and* $M_0 = 20$*. The thick solid line represents the plasma edge* $r(z) = R_B(z)$*, while the thin line corresponds to the divergence cone with no electron pressure effects. The background color maps the decimal logarithm of the density,* $\log_{10}(n/n_0)$.

### 2.2 Force and Torque Characterization

The force transmitted by the plasma to the target comes primarily from the ion momentum of the plasma. Electric thrusters employ heavy ions (e.g. xenon) accelerated to energy level up to a few keV. According to experimental tests ions of this type penetrate the substrate of a metal like aluminum by a few nanometers and deposit practically all their energy on the target. In addition, they give rise to backsputtering effects in which the energy of the sputtered material is typically two orders of magnitudes smaller than the the one of the incoming ions [7]. Therefore, neglecting the momentum of backscattered material, and the electron pressure of the plasma beam, the momentum transfer on a differential surface element $dS$ of the target is ultimately:

$$d\boldsymbol{F} \simeq m_i n \boldsymbol{u}_i \left(-\boldsymbol{\nu} \cdot \boldsymbol{u}_i\right) dS, \tag{11}$$

where $\boldsymbol{\nu}$ is the outwards-pointing normal unit vector of the surface element, $\boldsymbol{u}_i$ the velocity vector of the incoming ions and $n$ their local density. The corresponding force $\boldsymbol{F}$ and torque $\boldsymbol{N}$ exerted by the plume on a space debris can be therefore calculated by integrating over the surface $S_b$ exposed to the beam:

$$\boldsymbol{F} = \int_{S_b} d\boldsymbol{F}; \qquad \boldsymbol{N} = \int_{S_b} (\boldsymbol{r} - \boldsymbol{r}_G) \times d\boldsymbol{F}, \tag{12}$$

where $\boldsymbol{r} - \boldsymbol{r}_G$ is the relative position of the integrating point with respect to the center of mass of the debris.

A beam momentum transfer efficiency can be defined as the ratio between the axial force on the debris and the beam total momentum:

$$\eta_B = \frac{F_z}{F_0} = \frac{F_z}{\pi R_0^2 m_i n_0 u_0^2}. \tag{13}$$

Let us consider the case of a debris consisting of a uniform sphere of radius $R_S$ and center-of-mass at $(r_S, z_S)$. For $r_S = 0$ the sphere is aligned with the axis of the plume and both the radial (i.e. lateral) force and the torque are zero. Figure 4(a) plots the beam efficiency (i.e dimensionless axial force) and (b) the dimensionless radial force versus the local shape factor (or relative sphere radius):

$$\chi = \frac{R_S}{R_B(z_S)},$$

and for different values of the relative radial offset with respect to the beam width:

$$\gamma_r = \frac{r_S}{R_B(z_S)}$$

Evidently, as the fraction of plume intercepted by the sphere increases, the beam efficiency increases.

Contour plots of the dimensionless axial and radial force on a sphere as a function of its position in the beam space are depicted in Figure 5.

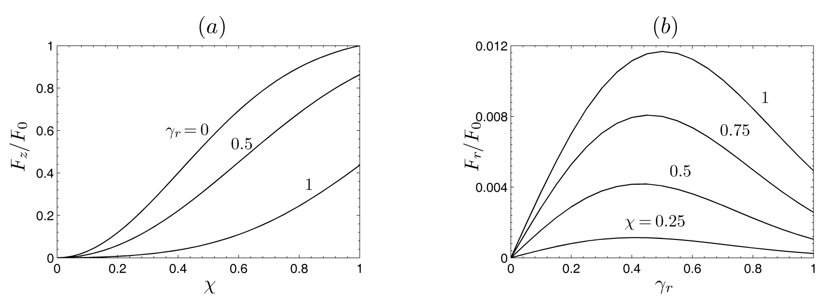


Figure 4: *Beam momentum transfer efficiency (a) and non-dimensional radial force (b) for a sphere as a function of the shape factor* $\chi$ *and the relative radial offset* $\gamma_r$.

## 4 Relative Dynamics Equations

Let us consider a local Frenet orbiting frame centered at the shepherd spacecraft and having its y axis along the instantaneous velocity vector, the z axis along the instantaneous angular momentum and the x axis following the right hand rule. After linearizing the local gravity field around the origin the equations of motion of the debris position $\boldsymbol{\rho}$ relative to the shepherd are:

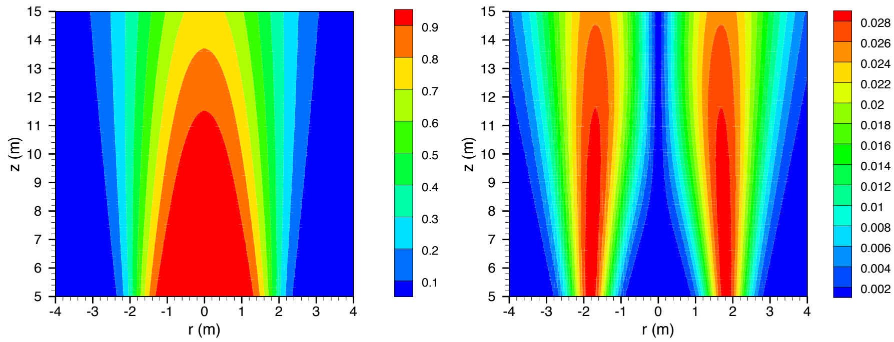


Figure 5: *Contour plots for the nondimensional axial (a) and radial force (b) for a sphere of 1.86*m *radius moving along the radial (r) and longitudinal direction inside a beam with negligible electron pressure and 10 deg divergence.*

$$\ddot{\boldsymbol{\rho}} + \left(\boldsymbol{\Omega}\boldsymbol{\Omega} + \dot{\boldsymbol{\Omega}} - \mathbf{G}\right)\boldsymbol{\rho} + 2\boldsymbol{\Omega}\dot{\boldsymbol{\rho}} = \frac{\boldsymbol{F}_D}{m_D} - \frac{\boldsymbol{F}_S}{m_S}, \tag{14}$$

where $\boldsymbol{\Omega}$, $\dot{\boldsymbol{\Omega}}$ represent the angular velocity matrix in Frenet axes and its time derivative, $\mathbf{G}$ is the gravity gradient matrix in Frenet axes while $\boldsymbol{F}_D$ and $\boldsymbol{F}_S$ are the net forces (thruster forces and orbital perturbations) on the debris and the shepherd spacecraft, respectively.

The above equations need to be accompained with the shepherd orbit evolution:

$$\ddot{\boldsymbol{r}}_S = -\mu\frac{\boldsymbol{r}_S}{r_S^3} + \frac{\boldsymbol{F}_S}{m_S}, \tag{15}$$

and by the space debris attitude equations of motion:

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \wedge (\mathbf{I}\boldsymbol{\omega}) = \mathbf{N}_{tot} \tag{16}$$

where $\mathbf{I}$ is the debris inertia matrix in body axes, $\boldsymbol{\omega}$ the angular velocity vector and $\mathbf{N}_{tot}$ the resulting torque around the debris center of mass, including the beam torque, gravity gradient and orbital perturbations torques.

If the initial debris orbit is circular and $\epsilon \ll 1$ the orbit evolves in a quasi-circular manner and Eqs. (14) can be well approximated by the perturbed Clohessy-Wiltshire equations:

$$\ddot{x} - 2\omega\dot{y} - 3\omega^2 x = \frac{F_{xD}}{m_D} - \frac{F_{xS}}{m_S} \tag{17}$$

$$\ddot{y} + 2\omega\dot{x} = \frac{F_{yD}}{m_D} - \frac{F_{yS}}{m_S} \tag{18}$$

$$\ddot{z} + \omega^2 z = \frac{F_{zD}}{m_D} - \frac{F_{zS}}{m_S} \tag{19}$$

where $\omega$ is the instantaneous mean motion:

$$\omega \simeq (1 \pm \epsilon\tau_0)^3 \, \omega_0$$

$$\dot{\omega} \approx 0$$

and the dots indicate derivatives with respect to the (dimensional) time $t$.

## 3 Numerical Simulations

The ion beam force and torque equations (12) have been integrated with the relative dynamics, orbit evolution and attitude dynamics equations (14,15, 16) and solved numerically with IBIS (Ion Beam Interaction Software), an in-house simulation package which can model the ion beam interaction with any rigid object.

For the simulations performed here we have assumed that the ion beam is constantly pointed along the shepherd instantaneous velocity vector, is kept contant in time, and transmits to the debris a force which only depends on the debris center of mass location relative to the shepherd and the debris attitude relative to the ion beam axis. The shepherd is equipped with three additional thrusters (in the R-bar, V-bar and out-of-plane direction) to control the relative position with the debris around a nominal value corresponding to the debris and shepherd coorbiting at a user-defined separation distance. An optimally-tuned PD control loop was employed to stabilize the relative motion after an initial relative velocity error was applied to the debris. For this preliminary work we have assumed the availability of an exact measurement of the relative position between the two spacecraft. Figures 7-9 describe the relative position evolution, the control effort and the debris angular velocity variation during the maneuver. As far as orbital perturbations, only J2 gravitational terms were accounted for.

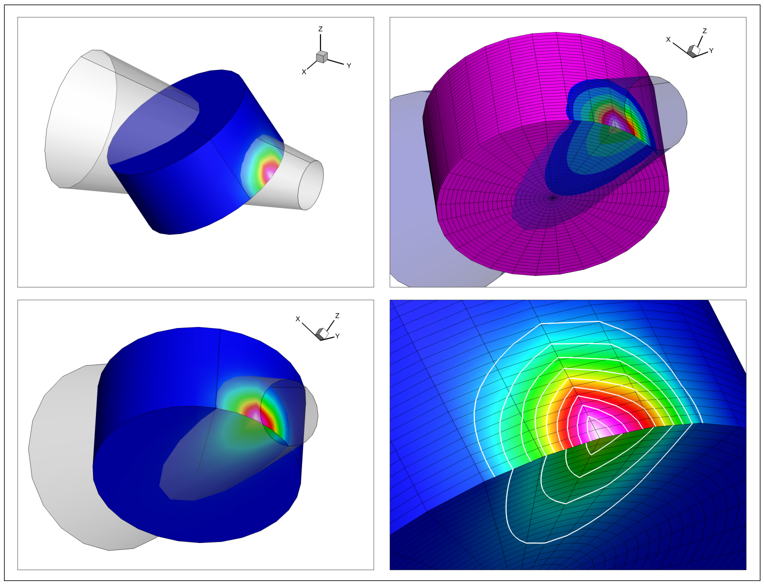

Figure 6: *IBIS software graphical output*

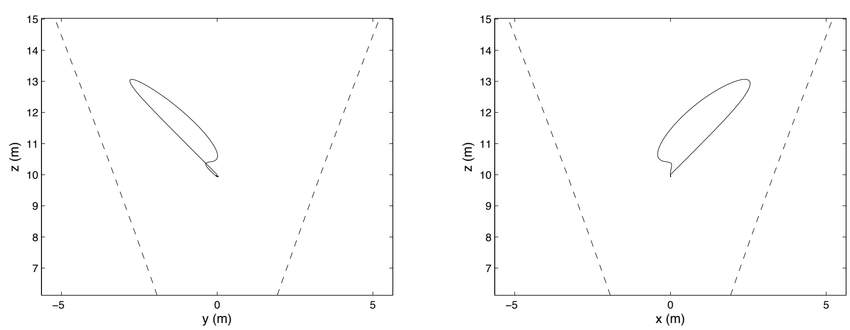


Figure 7: *Relative position between a 2* tonne *spherical debris in circular LEO orbit (altitude of 1000km) with* $\chi = 0.7$ *subject to an initial impulse of 0.01* m/s *along the* $x$ $y$ *and* $z$ *axis from its nominal equilibrium position. The shepherd mass is set to 300 kg. A beam of 0.1 N (deorbiting) thrust and 10 deg divergence is employed. An optimally tuned PD feedback control system along the R-bar V-bar and out-of-plane direction was employed.*

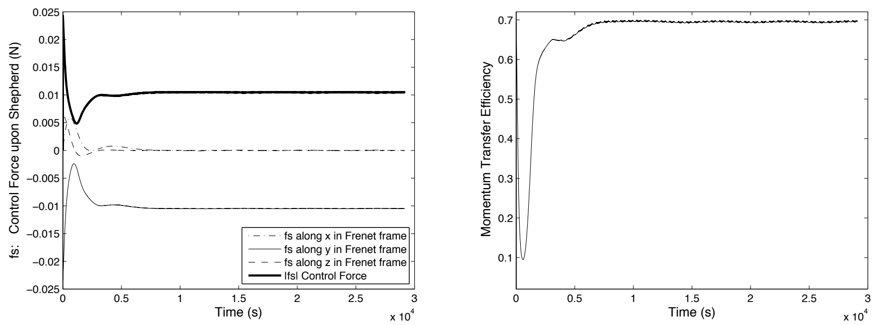


Figure 8: *Control force components (left) and momentum transfer efficiency (right) for the relative position control problem described in Fig. 7.*

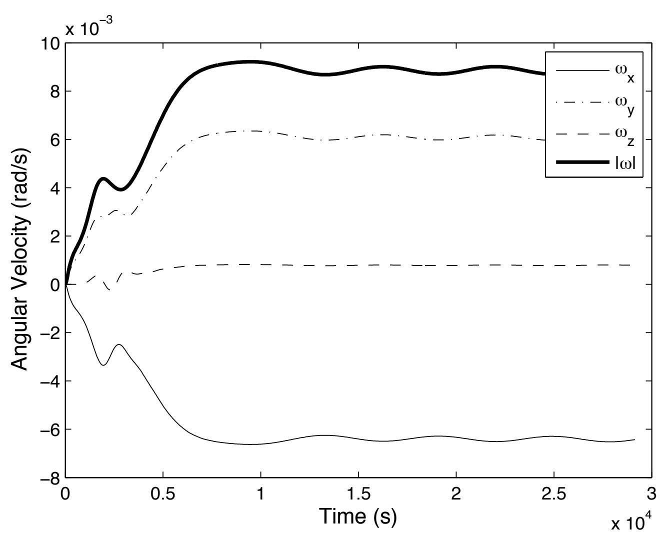


Figure 9: *Variation of the debris angular velocity vector (with respect to Frenet axes) for the relative position control problem described in Fig. 7.*

## 5 Conclusions

A model describing the interaction between an orbiting body and a collimated ion beam has been developed and employed for a preliminary evaluation of the feasibility of ion beam shepherd (IBS) concept. The force and torque transmitted by the beam on an object of arbitrary shape have been derived based on existing fluid models for the expansion of plasma beam in the far field, and have been integrated into an orbital and attitude dynamics model. Results show that the IBS-debris relative position for the case of a spherical debris can be stabilized as long as accurate relative position measurements are available. Future work will be needed to assess the case of space debris of more complex shapes (cylinder, prism, etc.) and to include errors in the relative position estimation for a realistic guidance system.


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