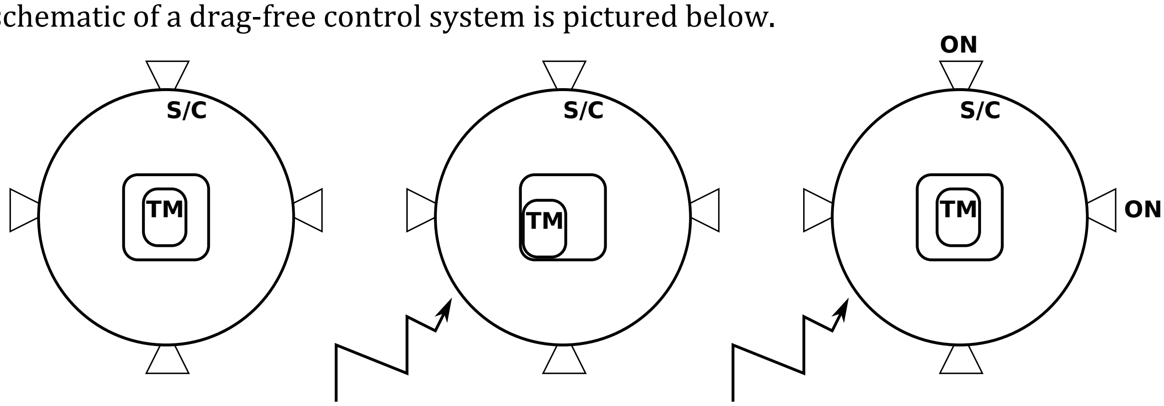
Space Propulsion Qualifier Exam
January 2018

SOLVE BOTH PROBLEMS

Problem 1

LISA Pathfinder (LPF) was launched on December 2015 as a precursor of future space-based gravitational wave observatories, such as LISA. One of the key outcomes of LPF is the experimental demonstration of the free fall of test masses (TMs) at the level required for gravitational wave detection. To demonstrate this key technology, a TM has to be free from any spurious acceleration, as any such acceleration would be in direct competition with the tidal deformations caused by the gravitational waves that want to be detected. In order to mitigate this acceleration noise, LPF carries a drag-free control system that acts to control the relative position and attitude of the TM with respect to the spacecraft (S/C).
A schematic of a drag-free control system is pictured below.



(1) Free fall (2) External disturbance (3) Drag-free control

Two different microthrusters are carried on LPF: **cold gas (nitrogen) thrusters** (ESA) and **colloidal thrusters** (JPL/Busek). You are asked to compare both types of propulsion systems for this application and address the main advantages of either technology. Assume nominal thrust is 20μN (the colloid thruster has 9 emitters per thruster head)[1].

1) Estimate the nominal I_{sp} in each case. Assume: (a) N_2 cold gas thruster at 300K, (b) EMI-Im ionic liquid propellant in pure droplet regime and a nominal current of 2.7μA per thruster head. What acceleration voltage is required?
2) How can the I_{sp} of either thruster be increased? How much increase can be expected?
3) If the thrusters are operating for 100 days, what is the propellant consumption in each case? Comment on differences in the propellant feed system.
4) Discuss the tunable parameters or degrees of freedom available for each thruster type that can be commanded by the Drag-free controller.

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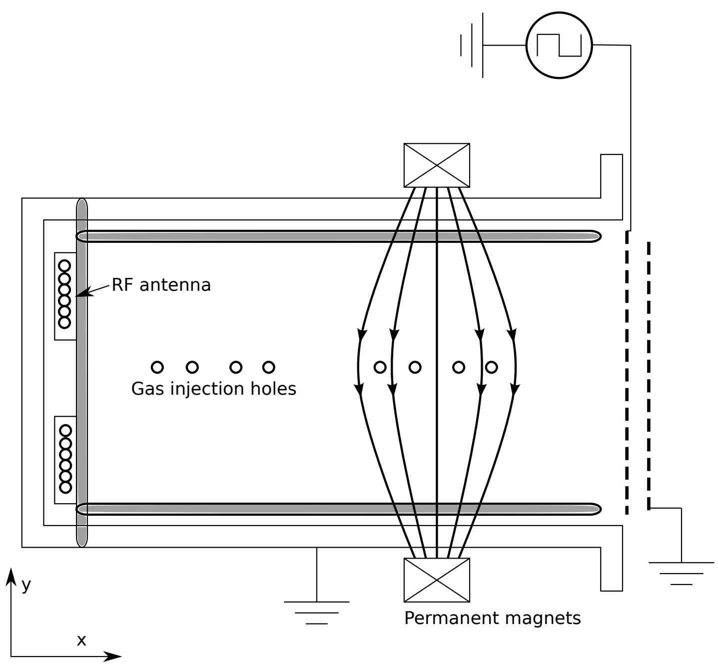
[1] Propellant properties

- EMI-Im: density=1520kg/m^3, viscosity=28cP, conductivity=0.84Si/m, surface tension=0.042N/m, relative permittivity=12, positive ion mass = 111.2 amu, negative ion mass = 280.1 amu
- Nitrogen: C_p=1040 J/kg/K

Problem 2

The French PEGASES concept (Plasma propulsion with Electronegative GASES) is an ion engine that produces an ion-ion plasma by using a magnetic barrier to impede downstream electron transport and favor negative ion formation by electron-neutral attachment. Successive positive and negative ion beams can then be extracted from this thruster by applying a square-wave bias to the dual-grid extraction system. Theoretically, no electron-emitting neutralizer would be needed, as the time-averaged beam can be made quasi-neutral. A schematic of the PEGASES thruster is shown below.



The propellant used is SF_6, the main positive ion produced is SF^+_5 and two types of negative ions are produced: SF^-_6 and F^-. The distance between grids is 2mm, the diameter of the thruster 8cm and the transparency of the grids around 60%. You are asked to define the missing operational parameters of this thruster by answering the following questions; assume space-charge-limited operation applies during the constant voltage phase of the waveform[2]:

1) What duty cycle of the square voltage wave is needed to ensure time-averaged beam quasi-neutrality if the main negative ion is SF^-_6? What if the main negative ion is F^-? Assume the amplitude of the voltage in the positive and negative polarities is equal.
2) The frequency of the square wave is selected to be 200kHz and the amplitude ±350V. How does this excitation frequency compare to the plasma frequency inside the chamber (ion temperature is 0.1eV)? To answer this question you will need to consider the sheath structure over the screen grid: will a sheath form? Define the characteristic times that may challenge the DC approximation during the constant voltage phases.
3) Plot the beam current versus time you would measure in the lab. What is the thrust?
4) Why can't Xenon be used in this configuration?

[2] Propellant properties
S = 32 amu, F = 19amu

Physical constants and conversions

Boltzmann	$k = 1.38 \times 10^{-23}$ J/K
Planck	$h = 6.626 \times 10^{-34}$ Js
Permittivity of vacuum	$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m
Electron charge	$e = 1.6 \times 10^{-19}$ C
amu to kg	1.66×10^{-27} kg