UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola Superior d'Enginyeries Industrial, Aeroespacial i Audiovisual de Terrassa

MSc. in Space and Aeronautical Engineering

Study of the performance of the propulsion units with nitrogen-jet thrusters for astronaut Extravehicular Activities (EVAs)

Master Thesis - Annex

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Contents

Appendix

Appendix A.1.

The code presented below was utilized for the performance analysis of the Simplified Aid for Extravehicular Activity Rescue (SAFER) propulsion unit.

```
format long;
close all;
clear all;
clc;

%--------------------------------------------------------------------------------------------------------------
% MSc. Space and Aeronautical Engineering (MASE)
% ESEIAAT, UPC

% Master Thesis (TFM)
% Student: Nikolaos Monokrousos
% Director: Lizandra Dalmases, Josep Oriol
% Codirector: Tejedor Herran, Blanca
% Academic Year: 2020-2021 (February 2021-June 2021)

% Subject: "Study of the Performance of Propulsion Units with Nitrogen-Jet Thrusters for Astronaut
% Extravehicular Activities (EVAs)"

% Code:
% 1) Performance analysis

%--------------------------------------------------------------------------------------------------------------
% Assumptions

% 1) The study of the gases that shall be followed for the performance of the Simplified Aid for
%Extravehicular Activity Rescue (SAFER) propulsion unit, used to perform self-rescue maneuvers
%during EVAs in the current missions, shall be implemented based on the assumption that the gases
% behave ideally.

% 2) The 4 propellant storage tanks comprising the SAFER propulsion unit are connected to the Cold
%Gas Propulsion System (CGPS) through one tube, thus the tanks providing the propellant to the
%thrusters behave as one.
```

```
%-------------------------------------------------------------------------------------------------------------------
% 4.1.1. Input Data

% Gas and Environmental Characteristics
Pa= 0;                  % Ambient pressure (Pa)
g0= 9.80665;            % Gravitational acceleration (ms-2)
R= 8.3145;              % Ideal gas constant (JK-1mol-1)
MWN2= 0.028014;         % Molecular weight of gaseous nitrogen (kgmol-1)
RN2= R/MWN2;            % Individual gas constant of nitrogen (JK-1kg-1)
gamma= 1.40;            % Specific heat ratio of nitrogen
viscN2= 15.95e-6;       % Dynamic viscosity of nitrogen (sPa)

% Thruster and Propellant Characteristics
Aratio= 100;            % Aratio=Ae/At: Exit Area to Throat Area ratio
Tc= 311;                % Chamber temperature (26.85°C)
Pc= 1482372;            % Chamber pressure=Pressure Regulator (Pa) (215 psig)
dv_min= 3.05;           % Minimum velocity change, ground processing (ms-1)
mp= 5.6;                % Propellant mass (kg), 4 tanks, 1.4 kg/tank
lamda= 0.95;            % Bell Nozzle coefficient
F_act= 4.448;           % Thrust produced per nozzle (N)

% System Masses Characteristics
mastro= 70;             % Mass of the astronaut performing the EVA
memu= 124.6;            % Mass of the EMU space suit AND the SAFER
mi= mastro+memu;        % Initial mass of the system (astronaut/EMU/SAFER)
mf= mi-mp;              % Final mass of the system (initial mass-propellant)

%-------------------------------------------------------------------------------------------------------------------
% 4.1.2. Calculations

% Mexit Calculation

mbar_thr= mbar_from_Mach (1, gamma);
mbar_exit= mbar_thr/Aratio;
options = optimset('TolX',1.e-10,'TolFun',1.e-10);
funaux= @(M) mbar_from_Mach(M,gamma)-mbar_exit;
Me= fsolve(funaux,2,options);

%-------------------------------------------------------------------------------------------------------------------
% 4.1.2.1. Thruster Performance Characteristics Calculations
```

```
% Thrust Coefficient in vacuum (cf)
cf=(2/(gamma+1))^((gamma+1)/(2*(gamma-1)))*(gamma*Me+(1/Me))/sqrt(1+((gamma-1)/2)*Me^2);

% Characteristic Velocity (cstar, ms-1)
cstar= sqrt(RN2*Tc)/mbar_thr;


% Pressure at the exit of the nozzle (Pe, Pa)
Pe= Pc*(1+((gamma-1)/2)*Me^2)^(-gamma/(gamma-1));

% Exhaust Velocity (ve,ms-1)
ve= sqrt((2*gamma*RN2*Tc/(gamma-1))*(1-(Pe/Pc)^((gamma-1)/gamma)));

% Speed of sound at the exit (ae,ms-1)
ae= sqrt(gamma*RN2*Tc/(1+(gamma-1)/2*Me^2));

% Specific Impulse (Isp,s)
Isp_coeff= cstar*cf/g0;

% Effective exhaust velocity (c,ms-1)
c= Isp_coeff*g0;

% Total velocity change, Tsiolkovsky Equation (dv_tsiol,ms-1)
dv_tsiol= c*log(mi/mf);

% Theoretical thrust, nozzle coefficient considered (F_theor,N)
F_theor= F_act/lamda;

%-------------------------------------------------------------------------------------------------------------------
% 4.1.2.2. Nozzle Throat Characteristics Calculations

% Throat Pressure (Pt,Pa)
P_thr= Pc*(2/(gamma+1))^(gamma/(gamma-1));

% Throat Temperature (Tt,K)
T_thr=2*Tc/(1+gamma);

% Gaseous Nitrogen (GN2) Throat Density (rhot,kgm-3)
rho_thr = P_thr/(RN2*T_thr);


% Throat Velocity (vt,ms-1)
v_thr= sqrt(gamma*RN2*T_thr);
```

```
%-------------------------------------------------------------------------------------------------------------------
-
% Iteration Method - Trial and Error .
% Start iteration using cd=1.

cd=1;

for i=1:4

% Propellant mass flow (m_dot,kgs-1)
m_dot= F_theor/c/cd;

% Throat cross-sectional area (At,m2)
A_thr= m_dot/(v_thr*rho_thr);

% Throat Diameter (Dt,m)
D_thr= 2*sqrt(A_thr/pi);

% Reynolds Number at Throat (Re)
Re_thr= rho_thr*v_thr*D_thr/viscN2;

% Discharge Coefficient (cd)
cd= 0.8825+0.0079*log(Re_thr);

end

% END OF ITERATION
%-------------------------------------------------------------------------------------------------------------------
% 4.1.2.3. Propellant Tanks Characteristics

% Total time to empty the propellant tanks (dt,s)
dt= mp/m_dot;

% Total propellant tank volume (Vp,m3)
Vp= mp*RN2*Tc/Pc;

%-------------------------------------------------------------------------------------------------------------------
% 4.1.2.4. Nozzle Dimensioning and Geometry

% Now that the throat dimensions have been defined using the iteration method of "Trial and Error", the
%dimensions of the exit can be calculated:
```

```
% For an assumed Aratio= 100, the exit cross sectional area (Ae,m2) is:
Ae= A_thr*Aratio;

% Exit diameter (De,m)
De= 2*sqrt(Ae/pi);

%----------------------------------------------------------------------------------------------------------------------------
% 4.1.3. Verification Calculations

% Thrust (F_calc,N)
F_calc= lamda*cd*(m_dot*ve+(Pe-Pa)*Ae);

% The percentage difference between the initial (either given or calculated with different equations) and
%the final values of thrust shown below, can be calculated as:
F_perc_diff= abs(((F_act-F_calc)/F_act))*100;

%----------------------------------------------------------------------------------------------------------------------------
%% END OF PROGRAMME
```

Appendix A.2.

The function presented below ("*mbar_from_Mach.m*") was utilized for calculation of the mass flow parameter, used in the calculation of the Mach number at the exit of the nozzle.

```
function mbar = mbar_from_Mach(M,gamma)

% Mass flow parameter calculation

s_gam= sqrt(gamma);                      % Auxiliary variable

ct1= 0.5*(gamma-1);                      % Constant parameter

exp1= (gamma+1)*0.5/(gamma-1);           % Exponential parameter

mbar= s_gam*M/(1+ct1*M^2)^exp1;          % Calculation of the mass flow parameter

end
```

Appendix B.1.

The code presented below was utilized for the orbital dynamics analysis and the numerical and analytical resolution of the Clohessy-Wiltshire equations, as well as for the extraction of a plot showcasing the potential return of the astronaut back to the orbiter, by activating the nitrogen-jet thrusters of the SAFER propulsion unit.

```
format long;
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clc;

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% Subject: "Study of the Performance of Propulsion Units with Nitrogen-Jet
% Thrusters for Astronaut Extravehicular Activities (EVAs)"

% Code:
% 2) Orbital dynamics and mission optimal parameters

%-----------------------------------------------------------------------------------------------------------------------
% Assumptions:

% 1) The position of the EVA crew member corresponds to a circular orbit and a motion on the
%equatorial plane.

%2) The spacecraft the exact same circular orbit as the EVA crew member.

%-----------------------------------------------------------------------------------------------------------------------
% 4.2.1. Input Data

RT= 6371000;      % Radius of Earth (m)
h= 400000;        % Altitude of the ISS (m)
r= RT+h;          % Distance of ISS from Earth's center of mass (m)
mu= 3.986e14;     % Earth’s standard gravitational parameter (m3s-2)
```

```
g0= 9.80665;       % Gravitational acceleration (ms-2)

m0= 194.6;         % Initial mass of the system (kg) (astronaut/EMU/SAFER)
Isp= 79.1717;      % Specific impulse (s): Isp_coeff
Thr= 4.448*0;       % Thrust (N): F_calc
                    % = 0 (N) for free-floating, = 4.448 (N) for SAFER activation
dt= 912.5061;       % Total time to empty the propellant tanks (s)

%-----------------------------------------------------------------------------------------------------------------------
% 4.2.2. Calculations

Vsc= sqrt(mu/r);           % Circular velocity (ms-1)
omega= Vsc/r;              % Angular rate (s-1)
omega2= omega^2;           % Square of the angular rate (s-2)

m0dot= Thr/Isp/g0;          % Propellant mass flow rate: mdot (kgs-1)

% Clohessy-Wiltshire (CW) Equations
% The CW equations can be used to determine in a straightforward way the motion that results from an
%initial know velocity.

% The initial relative position is defined as (x0,y0,z0)=(0,0,0) (m) since the Clohessy-Wiltshire (CW)
%equations are used to determine the relative position of the free-floating body to the orbiter (ISS).

% However, it can be assumed that the EVA takes place a couple of meters farther from the center of
%mass of the ISS.

%-----------------------------------------------------------------------------------------------------------------------
% 1st Approach: Numerical solution verification

x0= 30;            % x0: initial relative position in x-axis (m)
y0= 30;            % y0: initial relative position in y-axis (m)
z0= 30;            % z0: initial relative position in z-axis (m)

x0dot= 0.762;   % x0dot: initial relative velocity in x-axis (ms-1), x0dot= Vx
y0dot= 0.762;   % y0dot: initial relative velocity in y-axis (ms-1), y0dot= Vy
z0dot= 0.762;    % z0dot: initial relative velocity in z-axis (ms-1), z0dot= Vz

X0= [x0, y0, z0, x0dot, y0dot, z0dot, m0];
 % A safety factor of 0.20 will be used, instead of all the time required to empty the propellant tanks.
%Thus, it is assumed that the thruster has the capability of being activated for almost the 1/5 of the total
%time required to empty the propellant tanks. That time has been calculated to be 183 (s), but instead,
%the value of 180 (s) will be used (3 minutes).
```

```
Nt= 181;

t_span= linspace(0,180,Nt);

options= odeset('RelTol',1.e-10,'AbsTol',1.e-10);

[t,X]= ode45(@(t,X) Fsyst(t,X,omega,omega2,m0,m0dot,Thr),t_span,X0,options);

%------------------------------------------------------------------------------------------------------------------------
% 2nd Approach: Analytical solution verification

for i = 1:Nt

    x0= 30;             % x0: initial relative position in x-axis (m)
    y0= 30;             % y0: initial relative position in y-axis (m)
    z0= 30;             % z0: initial relative position in z-axis (m)

    x0dot= 0.762;    % x0dot: initial relative velocity in x-axis (ms-1), x0dot= Vx
    y0dot= 0.762;    % y0dot: initial relative velocity in y-axis (ms-1), y0dot= Vy
    z0dot= 0.762;    % z0dot: initial relative velocity in z-axis (ms-1), z0dot= Vz

    % Clohessy-Wiltshire (CW) Equations
    x_cw(i)= (-2*z0dot*cos(omega*i)+(4*x0dot-6*omega*z0)*sin(omega*i)-(3*x0dot-
6*omega*z0)*omega*i+(2*z0dot+omega*x0))/omega;

    y_cw(i)= (omega*y0*cos(omega*i)+y0dot*sin(omega*i))/omega;

    z_cw(i)= ((2*x0dot-3*omega*z0)*cos(omega*i)+z0dot*sin(omega*i)-(2*x0dot-
4*omega*z0))/omega;

end

%------------------------------------------------------------------------------------------------------------------------
% 4.2.3. Results and diagrams


% 3D Plot extraction

% 1) Numerical solution curve
figure(1);
plot3(X(:,1),X(:,2),X(:,3));
title ('Numerical solution of the Clohessy-Wiltshire (CW) equations')
```

```
xlabel('x-coordinate of the orbit (m)')
ylabel('y-coordinate of the orbit (m)')
zlabel('z-coordinate of the orbit (m)')
hold on;

% 2) Analytical solution curve
figure(2);
plot3(x_cw(:), y_cw(:), z_cw(:),'x')
title('Analytical solution of the Clohessy-Wiltshire (CW) equations')
xlabel('x-coordinate of the orbit (m)')
ylabel('y-coordinate of the orbit (m)')
zlabel('z-coordinate of the orbit (m)')

%-------------------------------------------------------------------------------------------------------------------
%% END OF PROGRAMME
```

Appendix B.2.

The function presented below ("*Fsyst.m*") was utilized for calculation numerical resolution of the Clohessy-Wiltshire (CW) equations, either with or without taking into account the activation of the nitrogen-jet thrusters of the SAFER propulsion unit.

```
function Z = Fsyst(t,X,omega,omega2,m0,m0dot,Thr)

Z= zeros(7,1);

m= m0-m0dot*t;    %Mass of the system at any examined moment

% Position:  X(1)= x, X(2)= y, X(3)=z
% Velocity: X(4)= xdot, X(5)=ydot, X(6)=zdot

%-------------------------------------------------------------------------------------------------------------------
% Correction u1:
% Proportional to the position vector r= (X(1),X(2),X(3)) of the astronaut with respect to the spacecraft,
% which is the origin of coordinates, with a negative sign.

u1(1:3)= -X(1:3);

% Correction u2:
% Proportional to the relative velocity vector v=(X(4),X(5),X(6)) with respect to the spacecraft, with a
%negative sign.

u2(1:3)= -X(4:6);

% Trial and error
eps_1= 0.1;      % Coefficient k1
eps_2= 2.;       % Coefficient k2

u= (eps_1*u1+eps_2*u2);

if norm(u)>1

   u= u/norm(u);

end

%-------------------------------------------------------------------------------------------------------------------
```

```
% Velocity terms

Z(1)= X(4); % relative velocity in x-axis (ms-1)
Z(2)= X(5); % relative velocity in y-axis (ms-1)
Z(3)= X(6); % relative velocity in z-axis (ms-1)

% Acceleration terms

Z(4)= 2*omega*X(6)+u(1)*Thr/m;                     % acceleration in x-axis (ms-2)
Z(5)= -omega2*X(2)+u(2)*Thr/m;                     % acceleration in y-axis (ms-2)
Z(6)= 3*omega2*X(3)-2*omega*X(4)+u(3)*Thr/m;       % acceleration in z-axis (ms-2)
Z(7)= m;

end
```