GUIDANCE METHOD FOR VENUS AEROCAPTURE MISSION WITH ATMOSPHERIC MODELING ERROR AND NAVIGATION ERROR

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ABSTRACT

Guidance methods for the atmospheric flight part of a Venus aerocapture mission are studied. A lifting entry vehicle is to be used, and in-plane atmospheric path is to be controlled through the bank angle modulation while out-of-plane motion is left open. Three control laws for bank angle, 1) Shuttle-like law with altitude rate h and drag deceleration D feed-back, 2) a simple system with only D feed-back, 3) an explicit law which finds required lift-to-drag ratio from precalculated relationship as a function of D and velocity V, are considered. Numerical simulations are carried out in the presence of atmospheric modeling error and pre-encounter guidance error, and each law is evaluated in terms of final orbit apoapsis altitude dispersion or total drag deceleration dispersion.

1. Introduction

In the future planetary missions, the use of aerocapture technique at the target planet with atmosphere would dramatically enhance the payload injection capability. Among many problems to be solved to realize this, lack of the precise knowledge about the planetary atmosphere may lead to a large final orbit dispersion or even to mission failure (non-capture at all). This study investigates the validity of several control laws for Venus aerocapture mission in the presence of atmospheric modeling error as well as pre-encounter navigation error. Lifting entry vehicle (say bi-conic type) is to be used, and in-plane atmospheric path is to be controlled through the bank angle modulation while out-of-plane motion is left open. Three control laws for bank angle are considered. Numerical simulations are carried out, and each law is evaluated in terms of final orbit apoapsis altitude dispersion or total drag deceleration dispersion.

2. Atmospheric Model and Modeling Errors

One of the major error sources for the aerocapture guidance is that of modeling the planetary atmosphere. Factors to be considered
for construction of a theoretical model are so various that it would not be realistic to rely on such a model. For engineering purpose, in this study, simple exponential law is employed with constant scale-height. And nominal density distribution and its variation, in terms of the scale-height and the density at a specified altitude (80km), are assumed based on the measurements by Pioneer-Venus.

Venus is covered with thick cloud and there is little fluctuation of the atmospheric density below the cloud. From the data of four probes of Pioneer-Venus, mean, minimum, and maximum density at 80km altitude are as follows:

- mean: 0.0119 kg/m$^3$
- minimum: 0.0082 kg/m$^3$
- maximum: 0.0132 kg/m$^3$

The variation of density at 80km is taken to be +/- 30%. Above the cloud, where the solar radiation is much more intense and the amplitude of planetary wave is large, this is not the case. As is shown in Fig.1, the fluctuation of temperature is between -40K and +40K, and is converted into that of scale-height as between -33% and +33%. The scale-height variation is taken to be +/- 40% with the nominal value of 10km.

3. Control Laws

In order to realize the aerocapture at a distant planet, effective control laws that can alleviate flight-path deviation due to various error sources must be devised. In this section, three control laws are discussed.

The vehicle called "bi-conic", which is capable of hypersonic L/D of 1.0-1.5, is considered, and control laws are those for bank angle. The ballistic coefficient and lift-to-drag ratio (L/D)$_c$ are supposed to be constant, and only in-plane motion is considered since it is of primary importance for capture. Hereafter L/D is defined as the in-plane component of lift-to-drag ratio and can be varied through the bank angle modulation between -(L/D)$_c$ and +(L/D)$_c$.

3.1 Error sources

Error sources to be considered here as dominant are as follows:

1) atmospheric modeling error
2) navigation errors in flight-path angle at atmospheric entry

The atmospheric modeling errors are dealt with as density error at 80km altitude and scale-height error as was mentioned before. The error of ballistic coefficient is absorbed to the density error since they always appear in a combined way.

The error of lift-to-drag ratio is not considered since it can be compensated by bank command, if an acceleration normal to velocity is measured. The errors of flight-path angle at atmospheric entry can be dealt with as that of B-plane position (Fig.2).
3.2 Shuttle-like control law (Law-S)

Resemblance between the aerocapture vehicle and Space Shuttle that they make unpowered lifting flight through the atmosphere makes it natural to apply the Shuttle law to the capture case.

Shuttle-like control law is an implicit one, which makes a vehicle to fly along a nominal trajectory. However, its applicability to the aerocapture mission should be carefully investigated when uncertainty of atmospheric density is large.

In the Shuttle-like control law, required \( L/D \) is obtained through the feedback of deviations of drag deceleration \( D \) and altitude rate \( \dot{h} \) from nominal as is given by Eq. (1). And, in this form, velocity \( V \) is taken to be the independent variable.

\[
\delta (L/D) = f_1 \delta D + f_2 \delta \dot{h}
\]

\[
f_1 = \frac{hs}{D_0^2}(\omega^2 - B) - \frac{hs}{D_0^2}(2\zeta \omega - A)(\frac{\dot{h}_0}{hs} + \frac{4D_0}{V_0})
\]

\[
f_2 = -\frac{2\zeta \omega - A}{D_0}
\]

\[
A = \frac{3D_0}{V_0} - \frac{2D_0}{D_0}
\]

\[
B = \frac{3D_0^2}{D_0^2} - \frac{3D_0}{V_0} + \frac{4D_0^2}{V_0^2} - \frac{1}{hs} \frac{V_0^2}{r} - g - \frac{2D_0}{D_0}
\]

The \( hs \) and \( r \) denote nominal scale height and planetocentric distance respectively. \( \omega \) indicates nominal conditions, and \( \delta (L/D) \) is equal to \( L/D \) when \( (L/D)_{0} \) is taken to be zero. Then feedback gains \( f_1 \) and \( f_2 \) are given as a function of velocity. Angular frequency \( \omega \) and damping ratio \( \zeta \) come from drag deceleration equation linearized about the nominal trajectory so that it takes the form,

\[
\delta \ddot{D} + 2\zeta \omega \delta D + \omega^2 \delta D = 0
\]

When \( L/D \) calculated by Eq. (1) exceeds the limit, \( +/- (L/D) \) will be employed. The estimation of \( V \) and \( \dot{h} \) during the atmospheric cruise is made by INS. A gravity model must be used along with measurements of lift and drag acceleration.

The larger the angular frequency is, the earlier errors converge. But if the value is too large, control capability get insufficient, that is, too large angular frequency induces a chattering in case of small drag deceleration. Therefore consulting with Ref.5, angular frequency is set up as,
\[
\frac{1}{\omega} = \begin{cases} 
2.0 \text{ sec} & (D < 3 \text{ m/s}^2) \\
9 & (D > 9 \text{ m/s}^2) \\
20 - \frac{11}{6} (D - 3) & (3 \text{ m/s}^2 < D < 9 \text{ m/s}^2)
\end{cases}
\] (4)

The damping ratio is recommended to be between 0.7 and 0.9. In this study the damping ratio is taken to be 0.88.

3.3 Control laws in simpler systems

In the last section, control law used in Space Shuttle was applied. But if only drag deceleration and its integration (pseudo velocity) are used without referring to flight-path angle, which is necessary to obtain \( \dot{h} \) substituted for \( \dot{D} \) to avoid numerical differentiation, simpler systems will result. Two such systems, one implicit, the other explicit, will be discussed in the following.

3.3.1 Implicit guidance with drag deceleration feedback (Law-D)

Substituting the pseudo velocity for the real velocity and deleting the feedback term of altitude rate, the following control law is obtained.

\[
\begin{align*}
L/D &= f_{i'}^1 \dot{\delta} D \\
f_{i'}^1 &= \frac{hs}{D_0^2} (\omega^2 - B)
\end{align*}
\] (5) (6)

Since this law does not necessarily guarantee the positiveness of \( \delta \) due to the lack of \( \delta h \) term, trajectory will oscillate. But it may still effect the capture. The angular frequency must be selected carefully, since small value causes flight-path divergence by making \( f_{i'}^1 \) in Eq.(6) negative while large value leads to a chattering between -(L/D)c and +(L/D)c which is difficult to execute. Here the value from Eq.(4) is used.

3.3.2 Explicit guidance using L/D table (Law-T)

The final objective of control in the atmospheric cruise is to make velocity at atmospheric exit or apoapsis altitude coincide with the nominal value. Implicit guidance makes this by trying to fly along a nominal trajectory, while explicit guidance makes it more directly. When only drag deceleration is measured, the final conditions can not be fully estimated. But with a table prepared by off-line calculation, the final conditions could be estimated.

The idea is based on a fact that for every B-plane entry position there exist a constant L/D trajectory and corresponding drag deceleration-pseudo velocity relationship, which achieves the nominal exit velocity. Looking up the table derived from the curves shown in Fig.3, at any moment during the atmospheric cruise an equivalent B-plane position and a L/D value to be used thereafter are obtained. Thus, the B-plane position error could be recovered by consulting with the table only once during the atmospheric cruise to find the L/D value to be maintained thereafter. This is not the case if there
exists atmospheric modeling error, but more frequent or continuous reference to the table and subsequent L/D switches may still make this method applicable under such a situation. The lower or upper bound value should be employed for L/D if the trajectory goes out of the table coverage.

Fig. 3 L/D Table for Law-T  
Fig. 4 Flight Profile of Nominal Trajectory

4. Numerical Results

The nominal target apoapsis altitude is taken to be 10,000 km, with corresponding total drag deceleration of 2.442 km/s. The nominal flight profile is given in Fig. 4. B-plane position is 15,977 km from the center, and the entry velocity defined at altitude of 300 km is 11 km/s. In this study nominal trajectory is defined as a trajectory such that the accomplished apoapsis altitude after leaving the atmosphere flying with L/D=0 becomes the nominal one, under the premise that this trajectory would provide maximum in-plane maneuverability. The following vehicle parameters were used as typical ones.

- Ballistic coefficient : 0.002 m²/kg
- Lift-to-drag ratio (L/D) : 1.0

Effects of the ballistic coefficient change would be compensated by shifting the nominal B-plane position while change in (L/D) would enhance or reduce the control capability.

4.1 Entry corridor for ballistic vehicles

Configuration of aerocapture vehicles can be classified according to their control capability. For comparison, capability of two types of non-lifting vehicles were analyzed. First is the vehicle which has no control capability. Second is the vehicle which can modulate the drag deceleration.

The entry corridors of the first and second vehicles are shown in Fig. 5. Ballistic coefficient of the second vehicle is assumed to
be variable from $1/\sqrt{2}$ to $\sqrt{2}$ times of nominal value. And the corridor was obtained simply by fixing the coefficient at the lower or upper most value since it would give the widest corridor in case of the drag modulation. From these figures it follows that,

1) Entry corridor is very narrow,
2) With drag modulation, entry corridor can not be widened appreciably,
3) The effect of the density error at 80km altitude is much smaller than that of scale-height error for the assumed range of variations, and that lifting capability is indispensable for successful capture. And, hereafter, only errors in B-plane position and scale-height are considered.

![Fig.5 Entry Corridors of Non-lifting Vehicles](image)

### 4.2 Guidance accuracy achieved by three control laws

Figs.6-(a),(b),(c) show apoapsis altitude, total drag deceleration error, and experienced maximum G achieved by Law-S on the scale height error/B-plane position error plane. Obviously this law can manage wide range of modeling and guidance errors and gives quite satisfactory results. Scale height error introduces apoapsis bias regardless of B-plane position error. Also, it can be seen that, by aiming at a lower B-plane position as nominal with corresponding nominal L/D program, permissible error region could be enlarged but with a larger maximum G.

Figs.7-(a),(b),(c) are the results by Law-T, showing similar trends as those by Law-S. Apoapsis dispersion is comparatively large but still acceptable, though larger maximum G may restrict the permissible error region.

For comparison, results by Law-T for the nominal apoapsis of 1,000 km are shown in Figs.8-(a),(b),(c). Somewhat anomalous behaviour of the apoapsis altitude, compared with those of total drag deceleration error, are due to the effect of the exit flight path angle that is not controlled in this law. No such anomaly was noticed for the corresponding Law-S case.

Fig.9 shows the apoapsis altitude variation brought about by Law-D. This result is similar to that by bang-bang type control with (L/D) when $D > D_0$ and $-(L/D)$ when $D < D_0$. Different from the other cases, strong dependence on B-plane position error is noticed. Probably it comes from the lack of capability to recover the B-plane position error due to the deletion of the $\dot{h}$ term.
Fig. 6-(a) Apoapsis Altitude by Law-S
(Nominal Apoapsis Altitude: 10,000 km)

Fig. 6-(b) Total Drag Deceleration Error by Law-S
(Nominal Apoapsis Altitude: 10,000 km)

Fig. 6-(c) Experienced Maximum G by Law-S
(Nominal Apoapsis Altitude: 10,000 km)
Fig. 7-(a) Apoapsis Altitude by Law-T
(Nominal Apoapsis Altitude: 10,000 km)

Fig. 7-(b) Total Drag Deceleration Error by Law-T
(Nominal Apoapsis Altitude: 10,000 km)

Fig. 7-(c) Experienced Maximum G by Law-T
(Nominal Apoapsis Altitude: 10,000 km)
Fig.8-(a) Apoapsis Altitude by Law-T
(Nominal Apoapsis Altitude: 1,000 km)

Fig.8-(b) Total Drag Deceleration Error by Law-T
(Nominal Apoapsis Altitude: 1,000 km)

Fig.8-(c) Experienced Maximum G by Law-T
(Nominal Apoapsis Altitude: 1,000 km)
5. Conclusion

Guidance method for the atmospheric flight part of Venus aerocapture mission was studied. Three control laws were tested by numerical simulations in the presence of the atmospheric modeling error and B-plane position error. Shuttle-like control law showed fine capability. The explicit law using L/D table showed acceptable capability even though it only requires on-board measurement of the drag deceleration.

The control capabilities were evaluated in terms of the apoapsis altitude dispersion. Though other error sources and aerodynamic heating aspects must be considered in the actual mission design, these results give an insight into the requirement on the control system for the Venus aerocapture mission.

References