

ROTARY-WING DECELERATORS FOR PROBE DESCENT THROUGH THE ATMOSPHERE OF VENUS

Larry A. Young⁽¹⁾, Geoffrey Briggs⁽²⁾, Edwin Aiken⁽³⁾, Greg Pisanich⁽⁴⁾

⁽¹⁾Army/NASA Rotorcraft Division, MS 243-12, NASA Ames Research Center, Moffett Field, CA, USA 94035, larry.a.young@nasa.gov

⁽²⁾Center for Mars Exploration, MS 239-20, NASA Ames Research Center, Moffett Field, CA, USA 94035, gbriggs@mail.arc.nasa.gov

⁽³⁾Army/NASA Rotorcraft Division, MS 243-10, NASA Ames Research Center, Moffett Field, CA, USA 94035, eaiken@mail.arc.nasa.gov

⁽⁴⁾QSS Group, Computational Sciences Division, MS 269-3, NASA Ames Research Center, Moffett Field, CA, USA 94035, gp@ptolemy.arc.nasa.gov

SUMMARY

An innovative concept is proposed for atmospheric entry probe deceleration, wherein one or more deployed rotors (in autorotation or wind-turbine flow states) on the aft end of the probe effect controlled descent. This concept is particularly oriented toward probes intended to land safely on the surface of Venus. Initial work on design trade studies is discussed.

1. INTRODUCTION

A NASA-sponsored NRC “Decadal Study” was recently completed [1] wherein solar system exploration priorities were assessed by a broad survey of planetary science requirements. One of the outcomes of this study was the high priority assigned to a probe/lander mission to the surface of Venus to gain an improved understanding (above that attained by the USSR Venera lander missions in the 1980s and the more recent Magellan radar orbiter) of the history of the planet through measurements of the elemental and mineralogical composition of the surface and of surface-atmospheric interactions. Given the young age of most of Venus’ surface, special interest focussed on gaining access to the oldest terrains, namely, the highland *tessera*.

In response to the Decadal Study, NASA is initiating the P.I.-led *New Frontiers* Program and at least one Venus atmospheric probe/lander mission is under study in a collaboration between academia, industry and NASA-JPL and NASA-ARC. This mission would ideally build upon the science, and to some degree the technology derived, from the Soviet missions in the 1960’s (the Pioneer Venus probes were not designed for landing). The Venera technology -- using bluff-body (flat-plate) decelerators -- provides passive control of the probe descent rate with altitude and thus allows for neither surface hazard avoidance nor precision landing capability (Fig. 1). The Venera technique – and ideally other passive aerodynamic decelerators – are acceptable for lowland sites. The Magellan radar images of the highland tessera indicate that such passive technology will make landing on the tessera very risky because of terrain roughness and steep slopes.



Fig. 1. Venera Flat-Plate Decelerator

To be presented at the 2nd International Planetary Probe Workshop, NASA Ames Research Center, Moffett Field, CA, August 23 - 27, 2004.

Future Venus lander missions call for an active controlled-descent decelerator. In many respects such

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE AUG 2004		2. REPORT TYPE		3. DATES COVERED 00-00-2004 to 00-00-2004	
4. TITLE AND SUBTITLE Rotary-Wing Decelerators for Probe Descent Through the Atmosphere of Venus				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research, Development and Engineering Command, Army/NASA Rotorcraft Division, Ames Research Center, Moffett Field, CA, 94035				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

control is easier for Venus than for Mars because Venus has a thick atmosphere with a surface pressure of about 90 bars (comparable to pressures a kilometer beneath the surface of our oceans). Such a dense atmosphere makes the use of active aerodynamic decelerators a potentially ideal solution for the descent over highland *tessera*. (The high surface temperatures of Venus do represent a challenge for mission lifetime and for mechanical device actuation and need to be accounted for in the later stages of the design process.)

One active aerodynamic controlled-descent concept is the rotary-wing (RW) decelerator (Fig. 2), wherein the autorotating rotors can precisely control both the rate and angle of descent so that hazards can be detected (by optical imaging and laser altimetry) and avoided and so that touchdown can be gentle. These probe autorotating rotors are capable of being slowed down by braking action as well as potentially being able to perform a collective pitch-angle step input for the final soft-flare landing maneuver.

2. CONCEPT DESCRIPTION AND PAST WORK

In general, use of active aerodynamic control to perform enhanced planetary probe entry and descent is a very desirable characteristic. In particular, use of active aerodynamic control is an essential entry probe attribute to avoid surface hazards during the final stages of landing in unknown and uncertain territory, when there is a high probability of encountering extremely rough terrain. The problem is further compounded with probe thermal management issues for Venus, i.e., it is necessary to provide for high descent speeds through regions of lower-priority interest -- to minimize overall descent time and corresponding heat build-up in the probe's interior -- and to provide for low-speed descent, a soft landing, and more time on the surface and in the lower atmospheric regions of high interest. Rotary-wing decelerators potentially promise a satisfactory solution to these problems.

Fig. 2 is an illustration of one approach to implementing a three-rotor RW-decelerator for a Venus probe. Fig. 2 also sequentially depicts (left to right, top to bottom) the release of the probe from the aeroshell, the deployment and full extension of the rotor booms and rotors, and the deployment of landing gear.

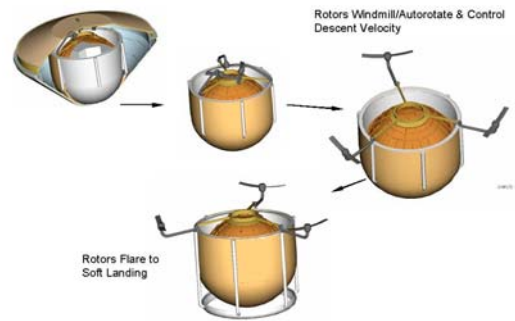


Fig. 2. Rotary-Wing Decelerator for Venus Probe

3. NOTIONAL MISSION & MAXIMIZING SCIENCE RETURN

Researchers [2-9] have previously examined rotor entry decelerators for space mission applications. But none of this past work specifically examined the feasibility of applying this technology to Venus missions. This work does, however, build upon earlier planetary aerial vehicle work by the Army/NASA Rotorcraft Division and the Center for Mars Exploration [10]. The thick surface atmosphere of Venus allows for the usage of very small rotors for deceleration. On the basis of pure aerodynamic deceleration potential, RW-decelerators can at best only match a flat-plate, or bluff body, decelerator – the real advantage of the concept is in the ability to effect a controlled descent (both rate and trajectory angle), soft flare landings, and possibly electrical power generation during descent. Note that the folding support arms shown in the conceptual sketch of Fig. 2 are perhaps an unnecessary design feature; with typical aeroshell shapes, and the compact rotor sizes of a RW-decelerator, rigid (always deployed) support arms are likely feasible instead.

4. GENERAL TECHNICAL APPROACH

The overall objective of the work is to establish the feasibility of RW-decelerators in terms of performance and cost in comparison to proven Venera-class decelerator technology in the context of providing Venus probes with hazard avoidance and safe landing capability on the ancient Venus highlands.

The problem being pursued is envisioned to have three components:

- First, engineering analysis to refine the RW-decelerator conceptual design and to identify key technologies that need to be matured/developed.
- Second, proof-of-concept prototyping of small-scale underwater “test articles” employing a multi-rotor RW-decelerator (as a terrestrial surrogate for a Venus atmosphere probe) to demonstrate trim-control laws.
- Third, feasibility demonstrations with a larger underwater surrogate probe (release/submergence of the prototype in a large body of water) of various active controlled-descent, hazard avoidance, and precision “landing” strategies (i.e. implementation of information and control system technologies).

This paper focuses on the preliminary engineering design analysis.

5. DESIGN SPACE AND SIZING ANALYSIS

A subset of the design space for the engineering trade studies for the Venus probe RW-decelerator concept is shown in Table 1. All RW-decelerators incorporating one or more rotors are capable of descent rate control. Only decelerator systems with three or more rotors are capable of descent angle/trajectory trim control. All RW-decelerators must incorporate rotor collective pitch-angle step input control to be able to perform a soft flare landing (decelerating to net zero vertical velocity). If some form of rotor collective pitch-angle control is not provided for then some moderate level of landing-gear impact (nonzero vertical velocity) upon surface contact will occur.

Table 1. Design Space

# Rotors	Descent Rate Control	Descent Trajectory Control	Soft Flare Landing	Pitch Control
1	X		X	X
2	X		X	X
3	X	X	X	X
4	X	X	X	X

Employing first-order quasi-steady analysis, Fig. 3 illustrates the first-order influence of rotor size (and number) on probe descent speed, as a function of altitude. For example, a simple estimate of rotor size for

a Venus RW-decelerator, for a near-surface design descent speed of 8.5 m/sec for a 200kg probe (without aeroshell), is 0.42 meters diameter for an individual rotor in a three-rotor decelerator system operating in ideal autorotation (pre-touchdown rotor “flare”). The probe pressure-vessel diameter is assumed to be approximately 0.7 meters. Note, that for the single-rotor case, rotor blade-root cutout is assumed to be equal to the probe pressure vessel diameter, i.e., $r_c=D$; for all other cases, it is assumed that $r_c=0$.

As noted earlier, Fig. 3 rotor size estimates were based upon a simple analysis; the details of the analysis are as follows. From [11], for ideal autorotation, the descent speed, V , is given by the approximate expression

$$V \approx bv_h \quad (1)$$

Where the constant $b \approx 1.71$.

Correspondingly, the ideal hover induced velocity is given by the expression

$$v_h = \sqrt{\frac{T}{2\rho A}} \quad (2)$$

Where T is the required rotor thrust, A is the rotor disk area ($A = \pi(R^2 - r_c^2)$), and ρ is the atmospheric density at the prescribed probe altitude.

Now, given Eqs. 1 and 2, the rotor size (in terms of R , the rotor radius) can be given in terms of the required (ideal) autorotation descent velocity, V .

$$R = \sqrt{\left(\frac{b^2}{2\pi}\right)\left(\frac{T}{\rho V^2}\right) + r_c^2} \quad (3)$$

Where, again, r_c is the blade-root cut-out for the rotor(s)

Each rotor will have to provide the following amount of Thrust, T , during descent, recognizing that the entry body in itself will have a drag coefficient of C_D and a frontal area of S .

$$T = \frac{1}{N} \left[(m - \Delta m_B)g - \left(\frac{1}{2}\rho V^2\right)C_D S \right] \quad (4)$$

$$\Delta m_B = 2\rho \left[\sqrt{\frac{S}{\pi}} \left(f - \frac{1}{2} \right) S + \frac{\pi}{3} \left(\sqrt{\frac{S}{\pi}} \right)^3 \right] \quad (5)$$

Note that Eq. 5 accounts for the buoyancy effects of the probe in the thick lower atmosphere of Venus, assuming the probe is a rounded-nose finite cylinder of fineness ratio, f . (Fineness ratio is the ratio of probe longitudinal axis length to the maximum radial axis dimension.) Buoyancy is a small, but nontrivial, contribution to the Venus probe descent speed profile; buoyancy, of course, is a substantial contributor for the proposed surrogate submersible probe testing.

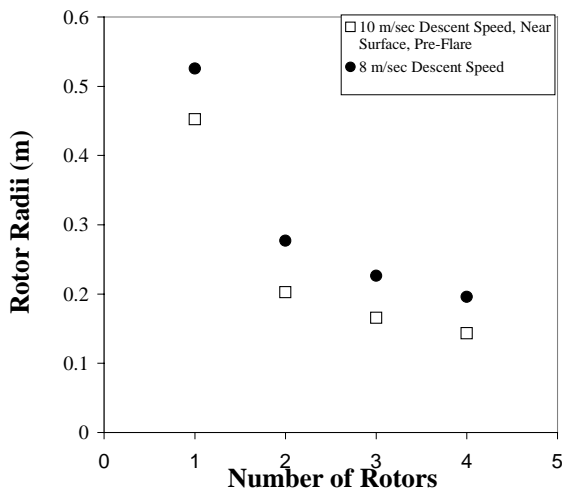


Fig. 3. Rotor Decelerator Size Relative to Autorotation Descent Speeds

Trim control (to vary descent-angle and trajectory) for a four-rotor RW-decelerator is fairly straightforward. Trim for a four-rotor-system simply entails differential rotor braking between the four rotors, note that opposing pairs of rotors spin in opposite directions. Fig. 4 illustrates the connection between the application of rotor differential braking torque and the subsequent (in sequence) reduced rotor thrust, probe bluff-body angular displacement, and the resulting bluff-body normal- and side-force generation. Symmetry considerations for the four-rotor decelerator system allow for yaw control to be effected in the same manner as the pitch control shown in Fig. 4, with an orthogonal pair of rotors. For the four-rotor decelerator system, pitch and yaw control are de-coupled from each other. Descent rate is influenced to a slight degree by pitch and yaw control braking-torque inputs, as they reduce the overall thrust by $2\Delta T$.

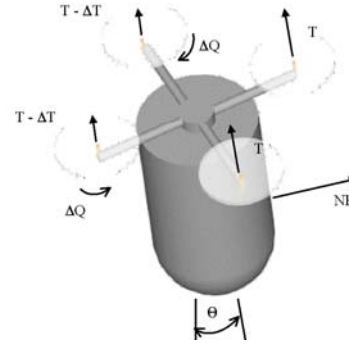


Fig. 4. Four-Rotor (Pitch) Trim Control

Trim control can still be implemented on a three-rotor decelerator system, but it entails a more complex approach. Overall, the three-, versus four-rotor, decelerator design has better volume/packaging characteristics while stowed in the entry aeroshell.

6. QUASI-STATIC DESCENT PROFILES

There are four phases of probe descent with rotary-wing decelerators: 1. release from the entry vehicle aeroshell and initial rotor spin-up and high-speed deceleration of probe, 2. transition phases where the rotor passes through the turbulent and vortex-ring states, 3. low-speed and low-altitude terminal descent, and 4. rotor flare and soft landing. The engineering analysis work to date focuses on the last two stages of probe descent. Future work will couple probe RW-decelerator control laws with a high-level closed-loop controller to validate the viability of hazard avoidance and precision landing using a variety of hypothetical sensors and terrain feature-recognition techniques as applied to Venus-representative simulated terrain.

Figure 5 shows the ideal autorotation descent speed profile with altitude, for the lower extremes of Venus's atmosphere, using a quasi-static aerodynamic analysis based in part on Eqs. 1-5; Venus atmospheric properties were taken from [14]. Figure 5 also illustrates how higher descent speeds result from RW-decelerator configurations having higher disk loading (ratio of rotor thrust to rotor disk area, T/A , N/m^3). This holds true for conventional helicopters as much as it does for the Venus probe rotary-wing decelerators. Therefore, a careful design balance must be maintained between the compactness of the rotary-wing decelerator package -- with correspondingly higher disk loading -- and achieving low probe descent speeds. Also shown in

Fig. 5 is the estimated terminal velocity profile for the probe body without the RW-decelerators or, alternatively, with the decelerators providing no effective braking action. This can be considered as being the maximum descent speed of probe through Venus' lower atmosphere.

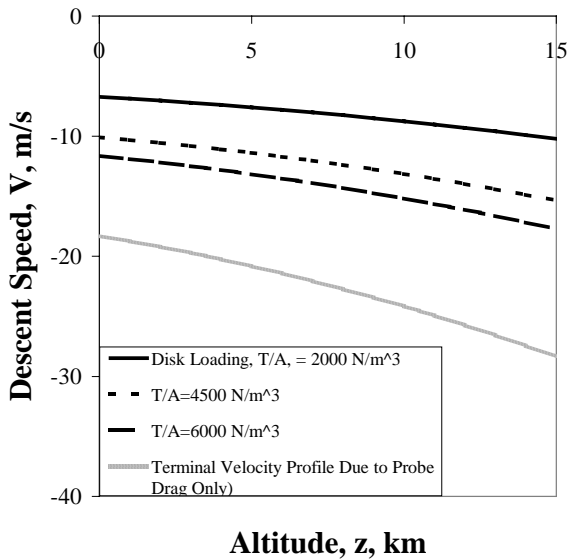
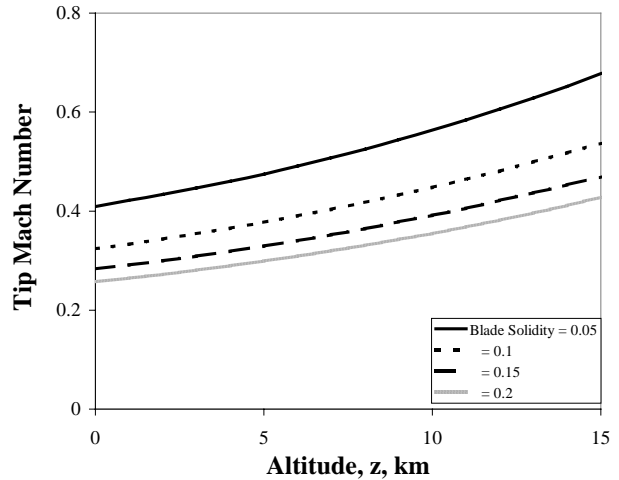
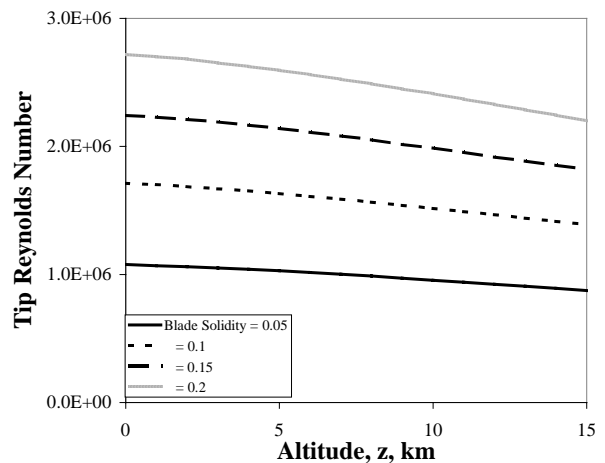


Fig. 5. Probe Descent Speed as a Function of Altitude (Ideal Autorotation)

Figures 6a-b are representative plots of rotor operating conditions, in terms of tip Mach and Reynolds numbers, during descent through the lower extremes of Venus' atmosphere. Note that blade solidity is the ratio of total blade planform area to rotor disk area. As can be readily seen in Fig. 6a, the lower the blade solidity the higher the tip speed required to provide for adequate lift for probe autorotation. Correspondingly, the higher the blade solidity – and therefore the mean effective blade airfoil chord length – the higher the tip Reynolds number. In both cases, though, the RW-decelerator tip Mach and Reynolds numbers fall within the range of engineering experience for conventional/terrestrial rotary-wing aerodynamics.



(a)



(b)

Fig. 6. Rotor Operating Conditions During Descent: (a) Tip Mach and (b) Tip Reynolds Numbers as a Function of Altitude (and Blade Solidity)

7. FUTURE SURROGATE PROBE TESTING

The use of underwater submersibles to demonstrate and evaluate teleoperation and robotic technologies for NASA planetary science missions is not a new technical approach. Previous work has been conducted, such as the Ames TROV project [12].

Though Venus's lower atmosphere has pressure levels comparable to the ocean depths on Earth, the analogy between the two is only of limited aerodynamic value. However, on the other hand, there is considerable value in the possible test and evaluation of surrogate

underwater probes for the proof-of-concept testing of descent trim-control laws and terminal stage guidance and navigation and autonomy technologies.

The majority of demonstrations will entail use of small-scale probes that will be released in an artificial pool/tank of water. The test and evaluation team will place artificial hazards (orange markers) at the bottom of the pool (Fig 7). Control of the probe hazard avoidance and precision landing guidance will be provided by using simple optical imagers, existing vision-system software, a pool-side lap-top computer, and radio-frequency (RF) or ultrasound I/O for telemetry and control inputs. The proposed simple vision-system initially to be used in the demonstrations has been previously used for other, similar vehicle guidance projects [12-13]. Additionally, other sensors and systems will be based in part on experience gained in the development of small robotic underwater vehicles. In the final demonstrations the probe will be of larger size and capability and there will be increased realism of terrain hazards at the bottom of the natural body of water (a lake such as Tahoe or Mono) where the underwater landscape can be conveniently evaluated prior to field trials.

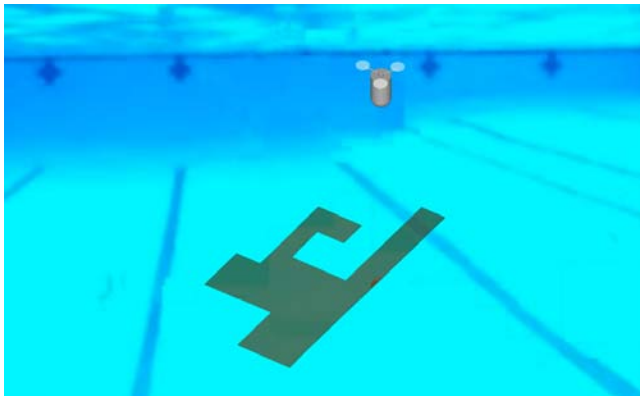


Fig. 7. Small-scale Surrogate Probe Testing

8. CONCLUDING REMARKS

Preliminary work related to the use of rotary-wing decelerators for application to Venus entry-probes/landers has been found to be very promising. A considerable amount of work remains to be performed – including work in the areas of control law development, hazard avoidance strategies, and surrogate probe testing.

10. ACKNOWLEDGMENTS

The contribution of Jim Kennon, Projects Division, to this work is gratefully acknowledged.

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