FINAL REPORT

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TRAJECTORIES OPTIMIZATION IN HYPERSONIC FLIGHT

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Principal Investigator

Nguyen X. Vinh

Professor of Aerospace Engineering
The University of Michigan
Ann Arbor, Michigan 48109

TIME PERIOD

This research was supported by NASA research grant NSG 1448 for the period from September 1, 1977 to August 31, 1979. A time extension was granted from September 1, 1979 to February 29, 1980.

The NASA technical officer for this grant is Mr. Robert S. Dunning, 152A-Theoretical Mechanics Branch, FDCD, NASA Langley Research Center, Hampton, Virginia 23665.

Dr. Nguyen X. Vinh, Professor of Aerospace Engineering at the University of Michigan, is the principal investigator. In addition, Dr. Adolf Busemann and Dr. Robert D. Culp participated as consultants in analyzing the drag force on a satellite at very high altitude. Two Ph. D. candidates at the University of Michigan, Mr. James M. Longuski and Mr. Jeng Shing Chern have significantly contributed to this research.

CUMULATIVE RESULTS

The proposed subject for the investigation, "Trajectories Optimization in Hypersonic Flight," has been successfully investigated. This includes the derivation of the equations of motion for three-dimensional flight of a lifting vehicle, taking into consideration all the main effects of different forces acting on a vehicle at orbital speeds. One of the main achievements is the formulation of a set of dimensionless equations of motion valid for both the flight with lift modulation inside a planetary atmosphere and the Keplerian motion in the vacuum. The equations are independent of the physical characteristics of the vehicle. The only parameters involved are the maximum lift-to-drag ratio of the vehicle and a constant characterizing the atmosphere. Hence, the results obtained can be applied without modifications to any future reentry vehicle, regardless of its size, mass and shape.

During the period of investigation, the following technical papers and NASA contractor reports have been published:

1. N. X. Vinh, N. A. Bletsos, A. Busemann, and R. D. Culp, "Flight with Lift Modulation Inside a Planetary Atmosphere," AIAA Journal, Vol. 15, No. 11, pp. 1617-1623, 1977.

2. N. X. Vinh, J. M. Longuski, A. Busemann, and R. D. Culp, "Analytic Theory of Orbit Contraction Due to Atmospheric Drag," Acta Astronautica, Vol. 6, pp. 697-723, 1979.

3. N. X. Vinh, "Optimal Singular Control with Applications to Trajectory Optimization," NASA CR-3087, March 1979.

4. N. X. Vinh and J. S. Chern, "Three-Dimensional Optimum Maneuvers of a Hypervelocity Vehicle," IAF paper No. 79-184; presented at the 30th Congress of the International Astronautical Federation, Munich, September 1979.

5. J. S. Chern and N. X. Vinh, "Optimum Reentry Trajectories of a Lifting Vehicle," NASA CR-3236, February 1980.

In addition, two doctoral theses have been written under this grant:

1. Jeng-Shing Chern, "Optimal Reentry Trajectories of a Lifting Vehicle," 1979.

2. James M. Longuski, "Analytic Theory of Orbit Contraction and Ballistic Entry into Planetary Atmospheres," 1979.

Dr. Longuski's thesis is now being prepared for publication as a technical report by the Jet Propulsion Laboratory, Pasadena, California.

The publication of the results in national and international technical journals and also as NASA contractor report reflects the success of this investigation. Graduate students who have been associated with this research, all have received employment offers from both the Government and the Industry because of their research experience. Dr. Longuski has also received an offer for an academic position.

FUTURE PUBLICATIONS

During these 2-1/2 years of investigation two innovative approaches for analyzing optimal trajectories in atmospheric flight have been developed. The first one consists of finding the best coordinate system for the analysis. The second one is the use of geometrical consideration; namely, the domain of maneuverability, for the investigation of the optimal control. Both methods have great potential since not only they lead to a wealth of analytical results as displayed in the above mentioned publications, but also they have provided significant results for the near completion of the following papers:

1. "Shallow Ballistic Entry."

2. "Canonical Transformations and Optimal Trajectories in Atmospheric Flight."

The analytical solution of the first problem is difficult because of the smallness of the initial entry angle. Solution by series expansion using the classical approach has small radius of convergence and hence of limited applications. So far, there exist no published results of this problem in the literature. The results we have obtained using perturbations theory are accurate and valid over the whole entry phase.

The second paper will be an illustration of the flexibility of our coordinate system. Using canonical transformation we are able to transform the general results obtained into pertinent results for any particular system, whether it is the system of orbital elements in hypersonic orbital flight or the Cartesian coordinate system for flight near the speed of sound at low altitude.

It is our intention to complete the investigation of these two problems. Upon their publications, past support of this NASA grant will be acknowledged.