gains is required because an even greater tendency to instability exists.

Another effect that influences the stability of the response of the system is the time lag between the output of the servomechanism and the resulting force applied to the vehicle. This lag results from the time required for tension and compression waves to travel down the suspension cable. This speed is equivalent to the speed of sound in the cable. If a braided steel cable is used, the speed of sound in the cable is about 1000 feet per second. For a cable 200 feet long, the lag is two-tenths of a second.

Despite the effort to make an accurate simulation of the trajectory and control characteristics of the lunar module in the lunar environment, one factor that cannot truly simulate conditions on the Moon is the gravitational force of the Earth acting on the pilot's body. The effect of this force can be minimized by strapping the pilot in and otherwise supporting his body so that this force does not interfere with his control activities.

Other factors that complicate the analysis of the servomechanism are the springiness of the cable, which changes with the altitude of the vehicle, the damping of the drive mechanism, and the change in weight with fuel usage. I considered as many of these factors as possible in an analytical study of the system. All these factors made the analysis difficult either with available theory or with the computers available at that date. I therefore considered an experimental study of the system necessary.

To test the feasibility of the contemplated system, a simplified system, called the pilot model, was built in which a pilot's chair was suspended by a vertical cable. A photograph of the pilot model in operation is shown in figure 5.1-1 with the engineering test pilot Jack Reeder at the controls. A servomechanism that reeled the cable in or out was mounted in the girders in the roof of the NACA Full Scale Tunnel, 60 feet above the vehicle. This facility was chosen because the wind tunnel had a compressed air supply that could be used to provide thrust for the rocket that was used to overcome the simulated lunar gravity of one-sixth of the vehicle weight. An available analog computer of fairly early design was used to calculate the signals driving the servomechanism. With this apparatus, the gains of the system were varied experimentally until a reasonably constant cable tension could be maintained as the pilot performed a simulated landing.

An important reason for using the overhead suspension is that if any loss of control occurs, either due to pilot error or some malfunction in the system, the vehicle can be locked in place or lowered slowly to the ground like an elevator.

The successful operation of the pilot model, despite some claims that it would not be feasible, gave me confidence to propose the design and construction of a full-scale system. I wrote a memorandum on the proposed system and made a trip with Lawrence K. Loftin to NASA Headquarters in Washington, DC. There we discussed the project with Ira H. Abbot, who at that time was an assistant director for space programs. He quickly agreed to support the project and to provide the necessary funds.

At the same time that my project was proposed, engineers at the Ames Research Center proposed a flight vehicle that worked on the same principle. This device, called the Lunar Landing Training Vehicle (LLTV), used a turbojet engine to support five-sixth of the vehicle weight. The engine was mounted on gimbals and controlled by servos connected to an inertial measurement unit so that it would always point vertically.
Lunar Landing Research Facility

FIGURE 5.1-1. Pilot model for LLRF being flown by NASA test pilot Jack Reeder.

The pilot's cockpit was mounted in a large frame that surrounded the jet engine and contained the necessary rocket engines to exert force to offset the simulated lunar gravity and to provide pitch, yaw, and roll control. I thought that this device would be very dangerous to fly because it had no means to recover in case of loss of control. Eventually, three of these vehicles were built. The cost of this project was undoubtedly many times that of the Lunar Landing Research Facility (LLRF), but the funding for the Apollo