DYNAMIC TESTING OF DOCKING SYSTEM HARDWARE

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ABSTRACT

Extensive dynamic testing has been conducted to verify the flight readiness of the Apollo docking hardware. Testing was performed on a unique six degree-of-freedom motion simulator controlled by a computer that calculated the associated spacecraft motions. The test system and the results obtained by subjecting flight-type docking hardware to actual impact loads and resultant spacecraft dynamics are described.

INTRODUCTION

During manned space operations in which two or more spacecraft rendezvous and dock for transfer of crew and cargo, the docking system hardware plays a critical role in achieving a successful mission. Because the docking system must perform flawlessly, its capability to perform reliably first must be verified in operational ground tests tailored to qualify the system for flight. In the Apollo Program, the dynamic ground testing was performed by means of a unique test system at the NASA Manned Spacecraft Center (MSC). Designated as the dynamic docking test system (DDTS), the system tests flight-type docking hardware on a six degree-of-freedom motion device combined with a computer that simulates the two docking spacecraft. This technique was employed in an extensive testing program to verify that the Apollo docking system design achieved the requirements of both Apollo and Skylab missions. The purpose of this paper is to describe the DDTS and the test results obtained with it.

APOLLO DOCKING SYSTEM PERFORMANCE REQUIREMENTS

Because a complete description of the Apollo docking system is provided in references 1 and 2, the description in this paper will be confined to the essential elements of the docking-hardware performance. To achieve the requirements of the Apollo lunar-landing mission, a unique mechanism was needed to accomplish linkup of the Apollo modules in space. This mechanism, called the Apollo docking system, consists of a conical drogue mounted on the lunar module (LM) and a probe and latches mounted on the command module (CM) (fig. 1).

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In an Apollo mission, a docking procedure involves the following sequence: The CM (active vehicle) approaches the LM (target vehicle). Contact is made; that is, the probe impacts the conical-drogue surface, slides to the apex, and latches (or captures) the drogue. The two modules are then alined, drawn together, and securely connected.

A lunar-landing mission requires two docking maneuvers: translunar docking (TLD) on the way from earth orbit to lunar orbit and lunar-orbit docking (LOD), which occurs when the LM ascent stage rejoins the orbiting CM after the lunar-surface excursion. These two dockings include diverse dynamic conditions. The TLD requires the docking hardware to absorb high energy and to carry large component loads as a result of docking two very heavy spacecraft. Conversely, light spacecraft are involved in LOD, which requires excellent capture performance.

For these two dockings, the docking hardware had to be tested considering several design requirements.

1. The hardware functions had to accommodate the following initial contact (IC) conditions: axial (closing) velocity V_X of 0.03 to 0.30 m/sec (0.1 to 1.0 ft/sec), radial (transverse) velocity V_L of 0 to 0.15 m/sec (0 to 0.5 ft/sec), angular velocity $\dot{\Theta}$ of 0 to 1.0 deg/sec, radial alinement (miss) of 0 to 0.30 m/sec (0 to 1.0 foot), any combination of pitch and yaw alinement of 0° to 10°, and a roll alinement of ±10° (fig. 4(a)).

2. The command service module (CSM) would be the active (closing) vehicle for TLD, and either the CSM or LM could be the active vehicle for LOD.

3. The hardware had to function over a temperature range of 366.48° to 219.26° K (200° to -65° F).

Subsequently, another set of requirements was developed for use in docking the Apollo CSM to the Skylab space station. Because these requirements were similar to those for the Apollo TLD, testing primarily was intended to assure that no redesign of the Apollo docking system was required for the Skylab missions.

A test program was established to verify the docking-hardware capabilities. The most difficult aspect of this test program involved the problem of validating the ability of the docking hardware to carry the dynamic impact loads, to capture, and to provide a stable alinement of the spacecraft. The unique test system used for these dynamic tests is described in the following sections.

DOCKING TEST SYSTEM DESCRIPTION

Concept

To perform dynamic docking tests, several alternate concepts were considered. One of the concepts incorporated pendulum-supported-mass-representative spacecraft and another concept involved an air-bearing-supported-mass-representative spacecraft. However, these arrangements had such inherent undesirable limitations as high frictional loads and only two translational degrees of freedom.

Accordingly, a new test technique was sought that would overcome the inherent limitations of using full-mass-representative spacecraft in the testing, even though such a technique involved an indeterminate degree of technical risk. The idea was to simulate the spacecraft mathematically in a computer, input a set of initial docking-impact conditions, program the equations describing the motions (three in translation and three in rotation) of each simulated spacecraft, and solve the equations in real time. These solutions could then be used to derive electronic command signals that would be used to control forces and motions of a set of actuators (one for each of the six degrees of freedom, three translational and three rotational). Although unique challenges were encountered during the implementation of the concept, the task was accomplished successfully. This concept is used in the dynamic docking test system, as described in the following paragraphs.

Basic Systems

The DDTS consists of two basic systems: a motion-generating device (fig. 2) and a large-scale hybrid computer (fig. 3). The docking hardware under test is installed in the motion device and is subjected to impact, force, and motion of a prescribed docking condition. The simulator has hydraulic actuators and bearings, along with mechanical pivots and guides, which provide the capability to move the test article in all six relative degrees of freedom. Furthermore, the device is designed to provide a motion envelope large enough to accommodate the Apollo docking hardware and the excursions resulting from the contact conditions as described previously. Within the computer, rigid-body mass properties and attitude control system characteristics for both vehicles are simulated mathematically. Compensation for electrohydraulic phase lags, coordinate system translation (coordinate references on the test device differ from spacecraft coordinate references), force-to-motion transformation, and gravity effects also are included in the computer.

In a test operation, the actuators are commanded to move the probe and drogue so that the required impact conditions (that is, translational and rotational alinements and velocities) exist at impact. As the docking-hardware components impact, the resulting loads are sensed by load cells and are transmitted instantly to the computer as input data to the equations of motion that produce the individual spacecraft dynamic responses. Operating as a real-time closed-loop system, this equipment generates the same impact loads and relative-motion dynamics that would occur between two actual full-sized spacecraft docking in a zero-g environment.

This simulation technique allows virtually any configuration of docking spacecraft to be evaluated with a given set of docking hardware. The vehicle mass properties and geometry, attitude control system characteristics, relative locations of the docking interfaces, and initial dynamic docking conditions all can be changed in minutes simply by inputting a new set of computer data cards. In addition, provisions have been incorporated to test the docking hardware over a wide range of temperatures (from 394.26° to 199.81° K (250° to -100° F)) so that thermal effects on the performance of the docking hardware can be evaluated.

Auxiliary Test Equipment

The complete facility includes two 30-channel data-acquisition systems and several subsystems (for example, hydraulic power pack, control console, closed-circuit television, intercom, and simulator-to-computer transmission lines). The latter three subsystems were considered necessary because space limitations necessitated locating the simulator and computer in two buildings approximately 402 meters (0.25 mile) apart. Thirty of the data-acquisition channels record computer outputs that describe simulated-spacecraft-relative-motion dynamics, and the other 30 channels record docking-hardware-component loads and kinematic strokes. Provisions are included in the facility to accommodate test-mechanism control and display panels and energy sources (for example, gas bottles for the probe). A test team includes five to 10 people, depending on the degree of documentation and data recording required by a specific series of test runs.

Activation and Checkout

Because the facility design incorporated several innovative concepts, numerous problems in activation and checkout were expected and encountered. The DDTS incorporated a previously untried approach which used a computer-operated servomechanism that included digital computations in the control loop; the complexity of checking out this approach was compounded because six independent, but coupled, high-force servos operated simultaneously over a frequency range of 0 to 10 hertz. System stability was the most severe recurring problem associated with the operation of the DDTS.

Checkout involved an extensive series of closed-loop runs, starting with one active servo; subsequently, the number of active channels was increased gradually until the system with all six servos had been exercised under a full range of operating conditions. This checkout was intended to culminate in a series of runs using actual probe and drogue test hardware. Concurrently, an elaborate kinematic mathematical model of the spacecraft and docking mechanism was implemented. This model was generated to serve several objectives; but, initially, a comparison of results with the DDTS results for specified contact conditions was intended to verify validity of the DDTS performance or to "calibrate" the facility (fig. 4).

In the checkout operations, many small modifications that could improve the phase and gain margins in the control loops were identified. Eventually, an elaborate stability analysis was implemented to evaluate destabilizing effects and to propose stability remedies. Ultimately, analog calculations were substituted for the real-time control-loop digital segment, and this arrangement was used for subsequent operations.

The DDTS Capabilities

The capability of the DDTS to produce prescribed impact conditions (including more than 20 cases) was demonstrated repeatedly. Early problems with reliability of the DDTS equipment largely were eliminated so that test productively easily could surpass available data-processing and evaluation capability. The computer implementation evolved to a general configuration that used all analog components for the real-time computations during a run. The digital section was employed to set up and check out the computer system before closed-loop runs were made with the simulator and to monitor analog operations during these runs.

Throughout the program, simulator improvements were incorporated to extend performance and mitigate the inherent limitations of the equipment. The salient limitation that had the most significant effect on testing was the total-system-stability margin, which was limited by the basic characteristics of the computer-controlled servo actuators. The use of all analog real-time computations in the control loop eliminated the major destabilizing characteristic. Accordingly, at the completion of the Apollo/Skylab test program, only two stability limitations existed.

1. Near the end of retraction, when probe-ring-to-drogue-ring contact had been established, the inherent stability margins were reduced to negligible values, thus allowing unstable divergent oscillation. After a few (but dramatic) oscillatory cycles, automatic interlocks disabled the device.

2. Under conditions in which the hydraulic actuators produced low-force, short-stroke (that is, high resolution) motions, the static friction of the actuators produced severe motion distortion that effectively nullified evaluation of the docking-hardware performance.

The DDTS can provide excellent tests of impact, capture, and most of the probe-retract cycle. The stability limitations discussed previously only affected the test by causing extraneous motions during the last part of the retract cycle. (These limitations are expected to be effectively eliminated during a DDTS upgrading currently underway.) Accordingly, the DDTS provided a versatile test tool to verify flight worthiness of the Apollo docking hardware.

DOCKING HARDWARE TESTS

Test Sequence

Testing of the Apollo docking system included four distinct phases.

Flight qualification. - The purpose of the flight-qualification phase was to certify that the docking system would function properly and reliably before the system was committed to flight operations. This phase was to prove that the design met all nominal mission requirements and that a demonstrated reserve capability existed to handle various foreseeable mission anomalies.

Parametric system testing. - The objective of the parametric system testing was to demonstrate docking system capabilities as affected by failures in the docking system or the spacecraft maneuvering system. Also, this phase was to evaluate the capture limits of the system and to increase confidence in the system capabilities.

Skylab verification. - The Skylab verification testing certified the capability of the Apollo docking system to meet the Skylab mission requirements, which introduced both different spacecraft masses and a new attitude control system. Also, off-normal high-load and capture stability capabilities required to cover the three Skylab spacecraft configurations were to be demonstrated.

Anomaly investigation. - Testing was performed in support of the Apollo 14 docking anomaly discussed in reference 2.

Test Results

As a result of the docking system tests (including more than 1000 runs), extensive data have been accumulated. In general, the testing produced conclusive evidence that the load-carrying and energy-absorption capability of the system fulfilled the design requirements and provided a significant margin over all known mission needs. However, significant docking-hardware problems were disclosed. Major probe deficiencies produced important changes, as follows.

Unreliable capture latch operation. - Because inability to capture completely negated the docking-hardware effectiveness, this problem received extensive corrective action and had substantial ramifications. For example, the probe-component functions were critically interrelated, and additional rework was necessary when DDTS testing showed that the initial alterations were insufficient. Furthermore, the entire probe inventory (including several flight end items) had to be reworked because this problem had been unrevealed through all previous development. Ultimately, the probe underwent a redesign and substantial changes in assembly and checkout procedures. The reworked configuration provided acceptable capture performance.

Probe binding under lateral loading. - The problem of probe binding, which only occurred when significant side loads were imposed on the probe, was resolved with rework, including the use of an additional lubricated bushing in the assembly.

Minor deficiencies included drogue susceptibility to impact damage when contact occurred near intercostal joints and excessive scoring (or scratching) of drogue surface by sharp edges on capture latches. Although the drogue demonstrated an exceptional capability to absorb impacts in the presence of severe damage to its inner surface, both of these problems were remedied partially by minor rework.

A variety of capabilities was confirmed by other test results. The tests under adverse motion conditions (that is, the two spacecraft pitching away from each other) showed excellent docking-hardware capture performance. Retraction and alinement functions were shown repeatedly to be more than adequate. Furthermore, the runs at high (366.48° K (200° F)) and low (219.26° K (-65° F)) temperatures demonstrated that the hardware performance was adequate for expected temperature extremes. Finally, the docking hardware demonstrated a substantial capability to accomplish capture and latching with damaged attenuators, malfunctioning spacecraft attitude control systems, or unusual spacecraft masses (for example, Skylab configuration).

When the docking capture anomaly occurred during the Apollo 14 mission, the DDTS was used to evaluate contingency lunar-orbit docking procedures. During the lunar-stay portion of this mission, 32 runs were performed on the DDTS. These runs ascertained that other procedures could be used to perform a successful docking should the capture latch anomaly recur. Subsequently, other contingent docking procedures were identified, and an additional 93 DDTS runs were performed to increase confidence in the docking system before the Apollo 15 mission.

CONCLUDING REMARKS

The unique and complex functions of the Apollo docking system necessitated the development of a dynamic testing capability, which in turn, provided a significant advance in dynamic test technology. This test system was used to produce a substantial demonstration of the dynamic performance capability and reliability of the Apollo docking hardware. Early testing identified needed probe and drogue improvements, and later tests subsequently verified the capability of the reworked docking hardware to meet Apollo and Skylab mission requirements. Currently, application of this facility, with major revisions to the actuation portion of the system, is being planned for testing the next generation of docking systems. These systems, one for the U.S./U.S.S.R. rendezvous missions and another for the space shuttle, also will be subjected to verification through intensive testing by the Manned Spacecraft Center dynamic docking test system.

This paper can only provide a limited description of the complex and extensive development efforts invested in the dynamic docking test system. The information presented in the following sections is essentially a summary obtained from the comprehensive MSC and contractor documentation produced in the course of the program by the various groups that participated in the activation and operation of the simulator. Special credit is due to C. Alan Kirkpatrick, MSC, who has handled the project operations since their inception.

REFERENCES

1. Langley, Robert D.: Apollo Experience Report. The Docking System. NASA TND-6854, 1972.

2. Langley, Robert D.: The Apollo 14 Docking Anomaly. Proceedings of the 7th Aerospace Mechanisms Symposium, Sept. 7 and 8, 1972. NASA TM X-58094, 1972.

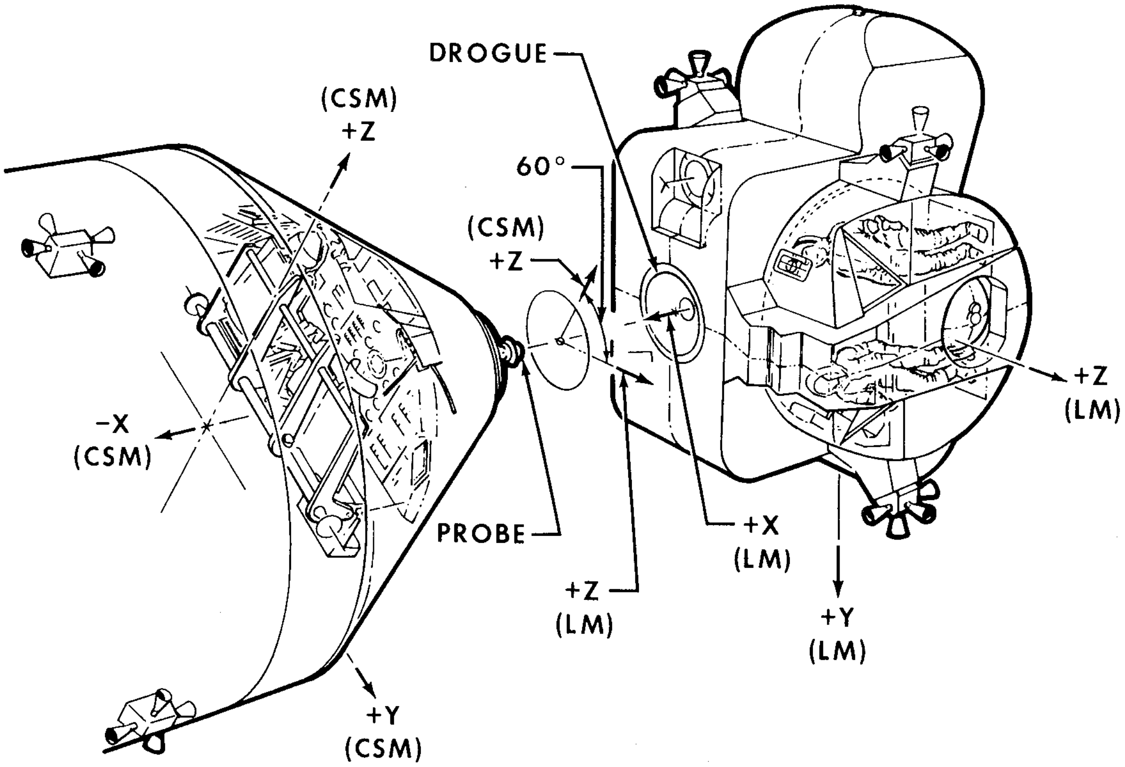


Figure 1. - The CSM/LM orientation before contact.

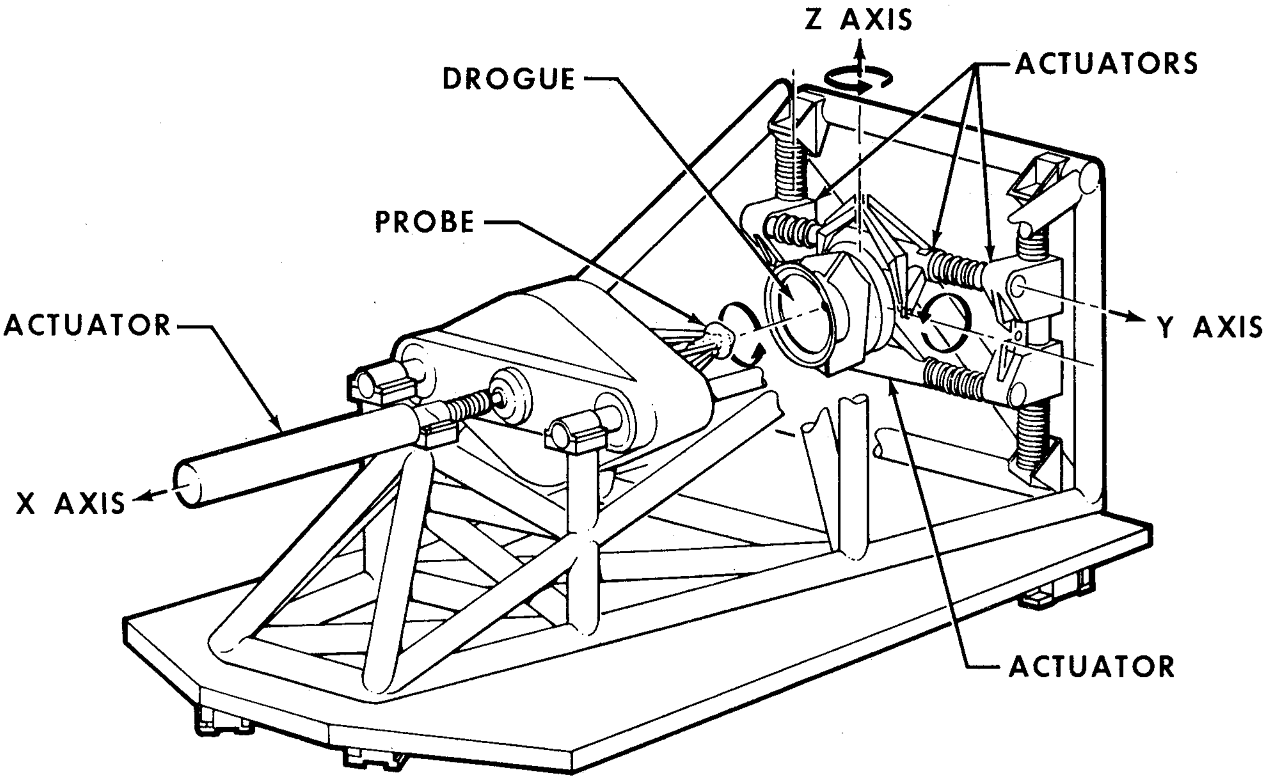


Figure 2. - Perspective of DDTS motion simulator.

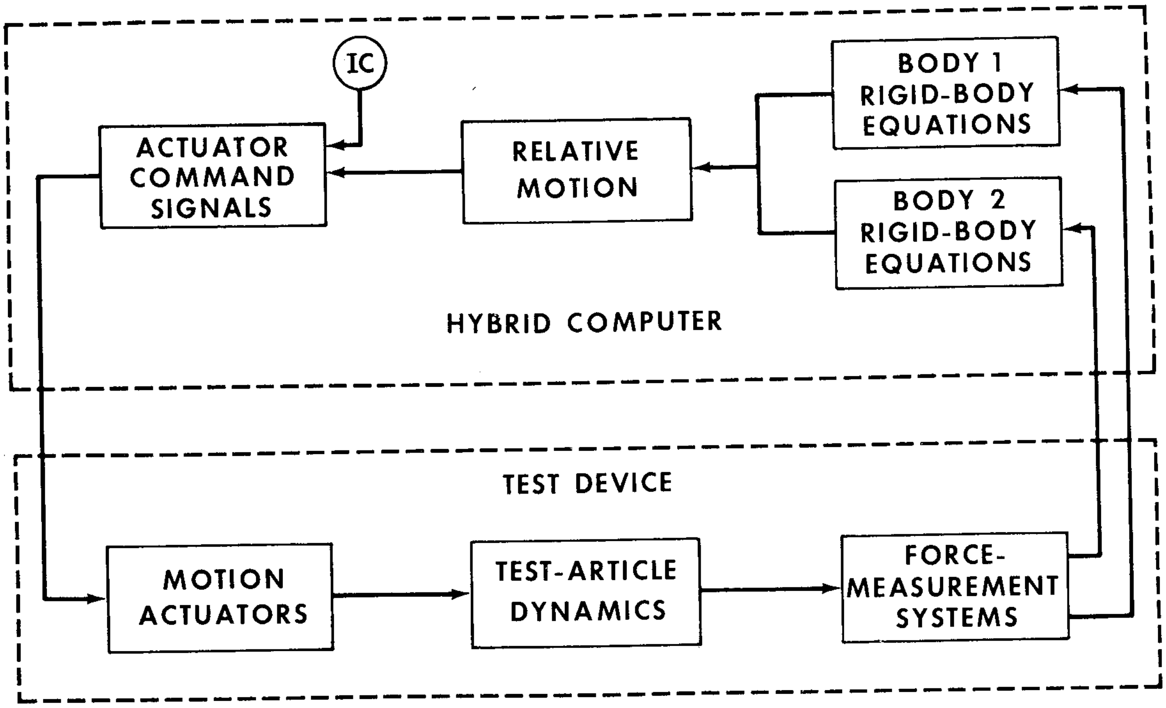
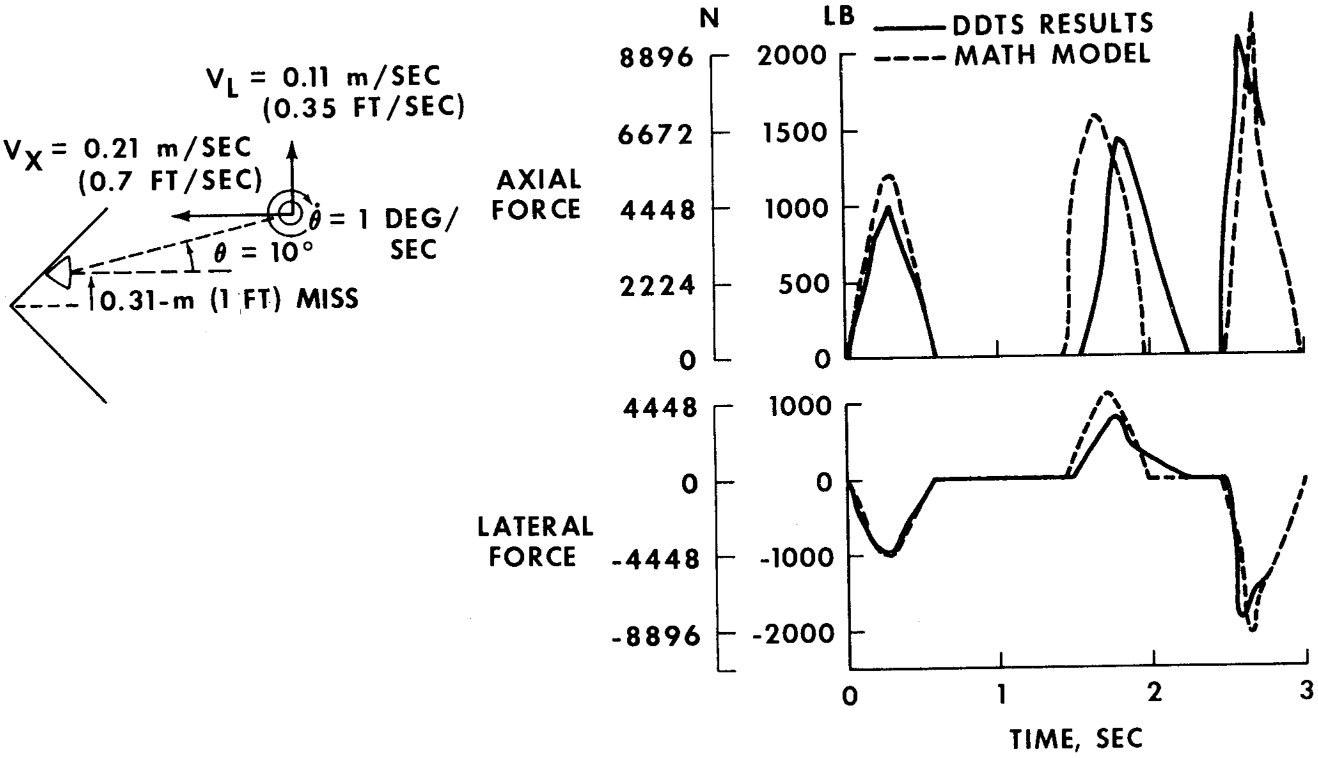


Figure 3. - Basic DDTS block diagram.



(a) Initial contact conditions.

(b) Force history.

Figure 4. - Typical docking system forces.