Maneuvering and Pointing Flexible Vehicles

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TEXT

THE PROBLEM (Figure 1)

WITH THE DEVELOPMENT OF TECHNIQUES TO ASSEMBLE LARGE STRUCTURES IN ORBIT, NEW CONTROL SYSTEM PROBLEMS EVOLVE. THESE LARGE STRUCTURES ARE TYPICALLY CHARACTERIZED BY LOWER STRUCTURAL FREQUENCIES, BUT NO COMPROMISES ARE MADE REGARDING MANEUVER AND STRUCTURAL SETTLING TIMES. TECHNIQUES MUST BE DEVELOPED WHICH WILL ALLOW THESE LARGE STRUCTURES TO BE MANEUVERED AND POINTED QUICKLY WITH MINIMUM SETTLING TIMES.

The Problem

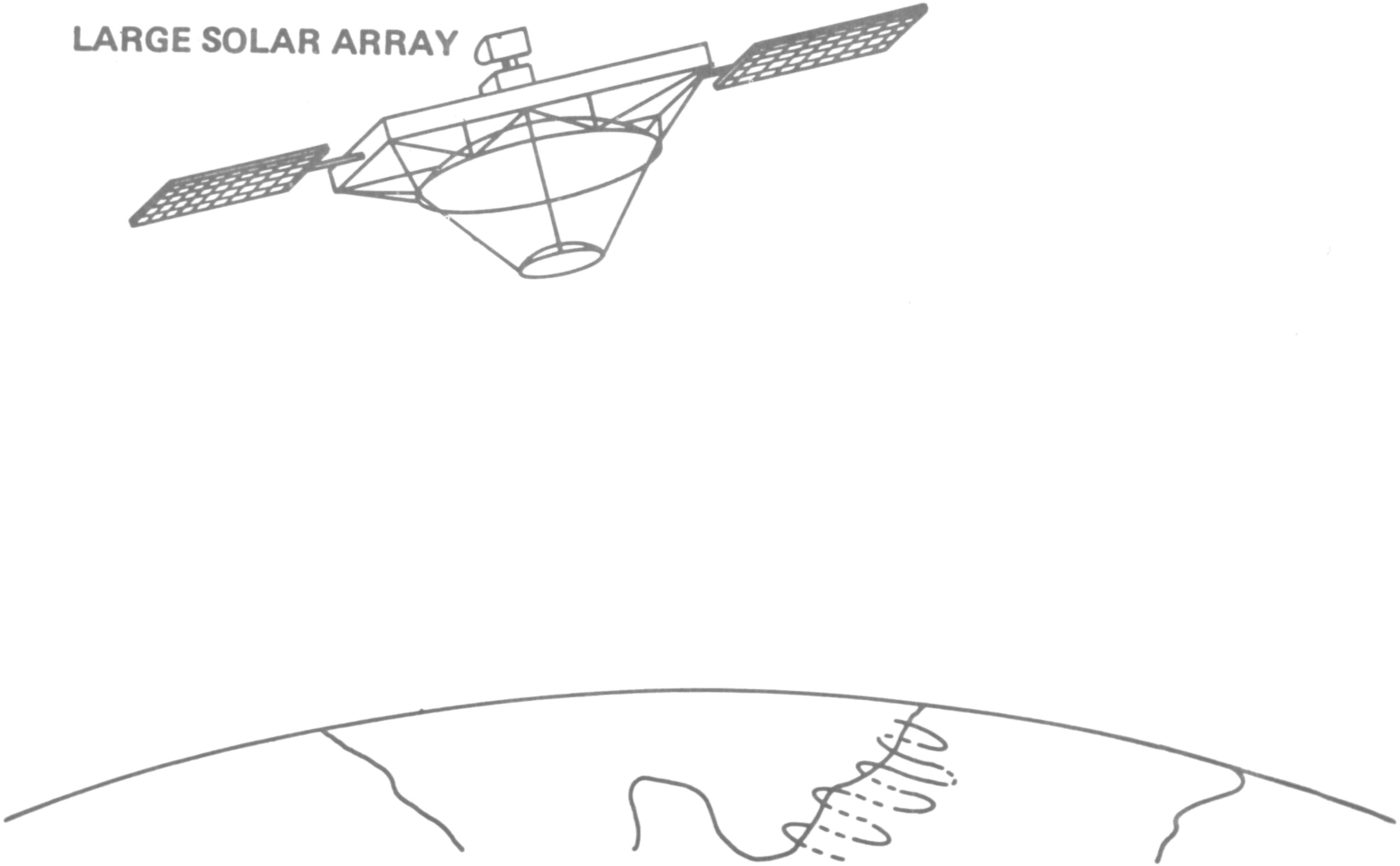

Figure 1

APPROACH (Figure 2)

BOEING USES A THREE-PRONGED APPROACH TO THIS PROBLEM. IN THE PRE-CONTRACT AWARD TIME PERIOD, ANALYSIS AND SCALE MODEL TESTS ARE USED TO DEVELOP AND VERIFY CONTROL SYSTEM DESIGN CONCEPTS; AFTER CONTRACT AWARD FULL-SCALE TESTS ARE USED IN THIS ACTIVITY WITH THE PURPOSE OF PROVIDING LIMITED PROOF OF PERFORMANCE AS WELL AS DETAILED DATA ON SYSTEM INTEGRATION.

Approach

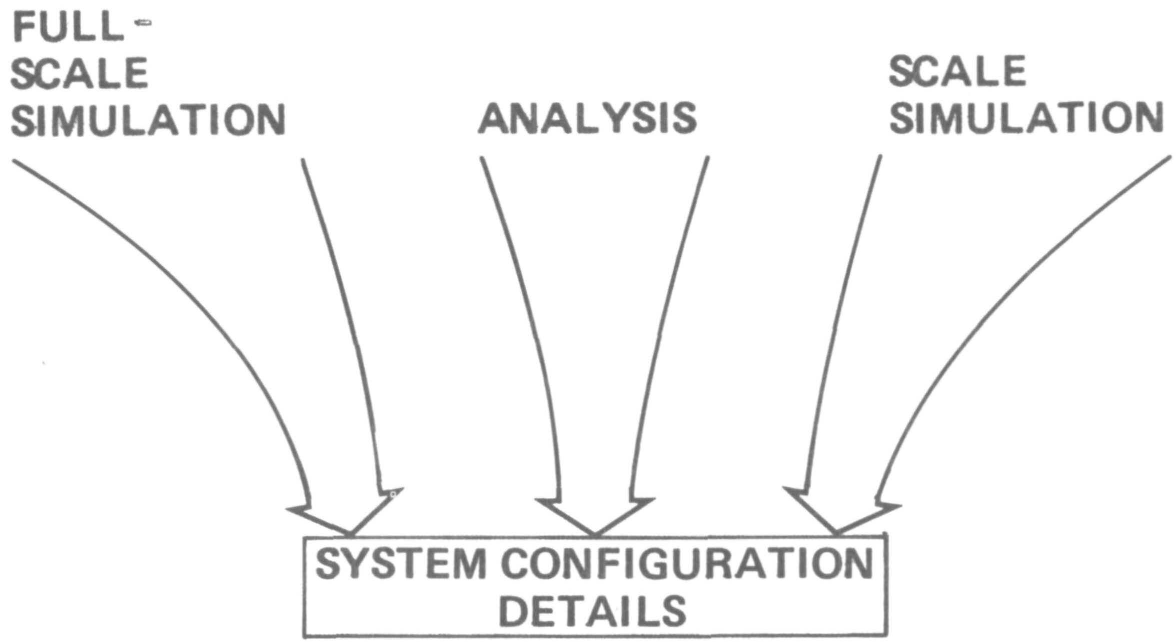

Figure 2

TEXT

MANEUVER APPROACH (Figure 3)

INITIALLY, THE ACCEPTED METHOD OF MANEUVERING VEHICLES WAS TO SLEW EACH VEHICLE AXIS AT THE RATE LIMIT CAPABILITY OF THE SYSTEM AND ACCEPT THE SETTLING TIME PENALTY. WITH THE ADVENT OF NEW COMPUTER TECHNOLOGY, A DIFFERENT APPROACH CAN BE USED WHICH IS BASED UPON GENERATING A VIRTUAL TARGET FOR THE SPACECRAFT TO EXECUTE DURING EACH SLEW MANEUVER. THIS METHOD PRODUCES SMALL INCREMENTAL ANGLE AND RATE CHANGES IN A PRE-PROGRAMMED MANNER WHICH HAS THE EFFECT OF MINIMIZING THE SIZE OR MAGNITUDE OF THE CONTROL ERROR SEEN BY THE VEHICLE.

Maneuver Approach

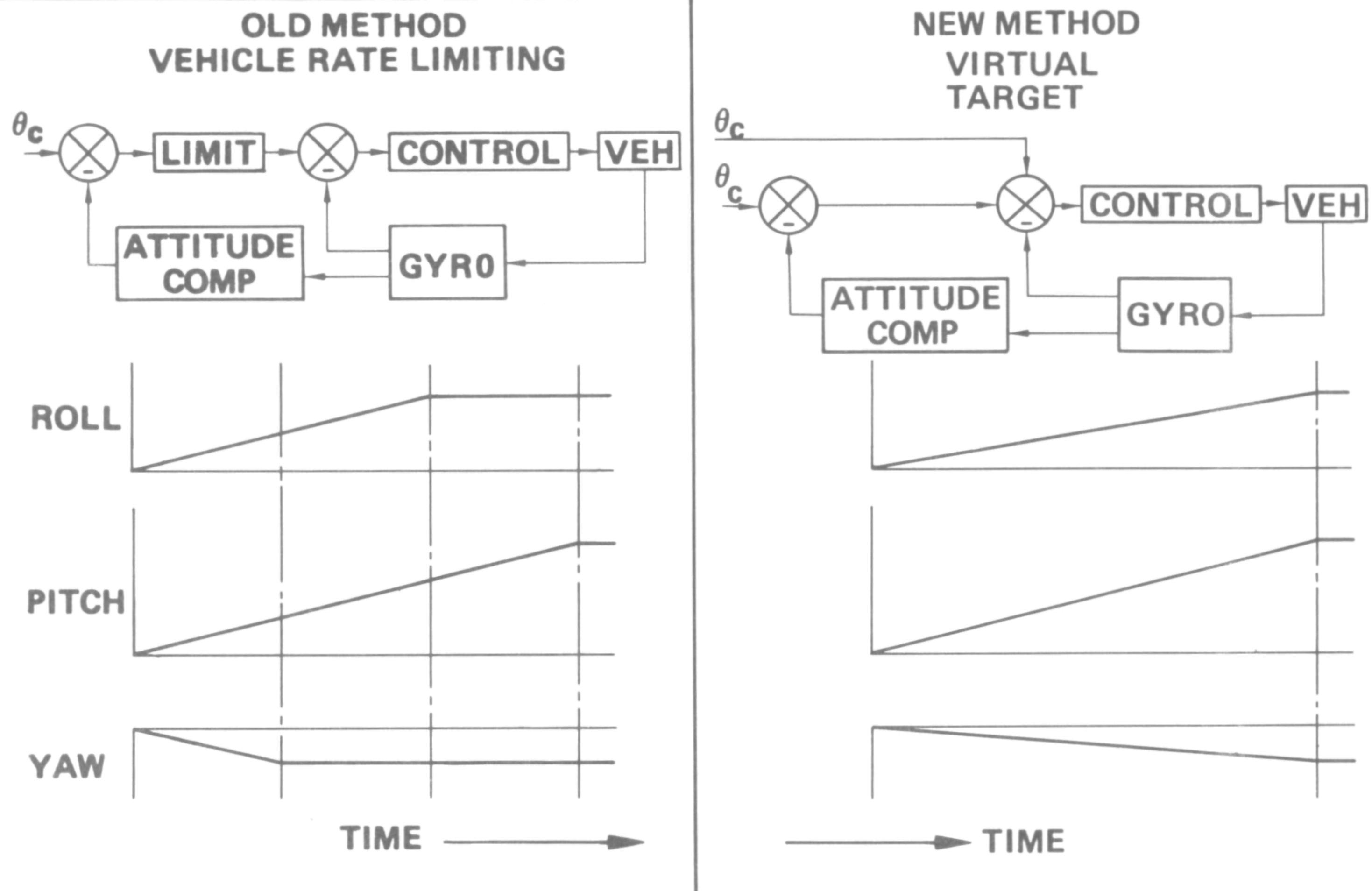

Figure 3

VIRTUAL TARGET APPROACH (Figure 4)

THE USE OF THE COMPUTER TO GENERATE THE VIRTUAL TARGET ALLOWS FLEXIBILITY IN SELECTING THE METHOD USED TO GENERATE THE DESIRED TRAJECTORY. IT HAS BEEN DETERMINED, BASED UPON BOTH ANALYSIS AND TEST, THAT IMPOSING A JERK LIMIT (RATE OF CHANGE OF ACCELERATION) AND AN ACCELERATION LIMIT UPON THE TRAJECTORY WILL NOT CAUSE EXCESSIVE STRUCTURAL EXCITATION. THIS IS FEASIBLE BECAUSE THE IMPOSED LIMITS ARE JUST NUMBERS FIXED IN THE COMPUTER PROGRAM WHICH GENERATES THE VIRTUAL TARGET.

Virtual Target Approach

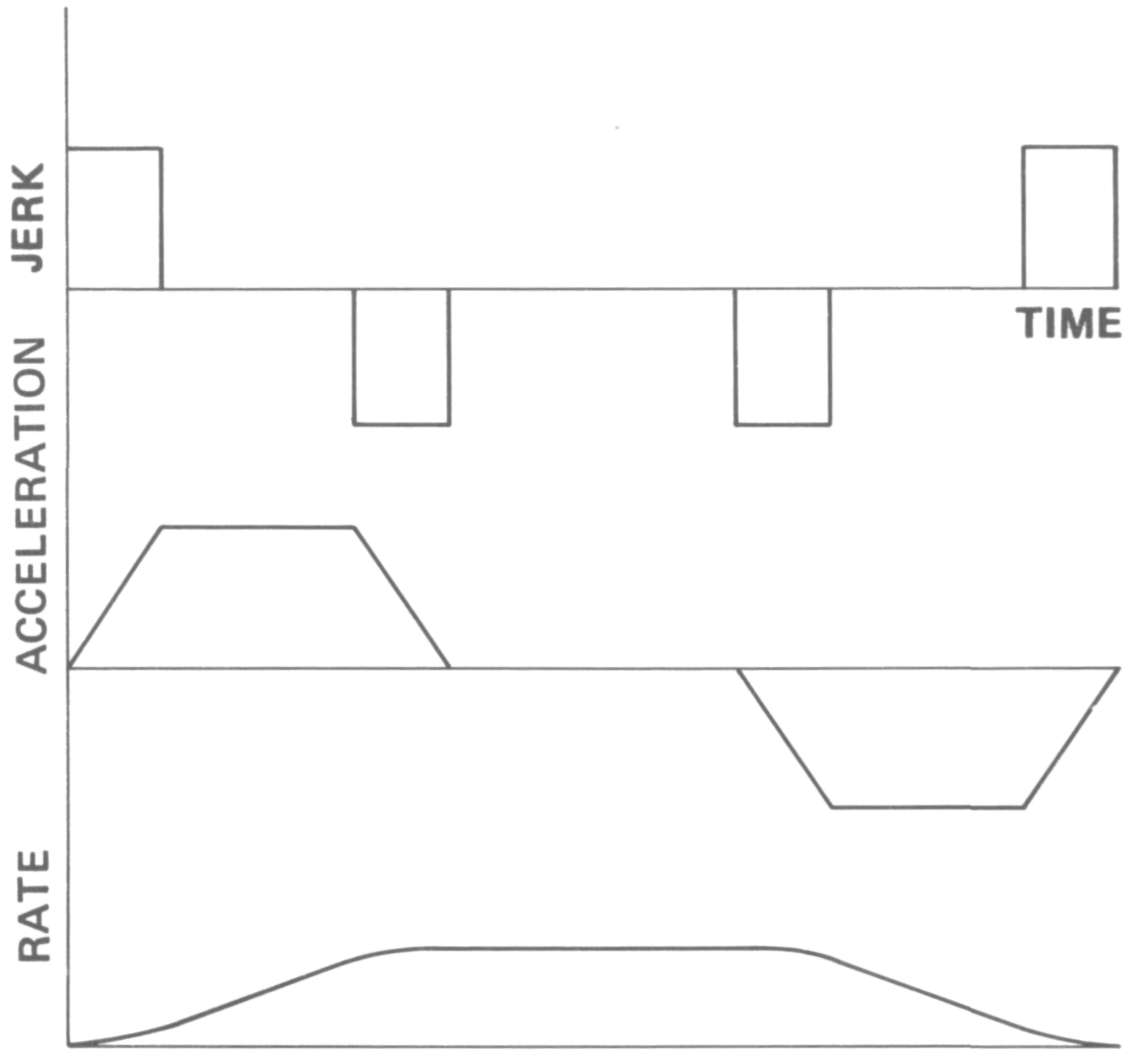

Figure 4

LOW FREQUENCY STRUCTURE RESULTS (Figure 5)

FOR STRUCTURAL FREQUENCIES GREATER THAN FIVE HZ, IMPOSING A JERK LIMIT IS ADEQUATE TO CONTROL STRUCTURAL EXCITATION. HOWEVER, WHEN THE STRUCTURAL FREQUENCY IS LOW, APPROXIMATELY 1 HZ, THE JERK AND ACCELERATION LIMITS ALONE ARE NOT ADEQUATE. THIS VIRTUAL TARGETING APPROACH CAN STILL RESULT IN LONG SYSTEM SETTLING TIMES FOR CERTAIN MANEUVER ANGLES.

Low Frequency Structure Results

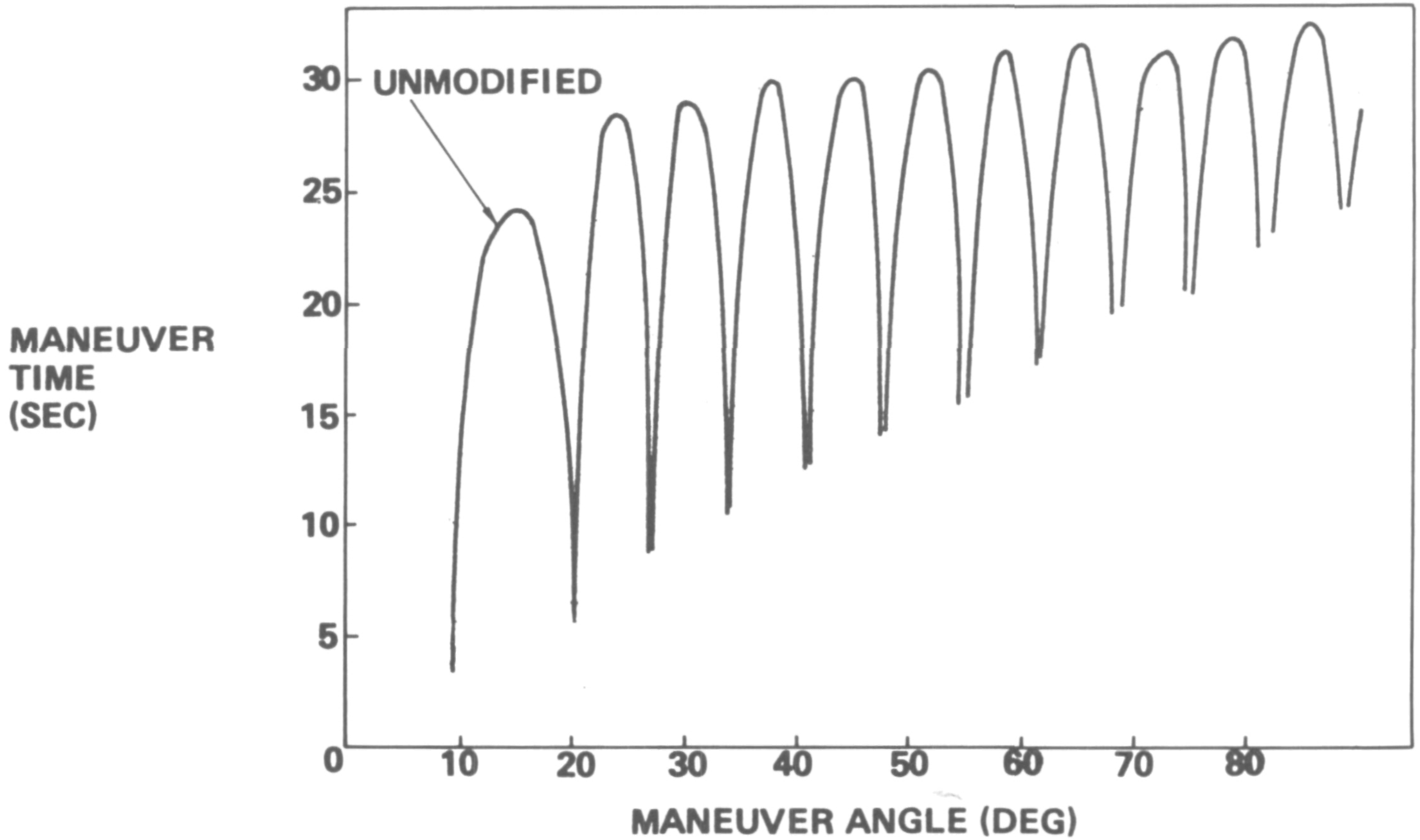

Figure 5

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CONTROL SYSTEM DESIGN PROBLEM (Figure 6)

AN ALTERNATE APPROACH TO THE SETTLING TIME WOULD BE TO ADD EFFECTIVE DAMPING TO THE STRUCTURAL MODES USING THE CONTROL SYSTEM. HOWEVER, AS THE STRUCTURAL FREQUENCIES DROP, IT BECOMES VERY DIFFICULT TO ADD DAMPING TO THE STRUCTURAL MODE WITHOUT SEVERLY COMPROMISING THE RIGID BODY CONTROL FREQUENCY. THIS IS ILLUSTRATED BY THE ROOT LOCUS TRAJECTORIES SHOWN IN THE FIGURE.

Control System Design Problem

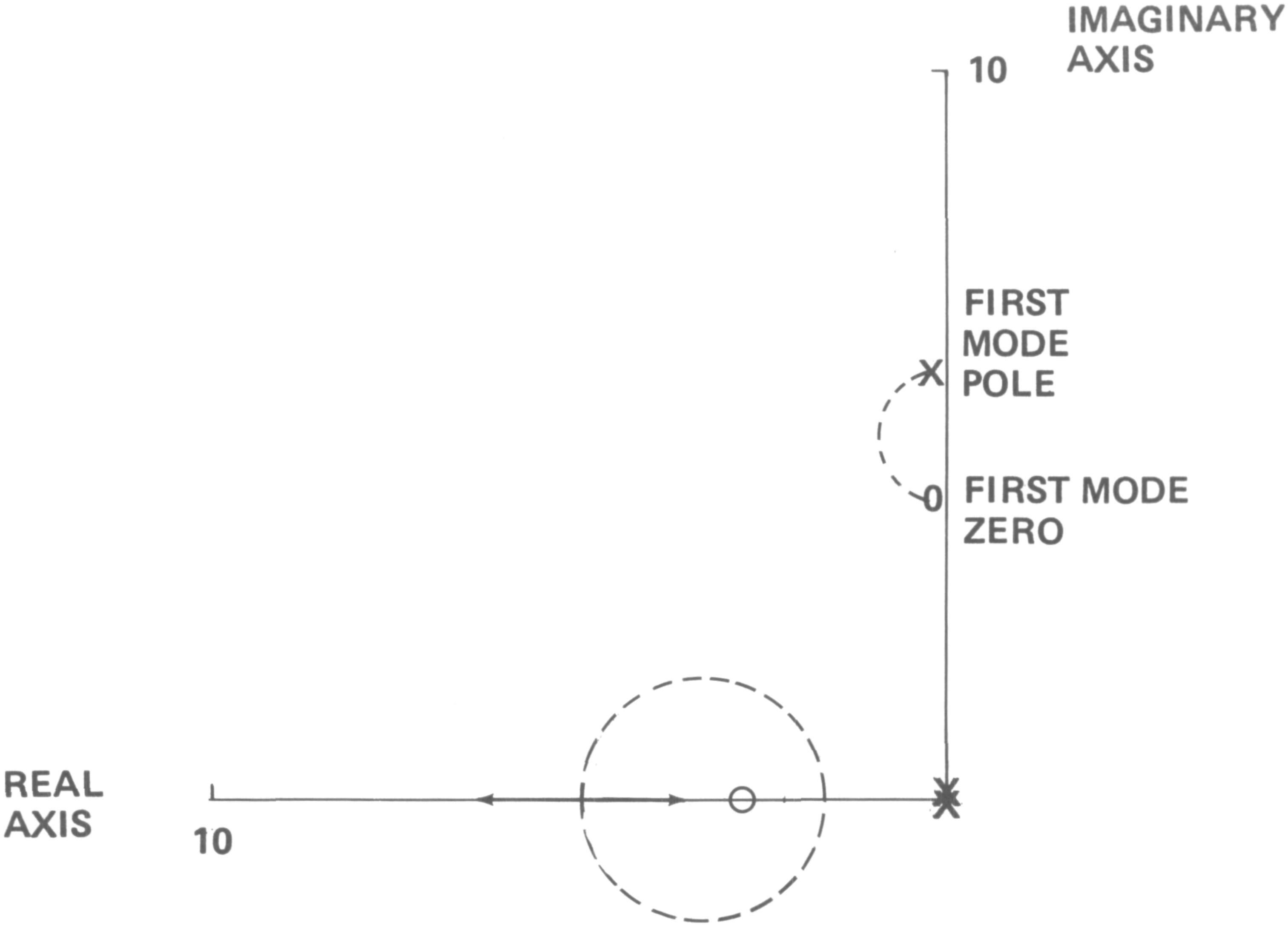

Figure 6

LOW FREQUENCY STRUCTURE ANSWER (Figure 7)

FOR THE LOW FREQUENCY STRUCTURE, A NEW APPROACH HAS BEEN DEVELOPED WHICH CORRELATES THE LENGTH OF THE JERK IMPULSE WITH THE DOMINANT STRUCTURAL FREQUENCIES. THE SINUSOIDAL SHAPE IN THE FIGURE REPRESENTS THE STRUCTURAL MOTION CAUSED BY THE JERK IMPULSES. FOR THE UPPER FIGURE, THE STRUCTURAL FREQUENCY IS PROPERLY PHASED WITH THE JERK IMPULSES. IN THE LOWER FIGURE, THE TIMING IS COMPLETELY WRONG AND THE STRUCTURAL MOTION IS REINFORCED BY THE JERK IMPULSES. THE BENEFIT OF PROPER TIME PHASING IS OBVIOUS.

Low Frequency Structure Answer

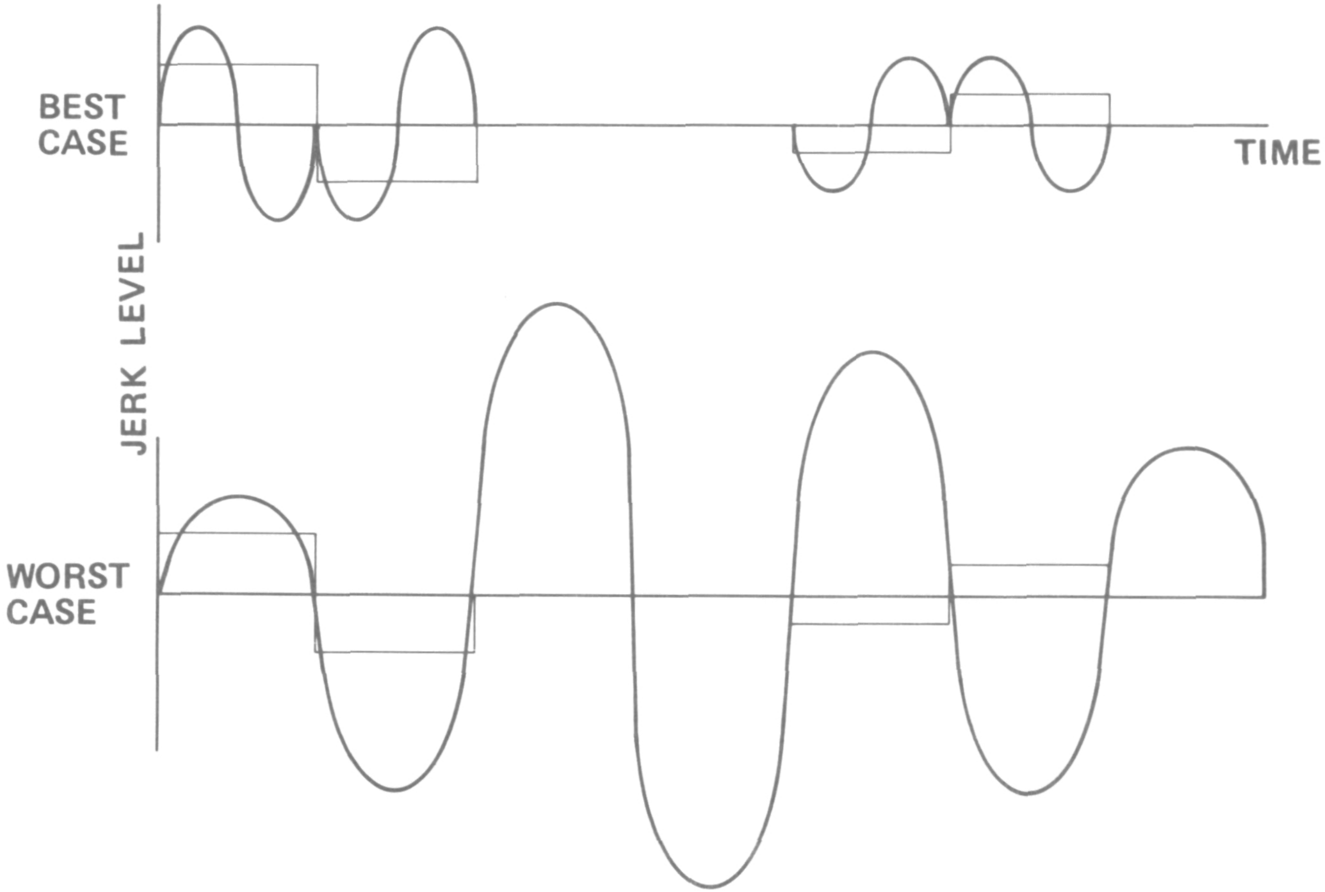

Figure 7

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ANALYTICAL SIMULATION RESPONSE (Figure 8, Figure 9)

THE NEXT TWO CHARTS SHOW THE RESULTS FROM AN ANALYTICAL SIMULATION USING THE NEW LOW FREQUENCY SLEW LAW. THE DESIGN GOAL FOR THIS SYSTEM WAS TO HAVE LESS THAN 100 MICRORADIANS OF ERROR ON THE ROLL AND PITCH AXIS LESS THAN 1.5 SECONDS AFTER THE END OF THE MANEUVER. THE DATA SHOWS THAT THIS OBJECTIVE WAS MET. THE DOMINANT MODE IN THIS SYSTEM WAS AT 1.1 Hz.

Analytical Simulation Response

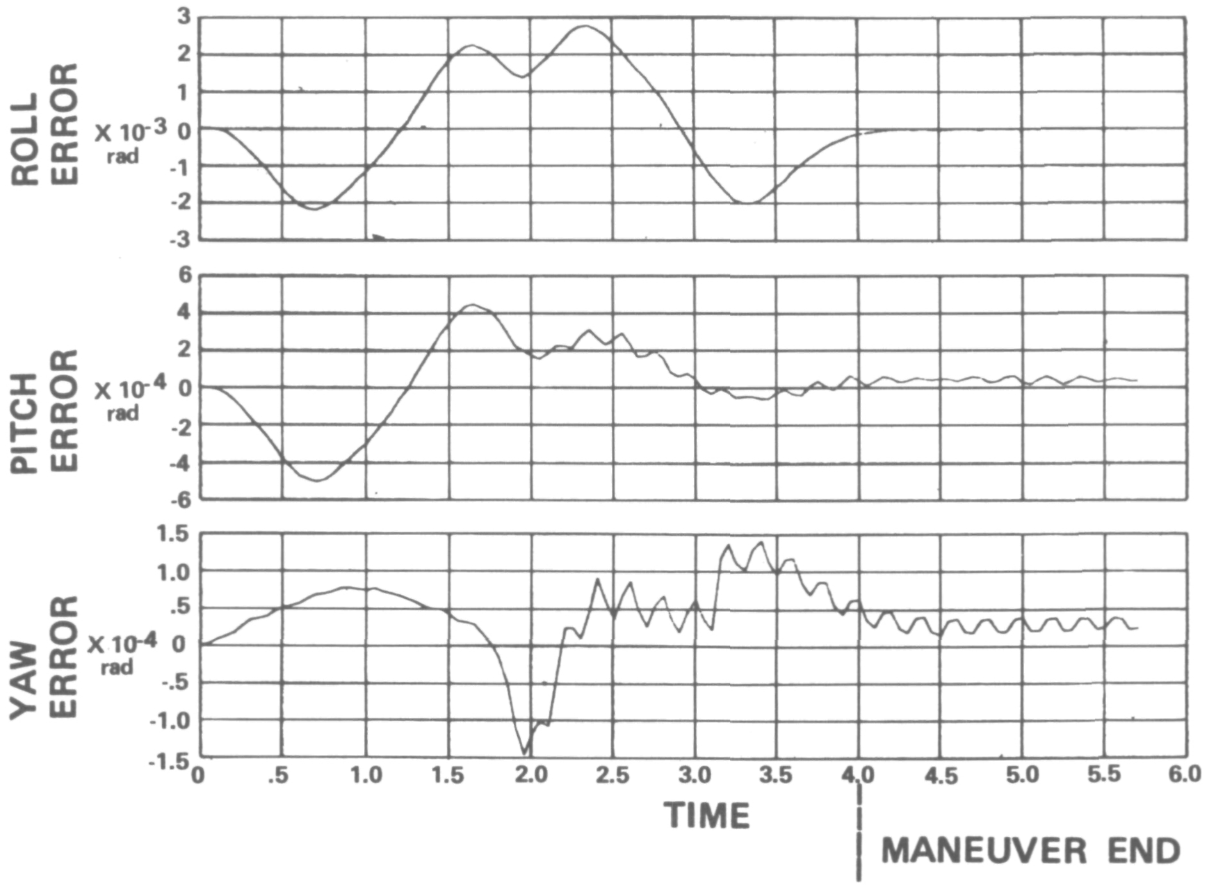

Figure 8

Analytical Simulation Response

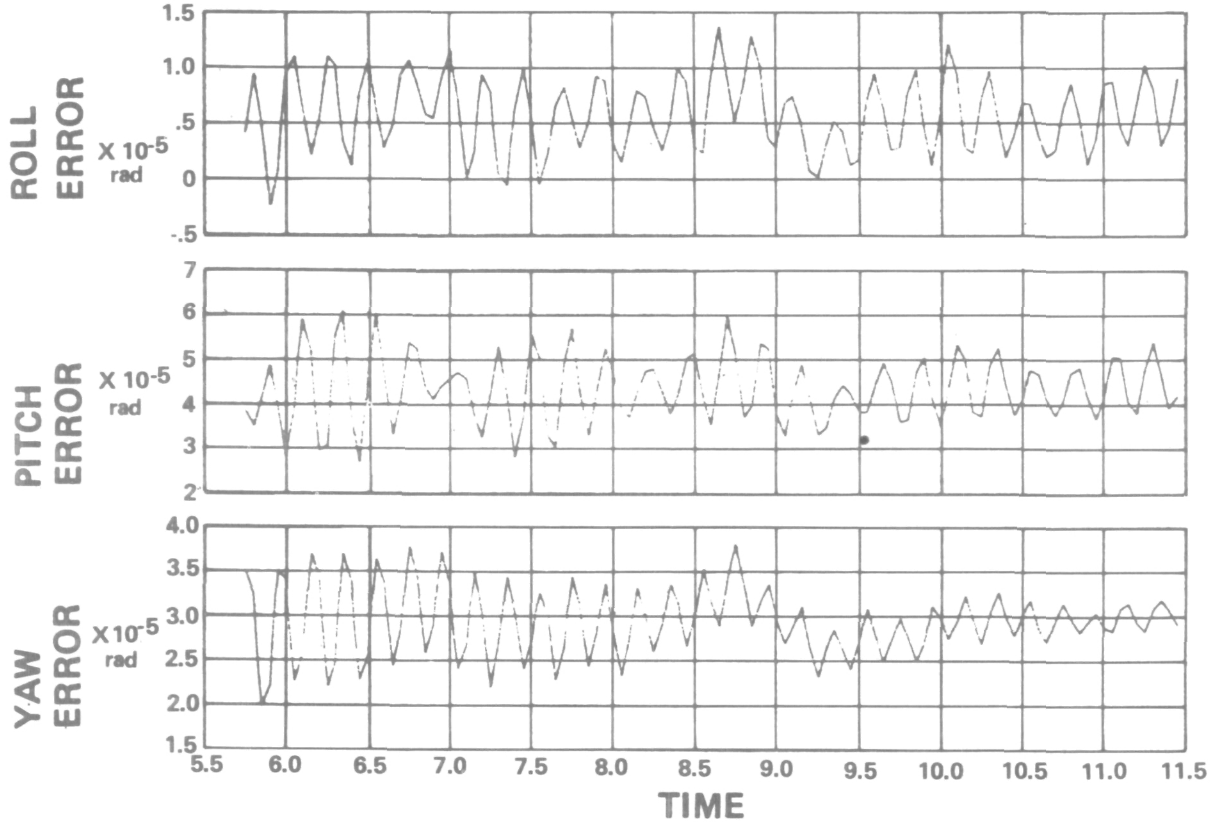

Figure 9

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SIMULATION FUNCTIONAL DIAGRAM (Figure 10)

FINAL PROOF OF THE SYSTEM CONCEPT WAS VERIFIED USING A SCALE MODEL AIRBEARING SIMULATOR. THIS HARDWARE WAS CONFIGURED AS SHOWN HERE IN A FLIGHT – TYPE OF CONFIGURATION AND REQUIRED GENERATION OF FLIGHT-TYPE OPERATIONS SOFTWARE TO CONTROL THE SYSTEM IN THE REAL TIME ENVIRONMENT. THE CHARACTERISTICS OVER-ALL ARE SIMILAR TO THAT WHICH WOULD BE OBTAINED WITH ACTUAL FLIGHT-TYPE HARDWARE.

Simulation Functional Diagram

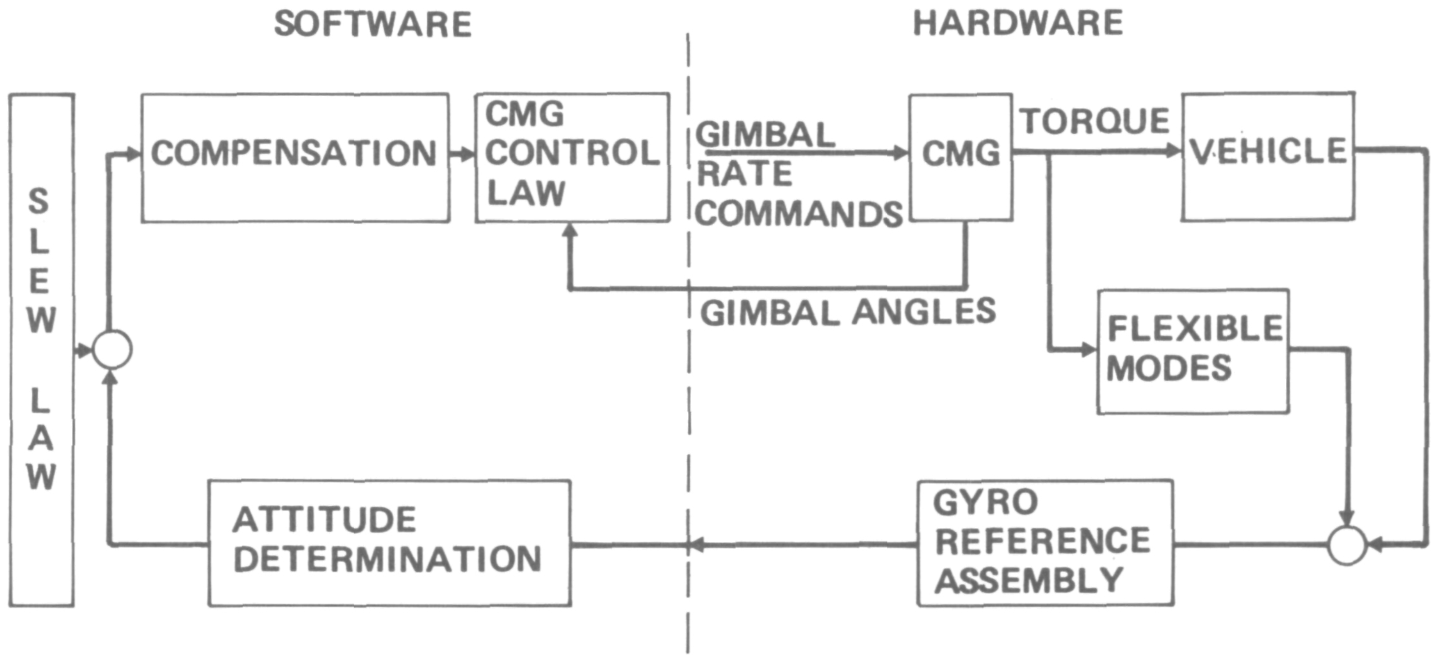

Figure 10

TEXT

ACTUATOR CONFIGURATION (Figure 11)

THIS FIGURE SHOWS SCHEMATICALLY THE SKEWED CMG CONFIGURATION USED FOR THE TEST: THIS CONFIGURATION WAS USED TO ASSURE THAT THE TEST RESULTS WOULD BE REALISTIC AND EXHIBIT THE SAME TYPE OF CROSS-COUPLED OPERATION THAT WOULD BE EXPERIENCED WITH A REAL SPACECRAFT.

Actuator Configuration

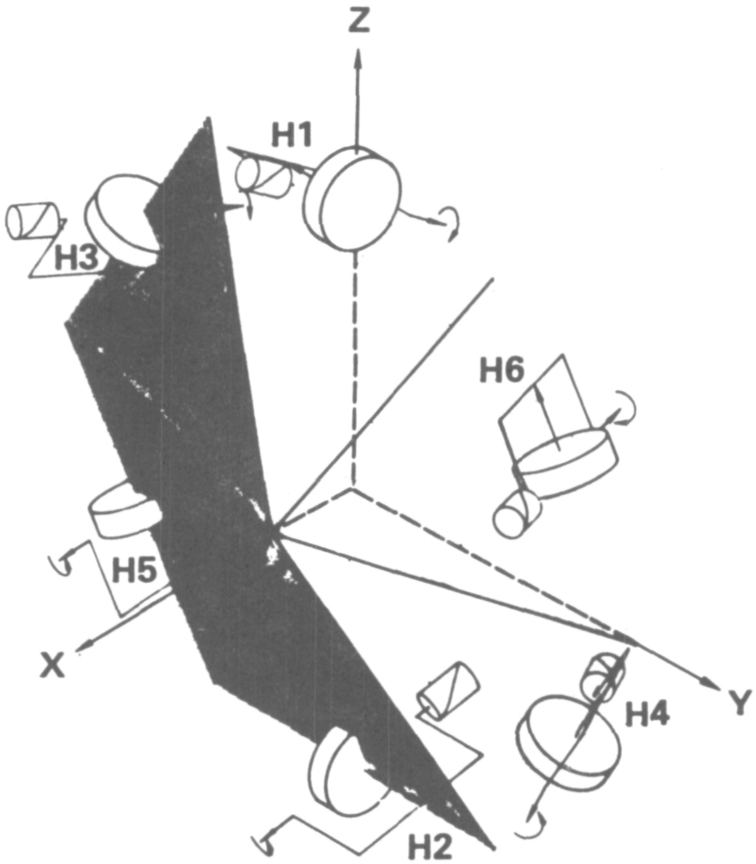

Figure 11

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HARDWARE SIMULATION (Figure 12)

THIS PICTURE SHOWS THE SCALE MODEL THREE AXIS AIRBEARING SIMULATOR. IT CONSISTS OF 2 SEPARATE SEGMENTS – A CENTRAL CORE WITH THE OPERATING HARDWARE ON IT, AND A PIPE FRAME WHICH IS USED TO REPRESENT THE FLEXIBLE VEHICLE CHARACTERISTICS. THE CENTRAL CORE CONTAINS THE 6 CMG'S, COMPUTER AND GYRO REFERENCE ASSEMBLY.

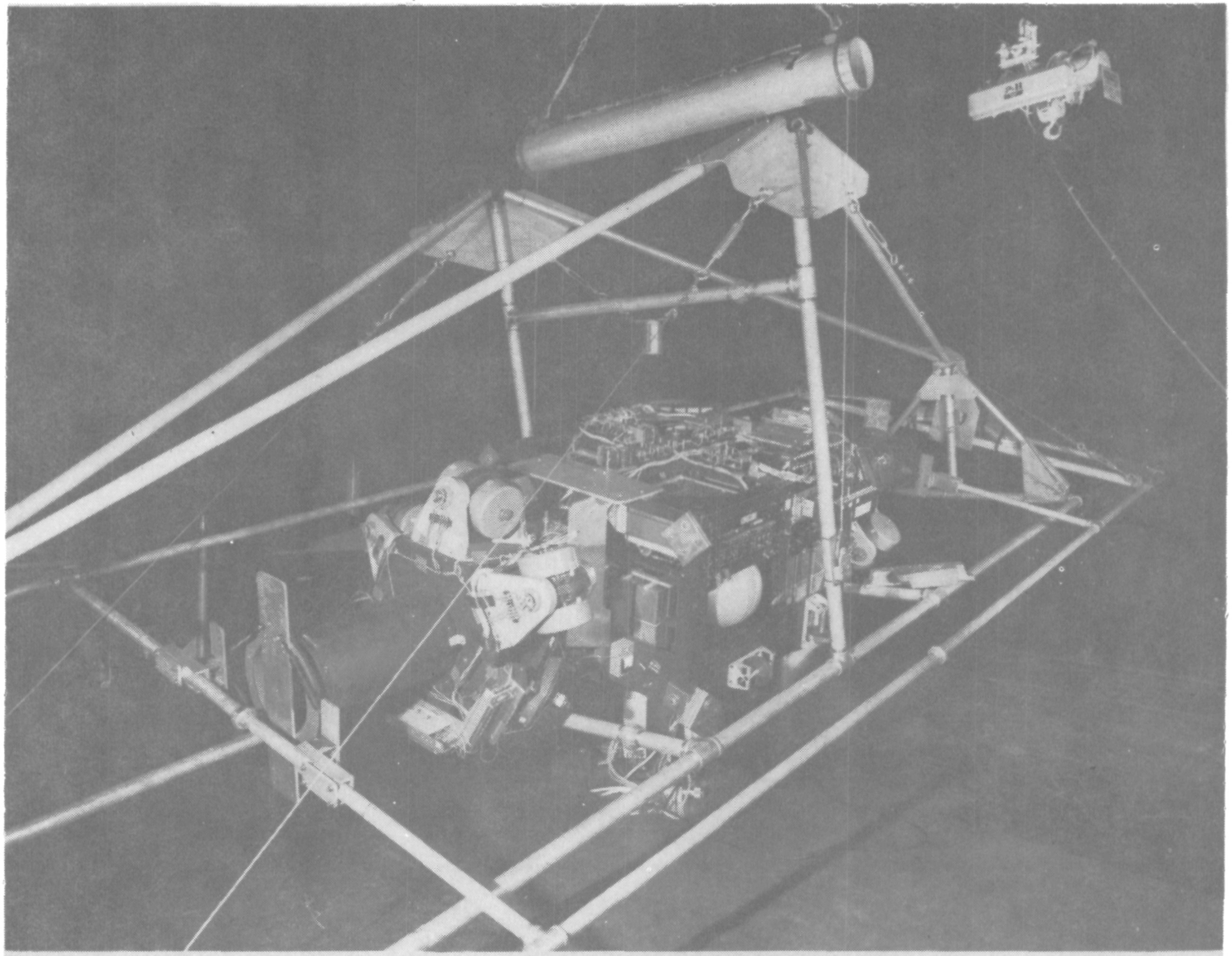

Figure 12

TEXT

FLEXIBLE MODE COUPLING (Figure 13)

THIS FIGURE SHOWS, FOR A SINGLE AXIS, THE METHOD WHICH HAS BEEN DEVELOPED TO SIMULATE THE FLEXIBLE MODE CHARACTERISTICS. IN ORDER TO SIMULATE STRUCTURAL FREQUENCIES AS LOW AS 0.5 HZ, ADDITIONAL SUPPORT METHODS MUST BE USED SEPARATE FROM THE MAIN AIRBEARING SYSTEM. IF THIS IS NOT DONE, VEHICLE MOTIONS AWAY FROM A NORMAL LEVEL ORIENTATION WILL BE STRONGLY INFLUENCED BY SYSTEM UNBALANCE. THIS DISTURBANCE MASKS THE DESIRABLE OPERATING CHARACTERISTICS. BY USING A SUPPORT FROM THE CEILING, THE FLEXIBLE MODE CAN BE SIMULATED BY USING A SIMPLE SPRING CONNECTION BETWEEN THE OUTER FRAME AND THE CORE SIMULATOR. THE NORMAL SYSTEM SHOWN IN THE PRECEDING PICTURE USES A 3-AXIS GIMBAL SYSTEM TO SUPPORT THE PIPE FRAME WORK AND ALLOW IT TO MOVE ABOUT ALL THREE AXIS IN COORDINATION WITH THE CORE SIMULATOR.

Flexible Mode Coupling

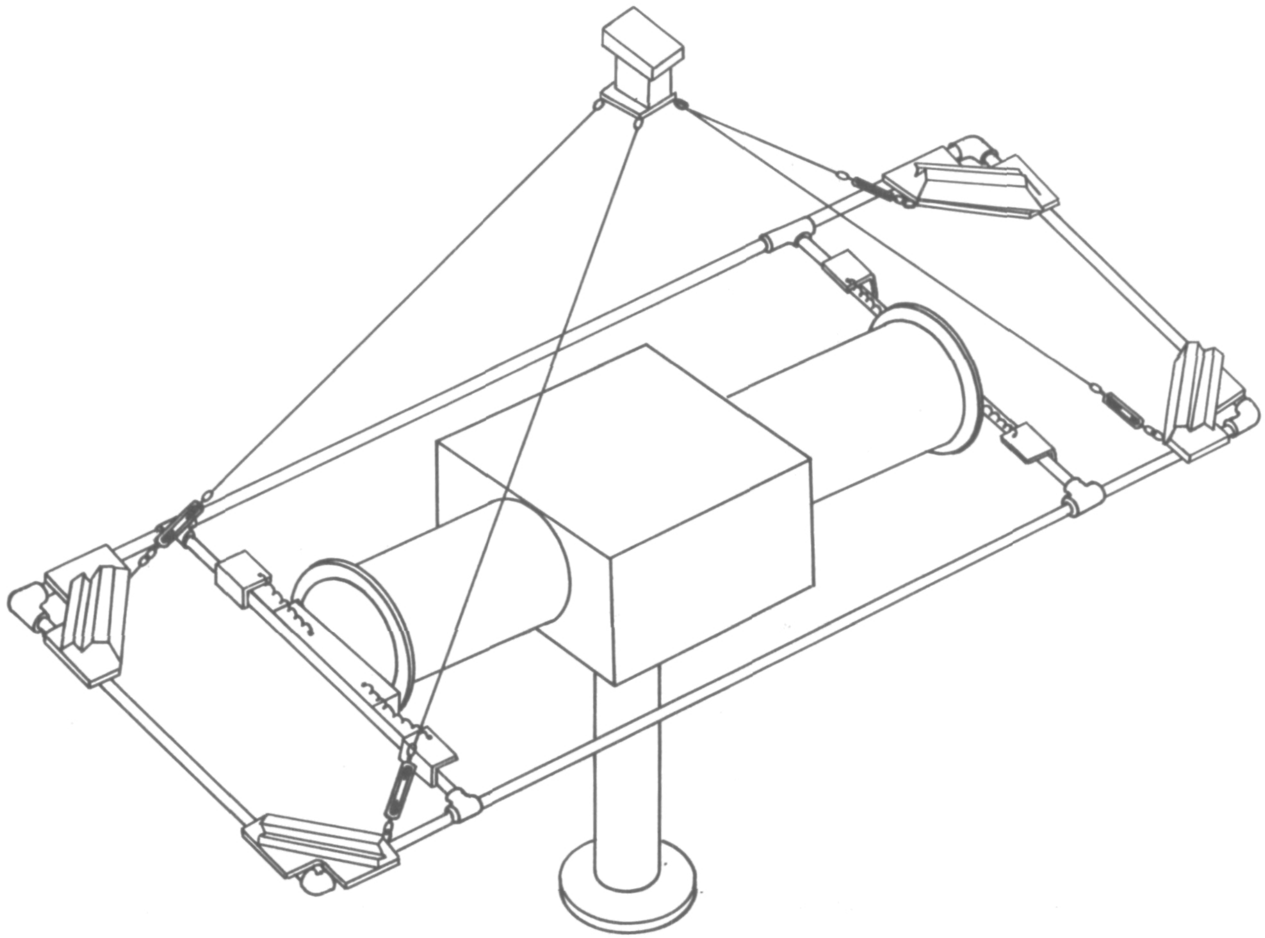

Figure 13

TEST RESULTS (Figure 14)

THIS HARDWARE RESULTS CHART SHOWS A COMPARISON BETWEEN THE OLD AND NEW VIRTUAL TARGET SLEW LAW APPROACHES. THE NEW APPROACH DOES IMPOSE A SMALL RIGID BODY MANEUVER TIME PENALTY; BUT THE SETTLING TIME FOR THE NEW APPROACH IS REDUCED FROM 24 SECONDS WITH THE OLD APPROACH TO LESS THAN 1 SECOND WITH THE NEW APPROACH. THE TOTAL TIME FOR THE NEW APPROACH, INCLUDING SETTLING TIME, IS SUBSTANTIALLY LESS THAN THE OLD JERK LIMITED SLEW LAW.

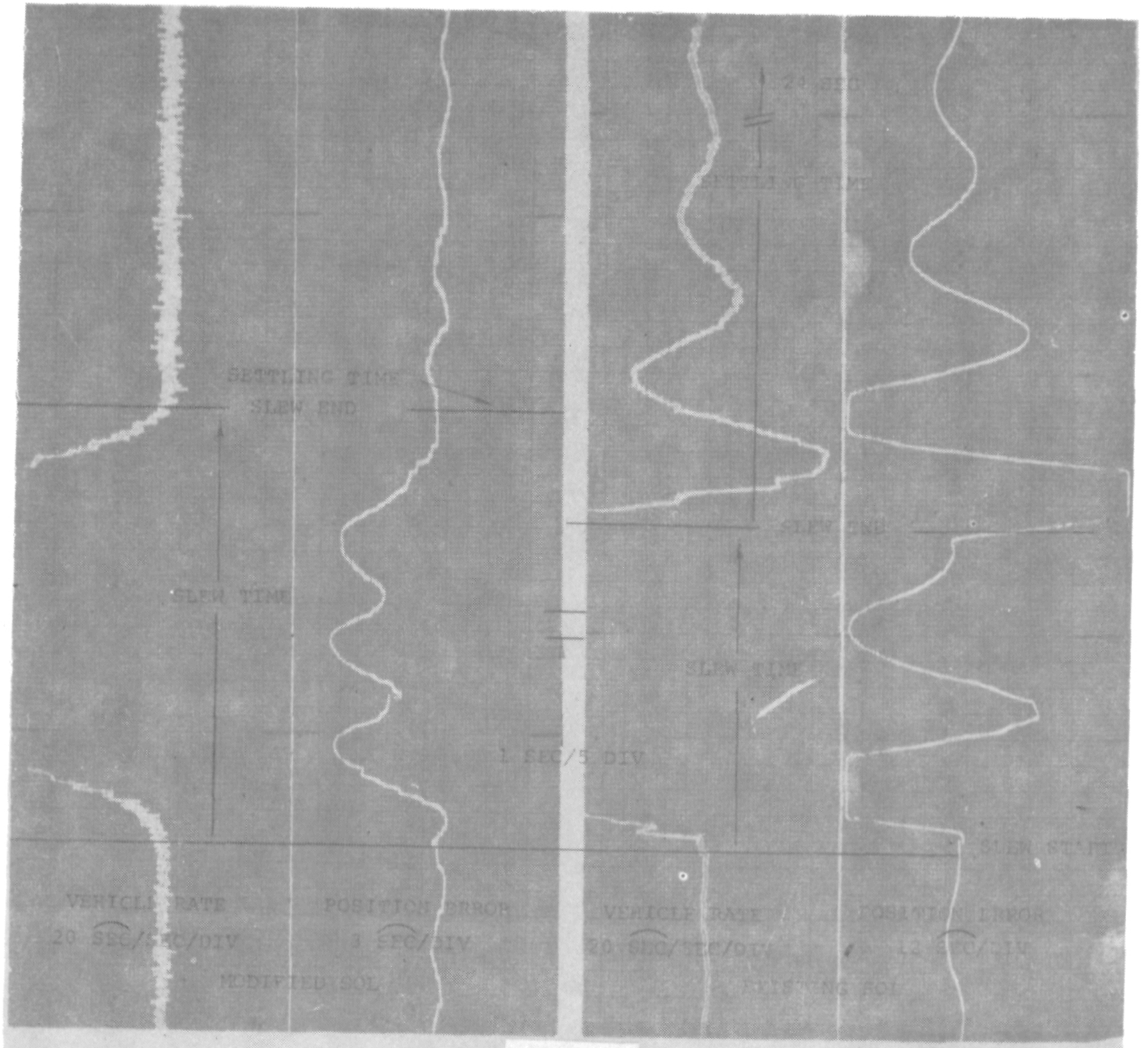
SETTLING TIME
SLEW END
SLEW TIME
1 SEC/5 DIV
VEHICLE RATE
20 SEC/SEC/DIV
POSITION ERROR
3 SEC/DIV
MODIFIED SOL
24 SEC
SETTLING TIME
SLEW END
SLEW TIME
VEHICLE RATE
20 SEC/SEC/DIV
POSITION ERROR
12 SEC/DIV

Figure 14