A SUMMARY REPORT ON THE TANDEM PROPELLER SUBMARINE PROGRAMS

Prepared for:

Office of Naval Research
Mathematical Sciences Division
Department of the Navy
Washington, D.C.

By: Roy S. Rice, Jr. and
William G. Wilson

Contract No. Nonr-3659(00)
CAL Report No. AG-1634-V-4
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FOREWORD

This report is a summary of the work performed to date by several contractors on the Tandem Propeller Submarine program. It covers the time period from October 1961 to June 1964 and was prepared at the request of Cdr. F. R. Haselton, scientific officer on the program for the Office of Naval Research. A final technical report on the current phase of work now being performed by the CAL under Contract Nonr-3659(00) (FBM) will be issued in August 1964.

ABSTRACT

The Tandem Propeller Submarine concept provides a new and useful means for the propulsion and control of underwater vehicles. The principles of operation are briefly outlined and the results of feasibility studies by several contractors are reviewed. A description of the equipment used in a free-running model test program together with discussions of some qualitative results of these tests is presented. A bibliography of reports relating to the program is included.

This report has been reviewed and is approved.

Edwin A. Kidd
Assistant Department Head
Transportation Research
Department

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1. INTRODUCTION

In October 1961, the Office of Naval Research initiated studies of a novel submarine configuration employing two large hub-to-tip diameter ratio propellers with variable pitch blades to provide propulsion and control forces. This configuration, which was invented by Cdr. F. R. Haselton of the Office of Naval Research, is called the Tandem Propeller Submarine (TPS). It offers special advantages in low and moderate speed maneuverability previously unobtainable with conventional submarine controls, as well as potential for deeper submergence, improved safety with control failure, and quieter operation. The particular features of the concept which make these improvements possible are described in Section 2 of this report.

The Tandem Propeller Submarine study program, which is sponsored by the Special Projects Office, is part of the Advanced Sea Based Deterrence research program. These studies involved work by a number of contractors on various aspects of the TPS leading to the development of a model system suitable for free-running tests and demonstrations. Brief descriptions of the results of these analytical and experimental programs are given in Section 3 of this report, and Section 4 contains information on system equipment and discussions of results for the free-running tests. Finally, some conclusions on feasibility of the TPS concept and recommendations for supplementary investigations are given in Section 5.

This summary report, which is intended primarily to provide information on the background and current status of the TPS studies, will be followed by a final technical report, to be published at the end of the current CAL program, covering the quantitative results of the free-running model tests.

2. THE TANDEM PROPELLER SUBMARINE CONCEPT

Conventional submarines utilize fixed-pitch propellers for the generation of propulsive force and variable attitude control planes for obtaining maneuvering moments. As with all lifting surfaces of this type, control effectiveness depends on the vehicle having sufficient forward speed to generate the forces needed for useful control. Thus, conventional submarines have no maneuverability from this source at zero speed and reduced maneuverability at low forward speed. In addition, maneuvering capability is limited to coupled pitch-dive and yaw-sideslip motions.

The TPS overcomes these restrictions by utilizing a combination of two counter-rotating propellers of large hub-to-tip diameter ratio design equipped with a number of variable-pitch blade elements. The tandem propeller propulsion and control concept is based on the ability of the blades to produce both axial and transverse forces as functions of the instantaneous blade angle magnitude. The utilization of two circumferential propellers located forward and astern of the center of gravity of the vehicle makes possible the generation of combinations of forces and moments to produce independent motions in six degrees of freedom. A brief description of how this is accomplished is given below.

The TPS propeller develops thrust in much the same way that a conventional screw propeller does. Its uniqueness lies in its ability to generate transverse forces, that is, forces lying in a plane perpendicular to the submarine longitudinal axis. An understanding of how these transverse forces are produced is obtained from simple blade-element theory. A greatly simplified explanation will be given below. The hydrodynamics of the generation of transverse forces in an actual propeller are complicated by the effects of propeller-induced inflow, swirl, propeller/hull interaction, cascading of blades, partial stall, etc., all of which are ignored in this simple treatment.

Under conditions of steady straight-ahead flight, the forces acting on a single blade are as shown in Figure 1. When the blade pitch is fixed, the angle of attack, α_0 , is constant and lift and drag do not vary as the blade rotates around the hull. Each blade produces a steady thrust, T, and a steady tangential force, F. The resultant roll moment caused by the tangential force, F, is cancelled by the counter-rotating aft propeller. Since F is constant, it produces no average transverse force when resolved along y (and z) and integrated over one revolution of the propeller.

If a cyclic variation (for example, a cosinusoid of one cycle per revolution) is superimposed upon the cyclic blade pitch, the instantaneous angle of attack becomes $\alpha_0 + \Delta\alpha \cos\sigma$ (σ is the azimuth angle of the blade). This produces an instantaneous change in the blade lift force given by $\Delta L = qAC_{L_\alpha}\Delta\alpha \cos\sigma$, and a corresponding change in the drag force, $\Delta D = qAfC_{L_\alpha}^2 \left[2\alpha_0\Delta\alpha\cos\sigma + \Delta\alpha^2\cos^2\sigma\right]$, due entirely to induced drag. Since the tangential force, F, is obtained by resolving the lift and drag forces along the tangent to the blade hub, the change in tangential force, ΔF , will contain two terms that are proportional to ΔL & ΔD and of the same form. The forces of interest are the transverse forces. These are obtained by taking the components of F, or ΔF , along y and z, that is (ignoring signs):

$$Y = \Delta F \cos\sigma \qquad\qquad Z = \Delta F \sin\sigma$$

These expressions for Y and Z are instantaneous forces. The average force per blade is obtained by integrating over one revolution of the propeller. If this is done for the Y force, integrals of the form

$$\frac{1}{2\pi}\int_0^{2\pi} qAC_{L_\alpha}\Delta\alpha\cos^2\sigma . d\sigma \quad \text{, due to } \Delta L$$

and

$$\frac{1}{2\pi}\int_0^{2\pi} qAfC_{L_\alpha}^2\left[2\alpha_0\Delta\alpha\cos^2\sigma + \Delta\alpha^2\cos^3\sigma\right] d\sigma$$

due to ΔD, will result. The $\cos^3$ integral vanishes, but the remaining integrals produce a Y-force proportional to $\Delta\alpha$ (a modulation of the lift force) and to $\alpha_0\Delta\alpha$ (a modulation of the induced drag force). Z is zero, but if a sine-cyclic pitch change had been chosen instead of a cosine-cyclic pitch change, Y would be zero.

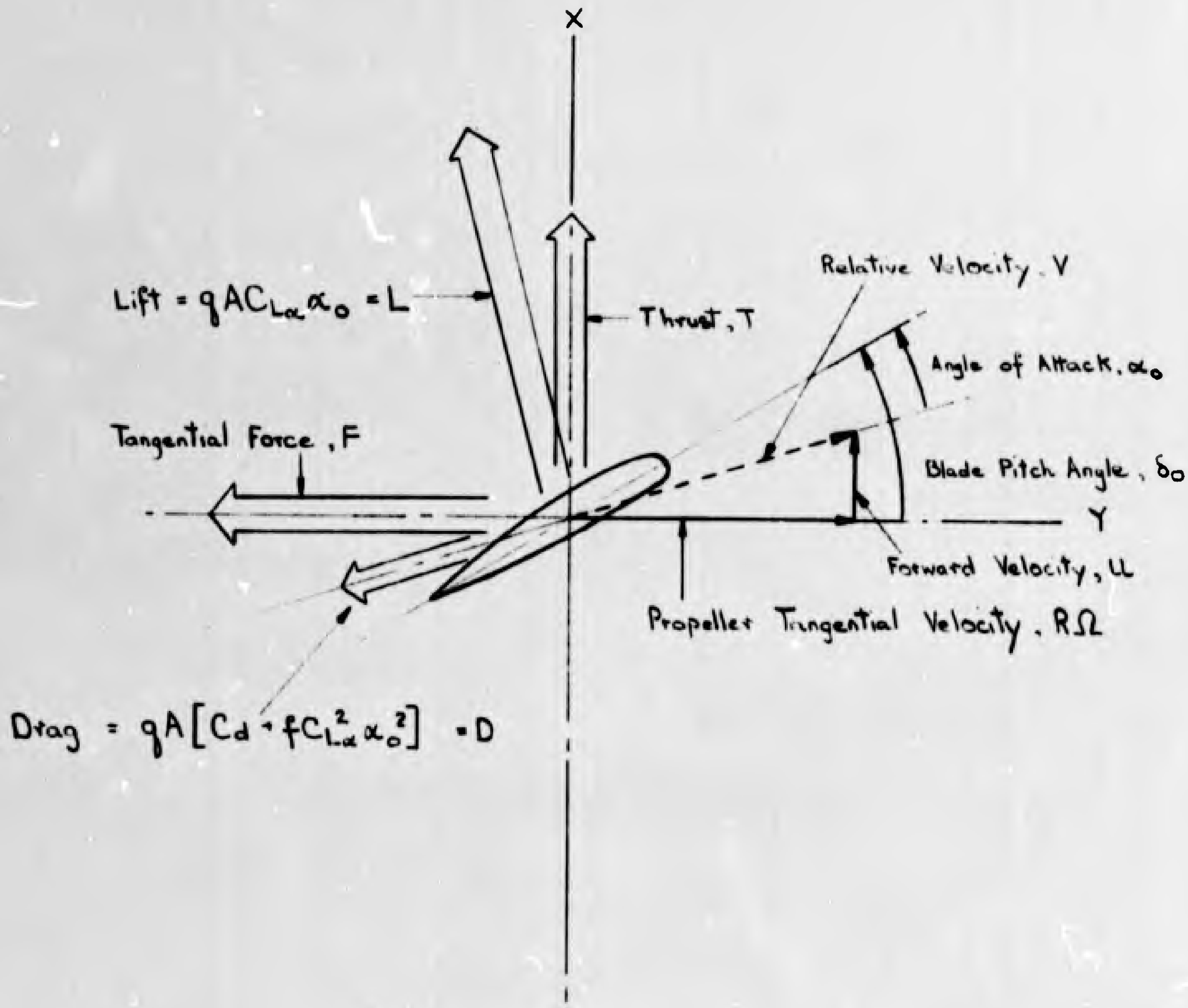

Figure 1: SINGLE BLADE, FORWARD PROPELLER.
View looking radially inward along Z axis.

When summed over N blades, the lift/drag modulation produces relatively small thrust perturbations, ΔT , and small undesired moments. The desired effect, however, is the production of a transverse propeller force. The magnitude and the direction of the transverse force can be controlled by adjusting the magnitude and phase of the cyclic pitch change (equivalent to the sum of a sine-cyclic and cosine-cyclic change). By adjusting the cyclic pitch of the forward and aft propellers, aiding or opposing, pure body side force or body vertical force and pure pitching or yawing moments can be obtained.

These combinations of cyclical pitch variations can be coupled with different conditions of the collective pitch angles on the two propellers to produce three separate operating modes of varying maneuverability for the TPS. The modes are:

1. Double-thrusting (or sprint) in which the blade collective pitch angles on the two counter-rotating propellers are oriented to give aiding thrusts for high forward speed. Pitch and yaw motions are controlled by cyclical pitch angle variations.

2. Single-thrusting (or cruise) in which the aft propeller produces thrust as before and the fore propeller, which is non-rotating in this mode, has the blades pitched collectively as necessary to counteract the aft propeller roll moment. In this mode, which would be used for long range operations, rotational motions of the submarine would be controlled in the same way as in double-thrusting.

3. Counter-thrusting (or hover) in which the blade collective pitch angles on the counter-rotating propellers are oriented to give opposing thrusts. Some net thrust still can be obtained to permit moderate fore-aft velocity, and combinations of transverse forces resulting in independently controllable motions in the other five degrees of freedom are available.

In addition to improvements in submarine maneuverability, the TPS concept offers other advantages for both tactical and utility vehicles. Since control forces are generated by the propellers, there is no need for external appendages such as bow and stern planes. Stern access is available for equipment such as detection devices or weapon launchers. Improved noise characteristics should be realized because propeller rotational speeds are low and because blade loadings can be kept small. By utilizing wet motors of inside-out construction for the propeller drives (i.e., the motor rotating element is outside the stator and operates completely immersed in sea water), rotating shaft seals can be eliminated. Mobility of tandem propeller equipped vehicles is not lost even if one propulsion unit becomes inoperative.

3. BACKGROUND

In this section, the results of earlier analytical and experimental studies of several important features of the TPS will be briefly reviewed and the evolution of the system used in the free-running model test program will be described.

The first year's program consisted of concurrent studies of three separate and broad aspects of the tandem propeller concept -- (1) propulsion and pitch-changing equipment requirements, (2) manual controllability of the vehicle, and (3) hydrodynamic and stability and control characteristics. The submarine configuration selected for these studies was essentially that of a SSN 594-class submarine without control planes (however, some differences in specific characteristics of the configuration were used in the various studies). Nominal values for the important characteristics of the assumed configuration are:

Length:	270 feet
Length/diameter:	8.5
Propeller speed:	50 rpm
Displacement:	4300 long tons
Metacentric height:	1.0 foot

The conclusions presented in the following discussions should be understood to refer to this or similar vehicles only.

Investigations of the hydrodynamics and stability and control were carried out by the Cornell Aeronautical Laboratory. Results of this program are given in References 1a and 1b. Emphasis was placed on developing a working theory of the hydrodynamics of the TPS and on investigating its stability and control requirements. The important results of the study leading to a general conclusion of feasibility are:

1. The increased control effectiveness of the TPS over conventional submarines at low speed is obtained at a sacrifice in high-speed control effectiveness.

2. The TPS configuration becomes dynamically unstable in pitch and yaw at relatively low forward speed, but direct axis feedback stabilization can be employed effectively to avoid these instabilities.

3. Single propeller operation (aft propeller) provides useful capability for trimming the vehicle and for stable maneuvering at speeds up to 15 knots.

4. At zero forward speed, counter-thrusting, collective pitch is required to produce pure transverse forces.

The referenced reports contain detailed information on the development of the six-degree-of-freedom equations of motion for the TPS, derivation of its stability derivatives, and stability augmentation methods as examined in an analog computer simulation study.

Studies of propulsion machinery and blade pitch-changing mechanisms are described in Reference 2. This work was performed by the Electric Boat Division of General Dynamics with assistance from both the General Electric Co., and the Elliot Co., on propulsion motor design. The important conclusions from this study are:

1. The use of flooded, inside-out electric motors as main drives for the propellers is considered feasible. Synchronous motors offer advantages resulting in lower weight and size for the propulsion machinery over squirrel-cage induction motors.

2. Electrical blade pitch-changing mechanisms appear to be more promising than either mechanical or hydraulic systems, although the advantages over mechanical systems are slight.

3. Control signal transmission to the blade actuators can be accomplished with a radio frequency communication link.

4. Power transmission to the rotor can be accomplished by rotating transformer techniques similar to wound-rotor induction motors.

Many details of design studies leading to these recommendations are fully described in the reference. These include consideration of environmental requirements, control and propulsion power requirements, bearing design, and pitch-changing mechanism details.

The results of the first year's study by Minneapolis-Honeywell on the manual controllability of a tandem propeller submarine are reported in References 3a and 3b. In brief, efforts on this program centered about analytical and experimental studies on the ability of a single human operator to handle the multiple control problem and on the requirements of the control display. Based on tests of a number of subjects, it was concluded that, with practice, a pilot could control a vehicle of the tandem propeller submarine's characteristics using compensatory tracking techniques with an analog type of display having a "roadway in the sea" presentation. Preliminary results of work on control stick design, display characteristics, operator/equipment compatibility, and operator learning are described in detail in the references.

Under subcontract to Honeywell on this phase of the effort, the Norden Division of United Aircraft Corporation examined control information display problems. This work is also reported in Reference 3b. It includes a comparison of instrument and pictorial displays in relation to the TPS requirements and a description of the contact analog method of presentation.

The Netherlands Ship Model Basin was employed to examine certain hydrodynamic characteristics of large hub-to-tip diameter ratio propellers preliminary to the design of a TPS model. The specific purposes of this work were to investigate the efficiency and power requirements of such propellers with cyclic pitch control. Results of the theoretical studies are reported in References 4, 5, and 6. An experimental program involving a single shrouded propeller mounted on a body of revolution was conducted during this period to obtain quantitative information on propeller performance.

From these tests, which are reported in Reference 7, it was concluded that the attainable thrust efficiency for these propellers is of the same level (about 70 percent) as for conventional screw propellers, and that the generation of transverse forces is significantly affected by forward speed and collective pitch variations.

During the second year of the program, studies on manual controllability and hydrodynamics and control were continued, and the development of a model suitable for the experimental evaluation of the tandem propeller concept was initiated. Principal effort was pointed toward refining the feasibility studies of the earlier phase, and toward obtaining a better understanding of the requirements for a workable model system.

The Netherlands Ship Model Basin proceeded toward the design of a model TPS with replaceable center sections so that either a 13-1/2 ft. or an 18 ft. vehicle could be assembled with the same pair of propellers. The essential design features of the model were: aluminum hull of water-tight construction, use of direct current power for propeller and blade drives, and removable shrouds on both propellers. Other physical characteristics of the model are listed later in Section 4. Details of the design decisions and plans for captive model tests by NSMB are described in References 8a, 8b, and 8c.

The second year of the Honeywell program on manual controllability of the TPS produced firm conclusions on the design requirements for the control column and display unit. Much of the effort was devoted to experimental study of human operator control with an aim toward comparing pursuit and compensatory tracking techniques in this application, evaluation of a particular tracking symbol, determination of the need for display quickening, and evaluation of a version of a contact analog display built by Norden. The primary conclusions and recommendations resulting from this study are:

1. Satisfactory manual control can be obtained with a single operator six-degree-of-freedom control column in which the short radius control motions produce compatible vehicle motions in the three rotations and long radius control motions produce compatible vehicle motions in the fore/aft and lateral directions. Vertical translations are controlled by thumb wheel rotations.

2. A contact analog type of display combining a special perspective tracking symbol in an inside-out presentation of a pursuit tracking task offers certain advantages to operator performance.

3. Display quickening is recommended for tracking task performance improvement. A supplementary fore-aft display, in addition to the contact analog, is desirable for improving operator perception of fore/aft motion.

Reference 3c provides detailed information on the simulator studies leading to these recommendations, as well as suggestions for the design of an improved control input device.

The second year of the CAL program on hydrodynamics and stability and control of the TPS was directed toward increasing the range of applicability of the low-speed propeller theory developed in the first year's work. The revised hydrodynamic theory was then used to re-examine low-speed control of the TPS. Results and conclusions include:

1. Earlier hydrodynamic analyses are refined and extended to include the effect of cyclic pitch on propeller-induced inflow.

2. A study of the stabilizing effect of an aft shroud with the propeller absent indicates that a shroud alone has a negligible stabilizing effect on the TPS.

3. A method for providing independent roll control in the counter-thrusting mode is outlined, whereby propeller speed variations are used to supplement collective pitch variations.

4. Methods for reducing control coupling are presented and a preliminary all-speed control system is outlined.

Details of these analyses, including the results of an analog computer simulation study of the low-speed control problems of the TPS, are described in Reference 1c.

By the start of the third year, the imminent availability of the model placed strong emphasis on the development of captive and free-running test programs to establish TPS feasibility on firm experimental bases. An extensive program of captive model tests was therefore conducted by the NSMB upon completion of the model fabrication effort. Force and moment measurements were obtained for a wide range of values of the model variables:

forward speed
collective pitch angle
cyclical pitch angles
sideslip angle
propeller rotational speed.

The propellers were operated both singly and in pairs, and with and without shrouds. Preliminary results are reported in Reference 8a and its supplements; a final report on this work is expected to be published in June 1964.

Following the NSMB tests, the David Taylor Model Basin conducted a series of captive model tests on their planar-motion mechanism. The acquisition of control information specifically required for the free-running test program and the determination of the model stability derivatives were emphasized in this effort. The results of the program will be covered in detail in a report to be issued by DTMB within a few months.

The captive model test data resulting from both the NSMB and DTMB tests identified several significant hydrodynamic characteristics of the TPS model:

1. The orientation of the control force vector for a fixed cyclic pitch phase angle changes significantly with changes in cyclic pitch magnitude, collective pitch magnitude, and forward speed. These effects are apparent from comparisons of Figures 2, 3, and 4, which are plots of transverse force direction and magnitude for some typical operating conditions.

2. A cyclic pitch phase angle shift does not produce a simple equivalent rotational shift in the resultant transverse force. Thus, sail, surface, or bottom effects appear to be significant influences on the generation of propeller control forces.

3. Equivalent fore and aft propeller characteristics do not produce equivalent control forces even when counter-thrusting at zero forward speed. Thus, propeller/hull interactions also appear to be significant. Compare Figures 4 and 5.

4. Control force orientation does not appear to change significantly with changes in propeller rotative speed. This is shown in Figure 6, a plot of control force direction and magnitude for a particular cyclical pitch value as a function of propeller speed.

5. Fore and aft propeller control forces can be superimposed with negligible errors (at least for the aft propeller thrusting and the fore counter-thrusting at low forward speed). It therefore appears that propeller/propeller interactions are not significant.

6. At zero forward speed, the propeller is stalled for collective pitch angles above 30 degrees. Figure 7 shows propeller thrust coefficients for this condition as well as those for a forward speed of four knots.

7. Typical thrust and torque coefficients for a typical propeller operating condition are shown in Figure 8. The resultant propulsive efficiency curve (also shown) shows a significant range of advance coefficient ($\Lambda = \frac{u}{nD}$)* for which efficiency is above 65 percent.

Based on the results of the captive model tests scaled to a submarine 270 feet in length with fineness ratio of 6.8, a simple calculation for forward speed can be made.

For: propulsive efficiency = 65%
drag coefficient = .003**
wetted area = 26200 ft^2
available power = 15000 hp

the attainable forward speed is:

$$u = \left(2 \times \frac{HP \times 550 \times \eta}{S \times \rho \times C_D}\right)^{1/3} = \left(2 \times \frac{15000 \times 550 \times .65}{26200 \times 1.94 \times .003}\right)^{1/3}$$

$$= 41.3 \text{ ft/sec} = 24.5 \text{ knots.}$$

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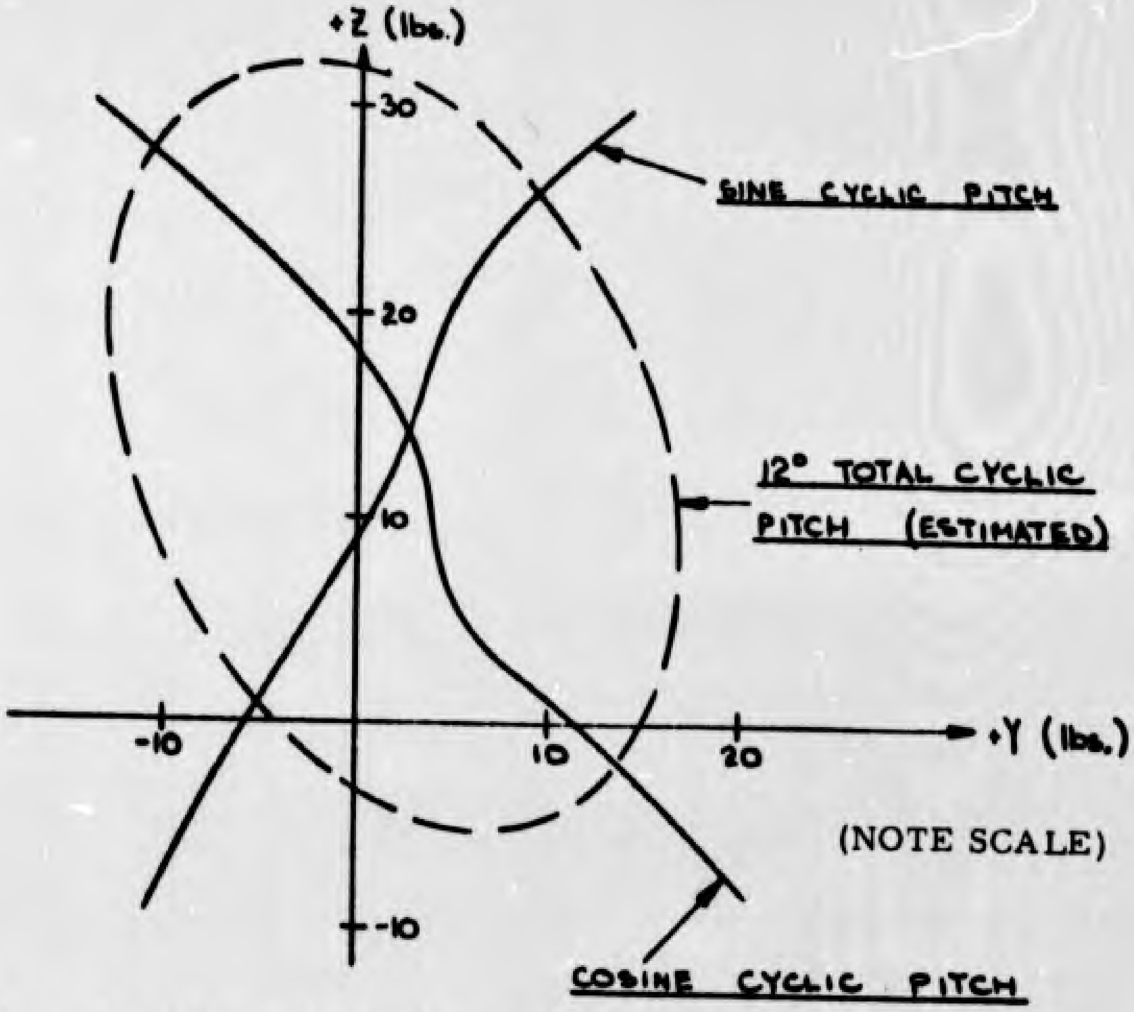
* where u is forward speed in ft/sec, n is propeller speed in rpm, and D is propeller tip diameter in ft.

** This is a mean value from a number of tests of the model, and does not include a Reynolds Number correction to full scale. This correction would tend to decrease the value of the coefficient.

The data from which Figures 2 to 8 were developed are typical of the preliminary results of the captive model test programs, and are applicable to vehicle designs differing only slightly from the model. The interactions of the several test condition variables result in considerable dispersion of the data, but general trends in the characteristics are faithfully shown in the curves. Evaluations of the significance of these variations will be made in the final technical reports covering these two experimental studies.



(NOTE SCALE)

Figure 2: **Aft Propeller Transverse Force Map**
(U = 4.5 Knots; Collective Pitch = 30°)
(Propeller Speed = 220 RPM)

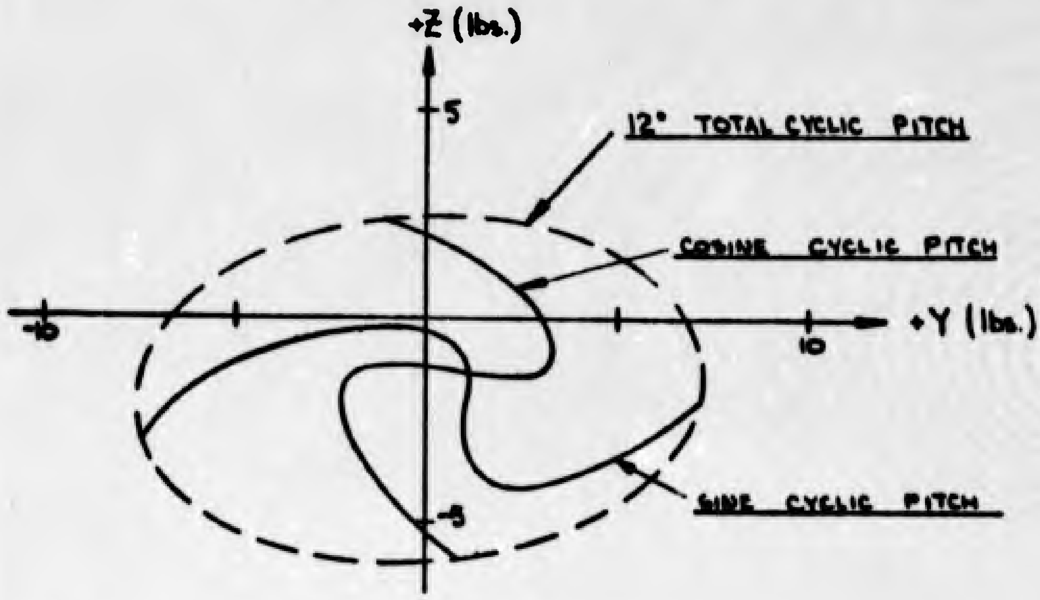


Figure 3: **Aft Propeller Transverse Force Map**
(U = 0; Collective Pitch = 15°)
(Propeller Speed = 220 RPM)

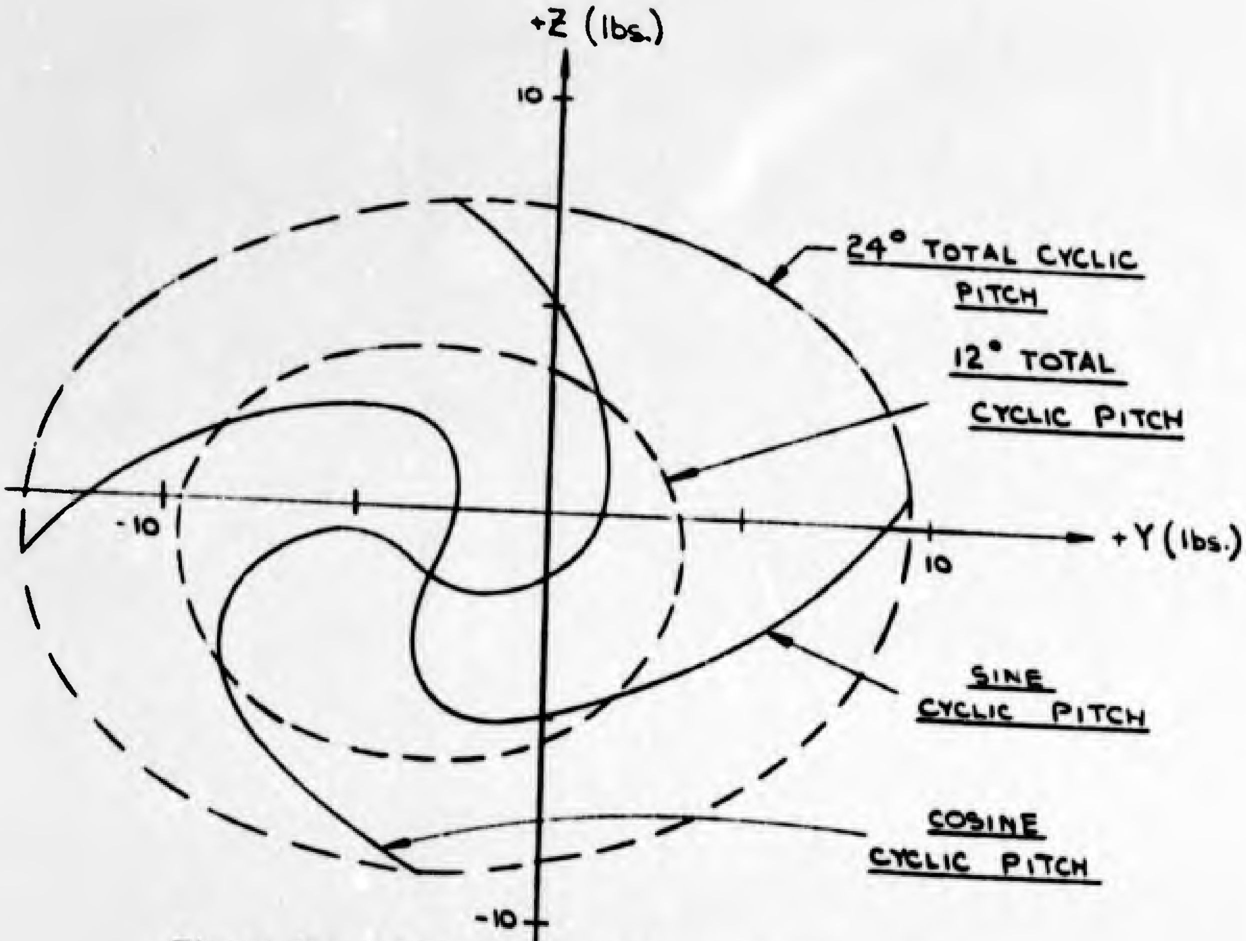


Figure 4: Aft Propeller Transverse Force Map
(U = 0; Collective Pitch = 30°)
(Propeller Speed = 220 RPM)

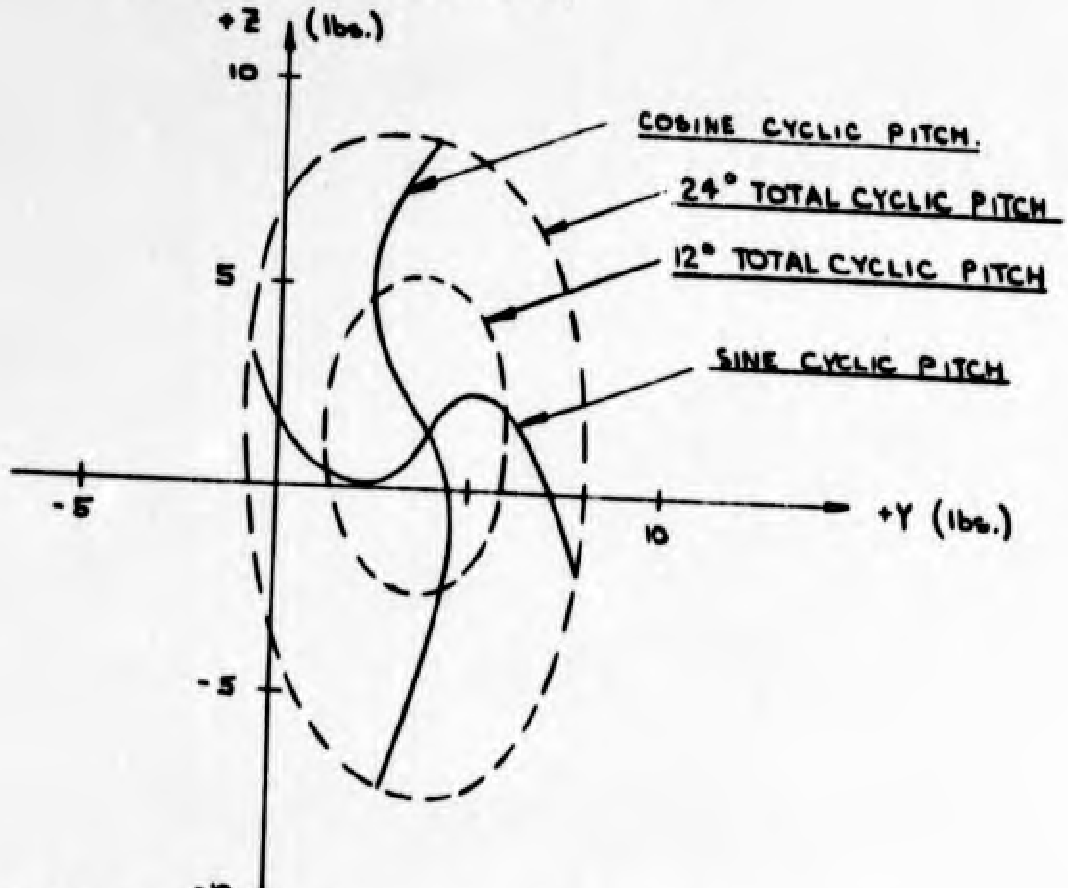


Figure 5: Fore Propeller Transverse Force Map
(U = 0; Collective Pitch = -30°)
(Propeller Speed = 220 RPM)

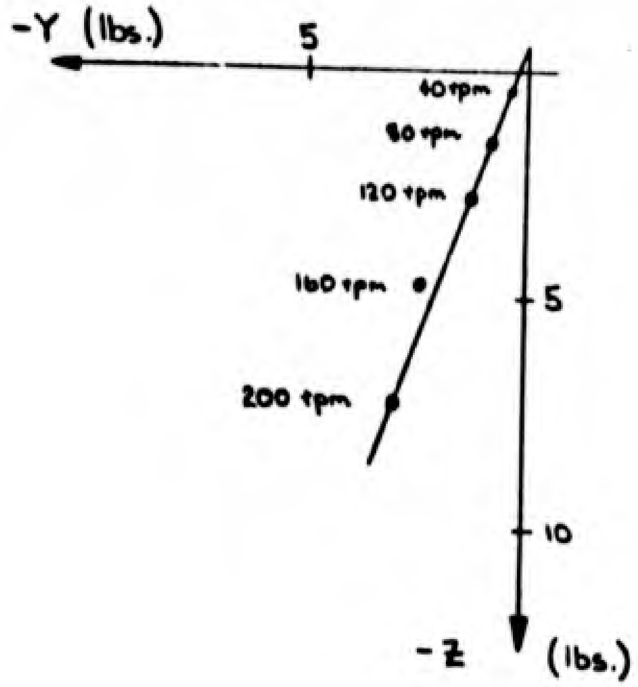


Figure 6: Aft Propeller Transverse Force Variation with Propeller Speed ($U = 0$; Collective Pitch = 30°) (Cosine Cyclic Pitch = 24°)

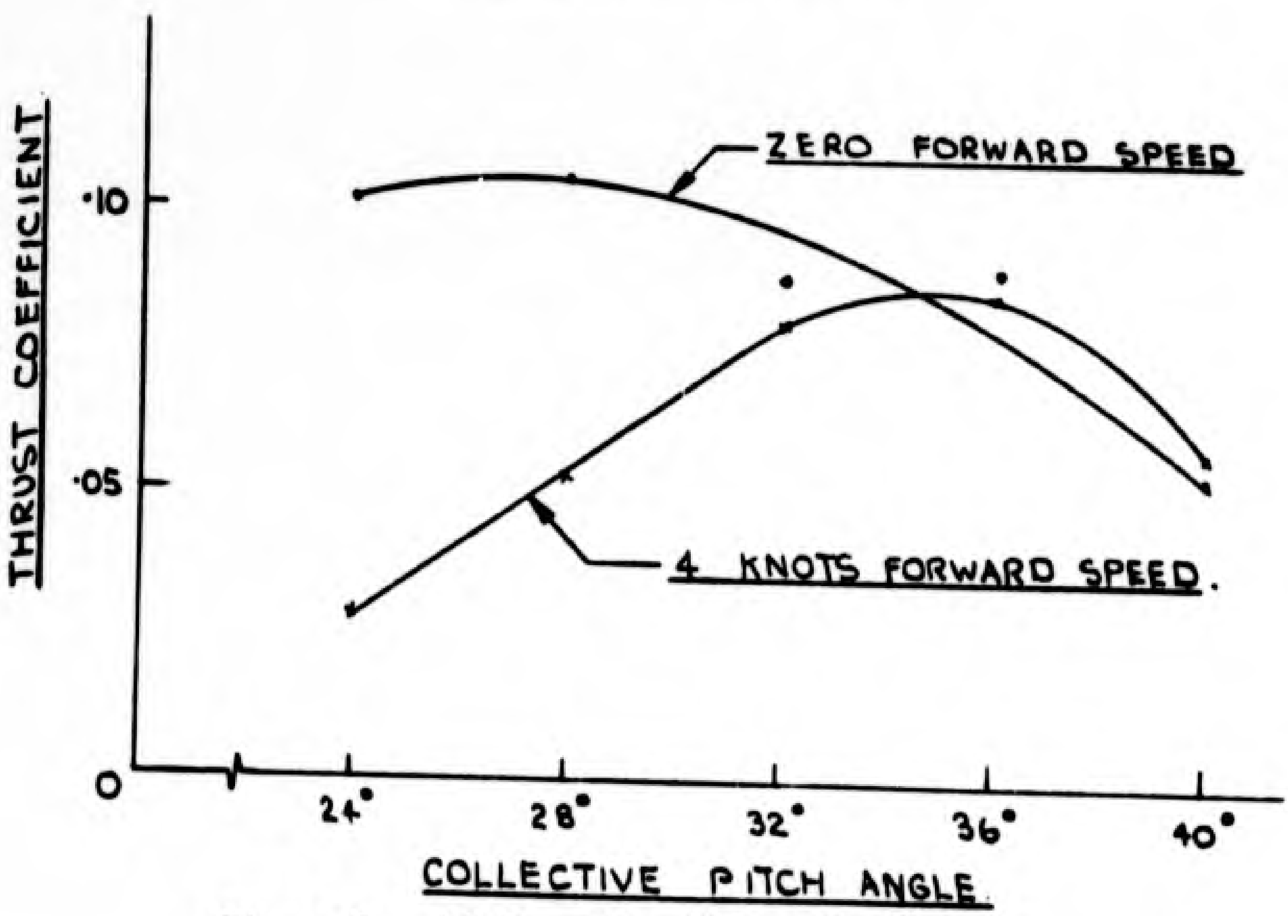


Figure 7: Aft Propeller Thrust Coefficient Variation with Collective Pitch Angle (Propeller Speed = 200 RPM)

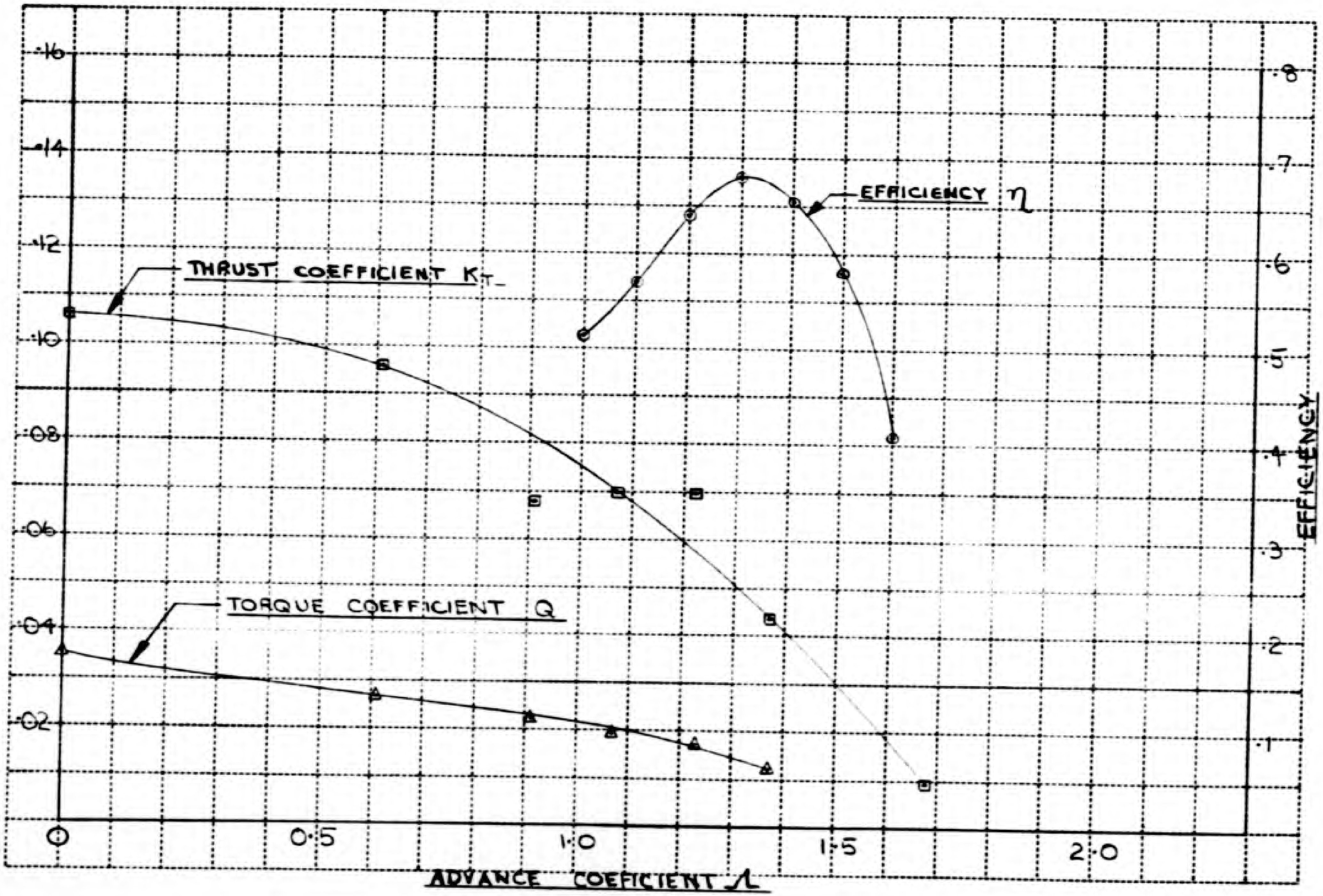


Figure 8: TYPICAL PROPELLER PROPULSION CHARACTERISTICS

4. FREE-RUNNING TEST PROGRAM

The free-running model tests were designed to bring together the results of the previous efforts in a system that would show the feasibility of the tandem propeller concept. Emphasis was placed on obtaining quantitative information from which to determine control system requirements for a vehicle of the model's configuration and qualitative evaluations of the suitability of single-operator control, and on demonstrating the maneuvering capabilities of the model in its counter-thrusting mode of operation.

Test Equipment

The system, as evolved for the free-running tests, is illustrated schematically in Figure 9. A short description of each of the important elements in the diagram is given below.

The 13-1/2 foot model was used for the free-running tests in essentially the same configuration as employed in the captive model tests. Its physical characteristics are listed below.

Length:	13.45 feet
Center of buoyancy:	5.95 feet from nose
Maximum hull diameter:	1.97 feet
Length/Diameter ratio:	6.83
Propeller tip diameter:	1.61 feet
Displacement:	1460 pounds
Propeller location -	
Fore:	1.51 feet from nose
Aft:	10.17 feet from nose
Blade characteristics -	
Number/propeller:	12
Chord:	.885 inches
Length:	1.77 inches
Description:	16 percent thickness, symmetrical
Collective pitch angle operating point (nominal):	30 degrees
Collective pitch angle range:	$\pm$ 10 degrees
Cyclic pitch angle range:	$\pm$ 25 degrees
Propeller speed (nominal):	200 rpm.

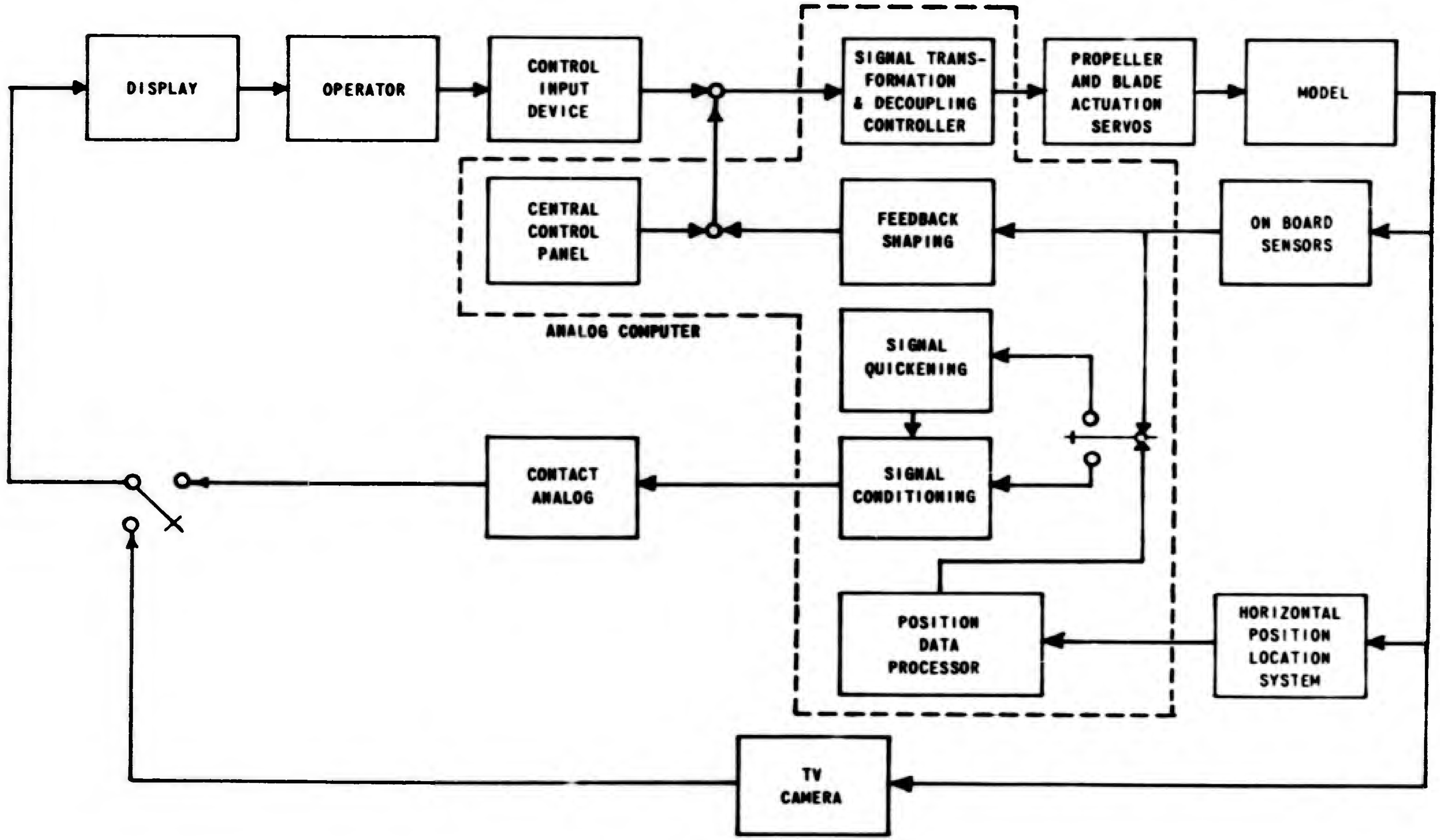


Figure 9 FREE-RUNNING MODEL SYSTEM BLOCK DIAGRAM

A photograph of the model is presented as Figure 10. The spines which appear near each of the propellers are merely for protection of the blades and have no noticeable hydrodynamic effect.

Motion-sensing instrumentation installed in the model consisted of: (1) three rate gyros for the measurement of angular rates of change about the three principal axes of the vehicle; (2) a vertical gyro for the measurement of pitch and roll angles with respect to a horizontal plane; (3) a free gyro pendulously mounted for the measurement of heading angle with respect to a reference direction in a horizontal plane; and (4) a depth indicator. All these instruments were used for data acquisition and display purposes; the rate gyro outputs and the roll angle information from the vertical gyro were also utilized in the stability augmentation system. See Figure 11.

In addition, an acoustic ranging system consisting of a model-borne transmitter, three accurately emplaced receivers, digital pulse-counting circuitry, a digital-to-analog converter, and analog computing circuitry was designed and built to provide horizontal position location information for data acquisition and control display. This system was based on, and utilized equipment from, a DTMB design to be used in the Model Basin's maneuvering and sea-keeping facility.* For this program, the count-to-distance converter was built to provide real-time location information as required by the contact analog system. An internal view of this unit is shown in Figure 12.

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* The DTMB equipment is described in David Taylor Model Basin Report 1594, A Model Tracking System for the DTMB Maneuvering Basin, by F. E. Frillman, September 1962.

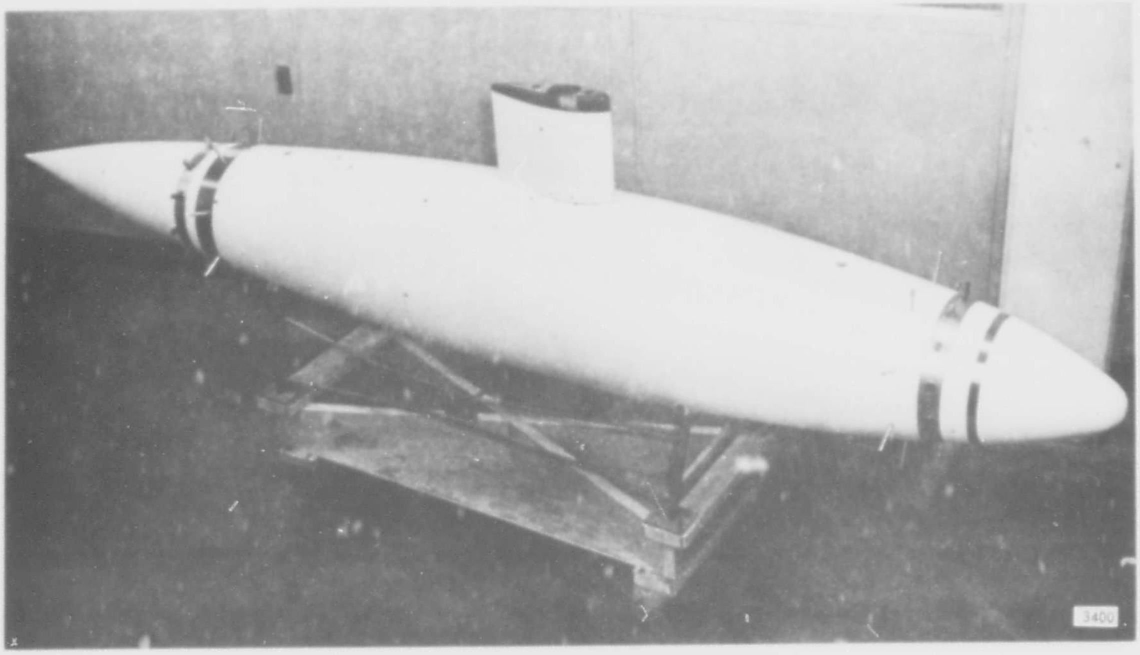

Figure 10 13-1/2 FOOT TPS MODEL

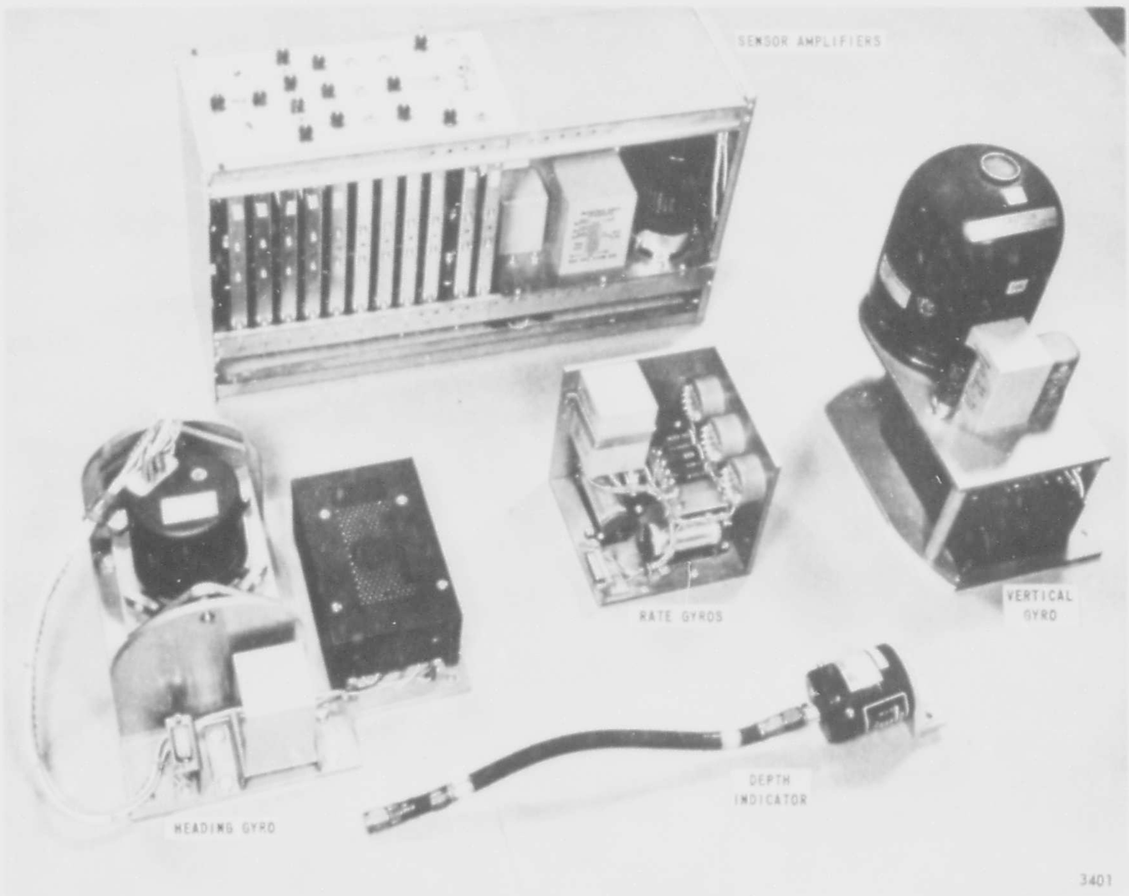

Figure 11 MODEL-BORNE INSTRUMENTATION

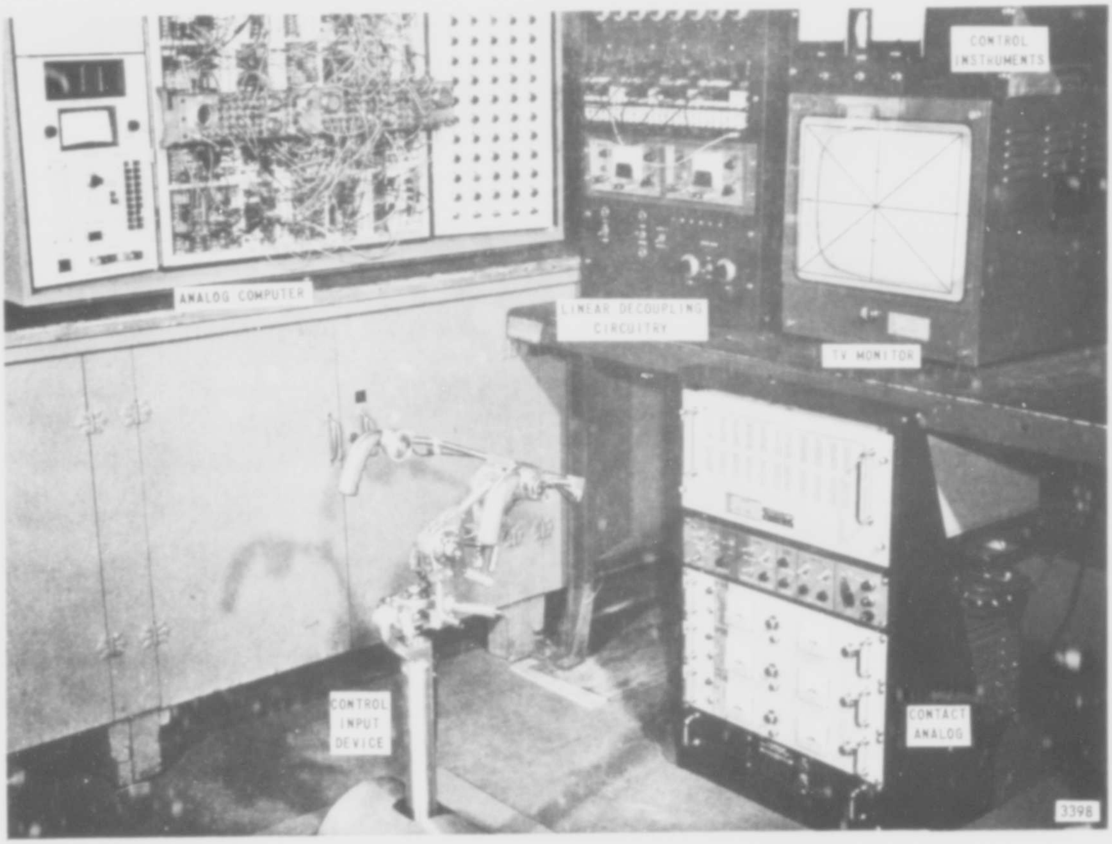

Figure 12 ON-SHORE CONTROL EQUIPMENT

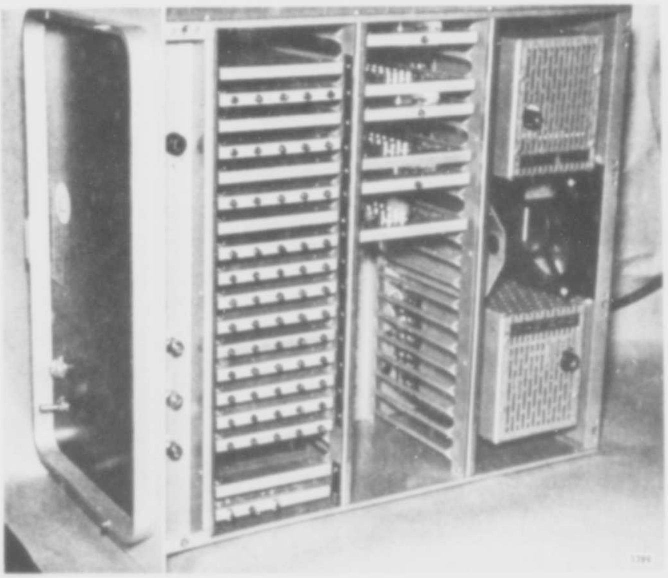

Figure 13 POSITION LOCATION SYSTEM CONVERSION UNIT

Closed-loop piloted demonstrations of manual controllability and model maneuverability were performed using primarily direct visual contact with the model. Provisions for indirect contact through utilization of the contact analog system and/or a model-mounted television camera were also available as shown in Figure 9. Model position and attitude information from the on-board instrumentation units and from the position location system are modified in a section of the analog computer for compatibility with the contact analog signal generator. Means for quickening this information are also provided in the computer. The processed video signal is then fed from the contact analog unit to the television monitor used for display. Elements of this system are shown in Figure 13.

The forward-looking television camera was mounted ahead of the sail and its associated control unit was mounted inside the model. The camera was specially modified for synchronization with the contact analog output to allow simultaneous display. The camera can also be operated alone.

The six-degree-of-freedom control input device, which is illustrated in Figure 14, is essentially an adaptation of the recommendations by Honeywell in Reference 3c on control column design. As shown in the illustration, motions of the control device are isomorphic with intended motions of the vehicle for all motions except vertical translation. For this case, the direction of motion of the thumb on either wheel produces compatible motion of the vehicle. Special mechanical details of the device include variable force-gradient and damping units in each degree of freedom, spring return to zero position, and zero position adjustment. Input commands are picked off from precision, infinite-resolution potentiometers on all six axes.

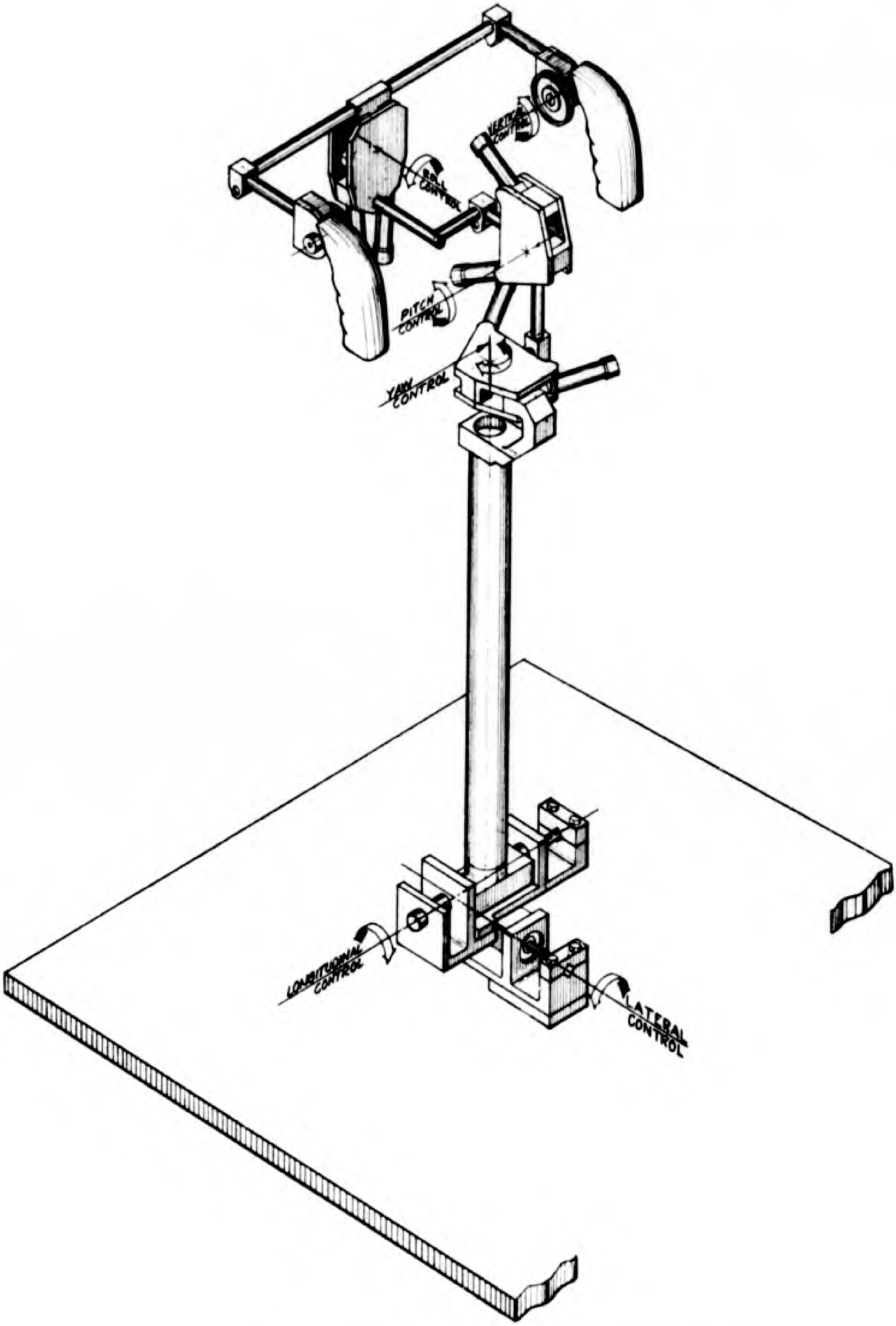

Figure 14 SIX DEGREE-OF-FREEDOM CONTROL INPUT DEVICE

AG-1634-V-4

For purposes of free-running tests, a simple flexible control system for the model was desirable for reasons of economy, and so that the inherent TPS model performance characteristics -- excluding the control system dynamics -- could be extracted from the test data. The model control system was therefore designed so that the control logic could be programmed on a small general purpose analog computer. A simplified block diagram of the control system is shown in Figure 15.

From left to right, the control system components and functions are as follows:

1. Command inputs from six-degree-of-freedom input device, or central control panel.

2. Summation of the command inputs with feedback from attitude, angular rate, and depth sensors. [In normal operation, only feedbacks from the three angular rates, $\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$, and from roll attitude, ϕ, were used.] The primary purpose of these feedbacks at low speed is to increase the stiffness in a given degree of freedom to coupled motions induced by a control command in a different degree of freedom. At high speed, these feedbacks are required for stability augmentation.

3. High gain amplifiers with limiters were included to provide essentially bang-bang operation. With single-valued control inputs, only two points (other than zero) on the control force "S" curves (Figures 4 and 5) are used, and control system complications required to follow the curves are avoided. The limiters were removed and the amplifier gain lowered for an alternative proportional control system.

4. The linear decouplers are summing amplifiers which transform the control input commands into the required cyclic and collective pitch and propeller speed inputs, e.g., the decouplers solve equations of the type:

$$\delta_{1f} = a_{11}\delta_M + a_{12}\delta_N + a_{13}\delta_Y + a_{14}\delta_Z$$

$$\delta_{2f} = a_{21}\delta_M + a_{22}\delta_N + a_{23}\delta_Y + a_{24}\delta_Z$$

The coefficients, a_{ij}, (potentiometer settings) were chosen so that single input commands gave, to the degree possible, "pure" vehicle responses (i.e., vehicle responses only in the commanded degree of freedom).

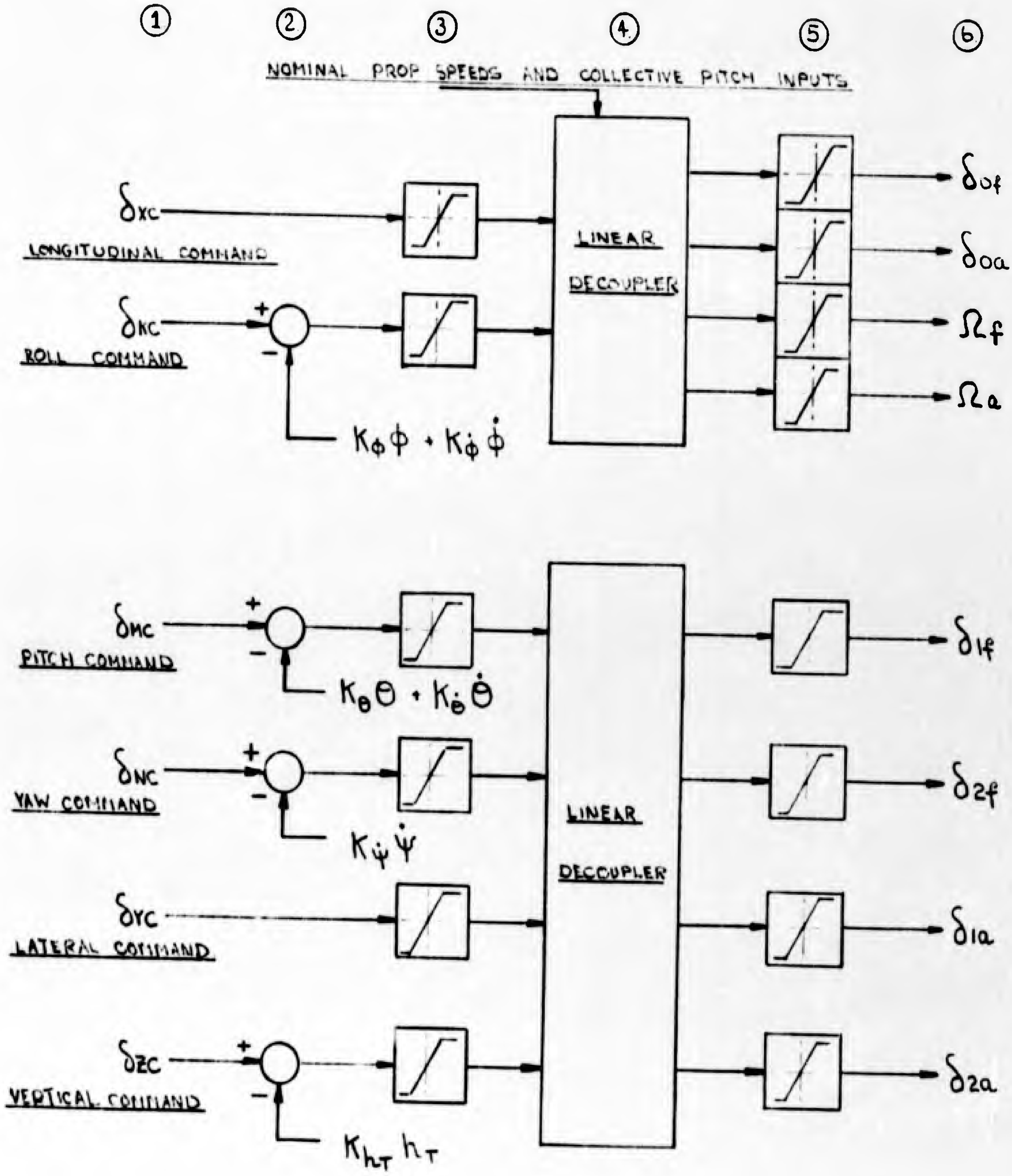

Figure 15: SIMPLIFIED CONTROL SYSTEM DIAGRAM

5. Output limiters were used to prevent the cyclic and collective pitch servos from hitting the actuator stops.

6. The vehicle control inputs included fore and aft collective pitch changes (δ_{0f}, δ_{0a}) up to $\pm$ 10^{o} about the nominal collective pitch (approximately 30^{o}), sine and cosine cyclic pitch changes (δ_{1f}, δ_{2f}, δ_{1a}, δ_{2a}) up to $\pm$ 25^{o}, and propeller speed changes (Ω_f, Ω_a) up to + 40 rpm about the nominal propeller speed (normally about 200 rpm).

The blade actuation servomechanisms are schematically diagrammed in Figure 16. The six servos (one collective pitch and two cyclic pitch controls on each propeller) are electrically identical. Each consists of a variable-gain balanced-output DC amplifier driving the coils of a split-field DC motor, which is integrally housed with a gear reducer and DC tachometer. Position information feedback is obtained from a geared single-turn potentiometer and rate damping of the closed loop is provided by the tachometer. Mechanical energy transfer to the blades is achieved through use of a sliding wobble-plate mechanism. The rotational motions of the servos are converted to linear motions by slip clutch-connected lead screws which drive a cylindrical race axially for collective pitch changes and tilt this race for cyclical pitch changes. The blades are coupled to the race through individual crank and roller assemblies.

The propeller drive control system is shown schematically in Figure 17. Power is supplied to the two DC drive motors for each propeller from amplidyne generator pairs, and speed control is exercised through a simple tachometer feedback servomechanism system. Mechanical coupling from the motors to the propeller consists of two step-down gear meshes linked by a flexible coupling.

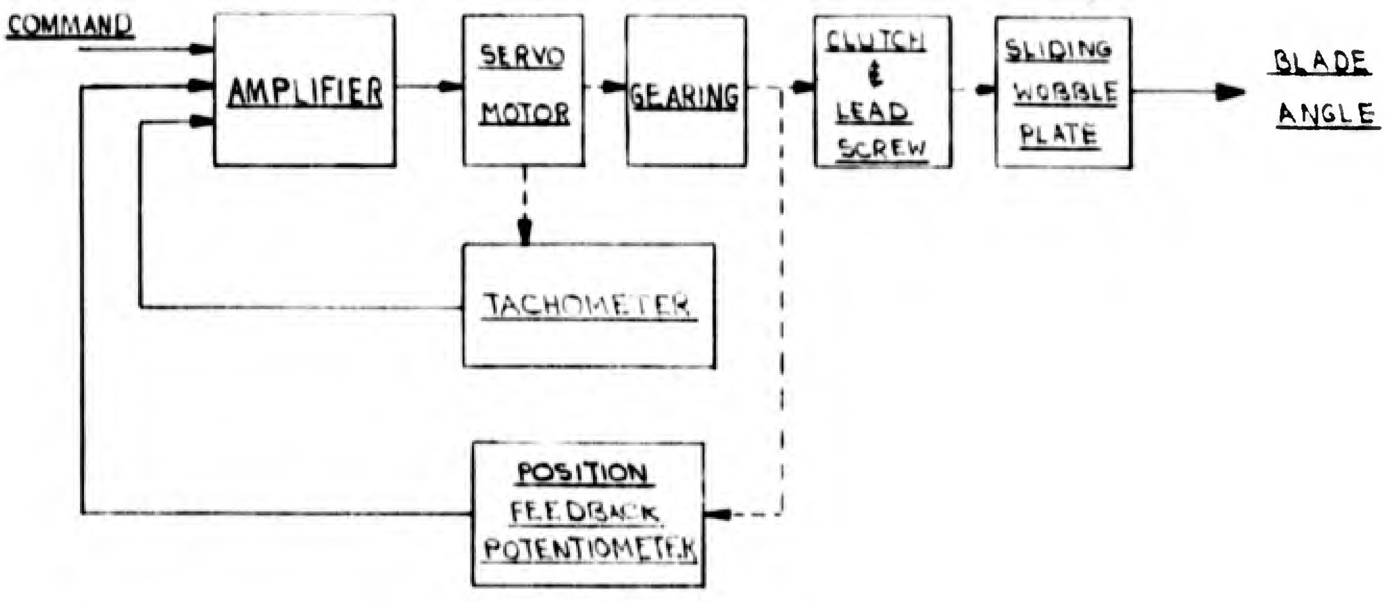

FIGURE 16 : BLADE ANGLE CONTROL SERVO.

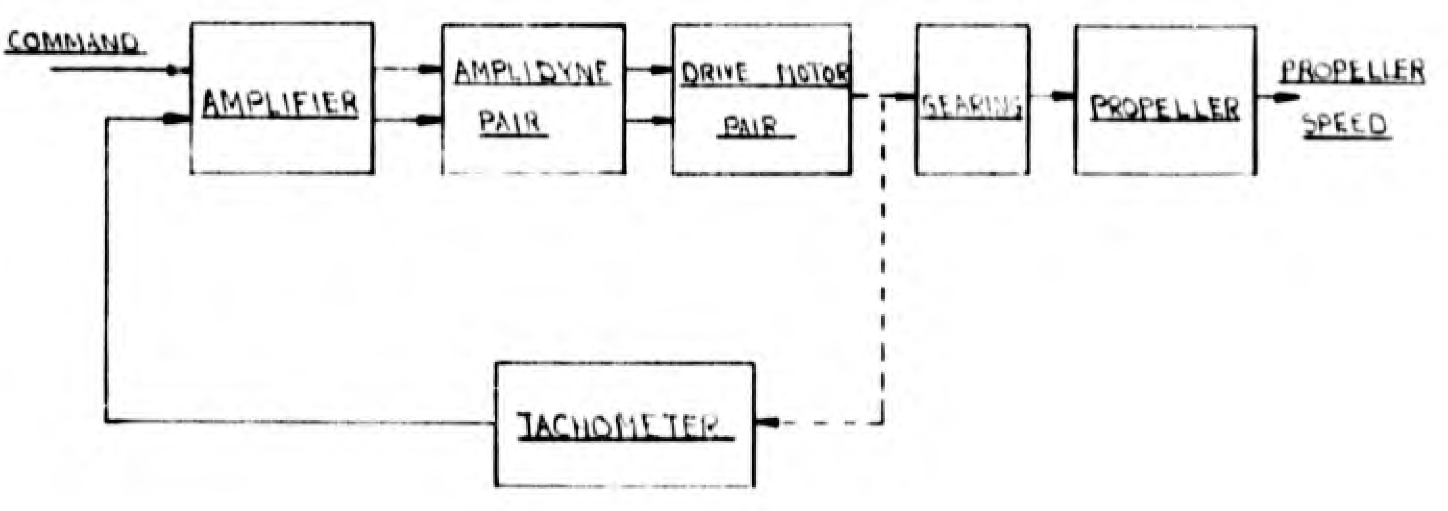

Figure 17: PROPELLER DRIVE CONTROL

Free-Running Tests

In March and April of this year, free-running model tests of the TPS were carried out at the David Taylor Model Basin. Preliminary checkout, adjustments, and recorded test runs were completed in the Circulating Water Channel where the model could be carefully observed. Later, free-running tests were performed at an outdoor test pond -- a 25-foot deep pentagon over 100 feet on a side. Some specific results of this test program follow.

1. Records of model responses. Separate six-degree-of-freedom time histories of the model to single-degree-of-freedom step control inputs were recorded. Control inputs were commanded while the model was hovering in the counter-thrusting mode of operation. Data were obtained with and without control feedbacks. These data will be used to develop a simple mathematical representation of the dynamics of the model and to quantitatively evaluate performance criteria. For example, the maximum translational and rotational rates for the model in the counter-thrusting mode are as follows:

longitudinal velocity:	1.2 ft/sec
lateral velocity:	0.5 ft/sec
vertical velocity:	0.5 ft/sec
rate of pitch change:	6 degrees/sec
rate of heading change:	6 degrees/sec
rate of roll change:	6 degrees/sec.

2. Model controllability. The controllability of the model with a single operator was qualitatively established. In the counter-thrusting mode of operation, novice operators with only a few minutes of instruction and a few minutes of practice were able to control the model without difficulty. Operators with prior knowledge of the control characteristics of the vehicle or with previous piloting experience of a similar nature (helicopters, TPS simulators), and with a quarter- to a half-hour of learning time, were able to perform complicated and precise maneuvers with the model. For example, they were consistently able to place the nose or tail of the model within six inches of a specified point on a target in the water.

3. Partially disabled operation. Several equipment failures during the free-running model tests provided opportunities for the assessment of partially disabled operation:

a. The loss of a collective pitch servo with the collective pitch near the nominal position reduced fore and aft velocity capability and decreased roll stability. The model remained controllable even by a novice operator.

b. The loss of a cyclic pitch servo prohibited one pure translation and decreased the rate of change of attitude about one axis. With some difficulty, the operator could still position the vehicle as desired.

c. A collision with an unknown object resulted in the uniform bending of all forward propeller blades approximately 30 degrees. The operator was unable to detect any change in vehicle controllability.

d. The loss of the position feedback reference to all six servos left the vehicle completely uncontrollable. The propeller rotation was stopped until the system failure was repaired.

e. The loss of feedback signal from an attitude or rate sensor increases coupling and thus increases the difficulty of the operator's task.

4. Operation without visual contact. In addition to operating with direct visual contact with the model, precision maneuvers were performed with the operator watching a TV monitor presentation of a picture taken by a forward-looking TV camera on the model. A voice link with a direct observer was supplied for safety. As the pilot had some difficulty perceiving range on the monitor, distance from objective was also given orally. Errors of only a few inches were consistently achieved while rendezvousing with a target point.

The model was operated briefly via the contact analog (Conalog) display in the Circulating Water Channel, where maneuvering space was severely limited. In the outdoor facility where operation with the Conalog was intended, interference noise in the acoustic ranging system distorted the Conalog inputs. As direct visual contact proved to be a satisfactory means for demonstrating maneuverability and scheduling was tight, time was not taken to make the system operative.

5. Near surface operation. Operation near the surface with the aft propeller thrusting and the fore propeller counter-thrusting proved difficult. If one propeller breaks the water surface, the thrust and torque are reduced and the unbalanced forces and moments tend to roll the model and to push it further out of the water, accentuating the problem. It is likely that reversing the thrusts of both propellers (so that the fore propeller is thrusting and the aft counter-thrusting) would relieve the problem.

6. Automatic depth keeping. Depth feedback was added to provide position control in depth. Because of mechanical stiction in the depth sensor, which required a differential pressure equivalent to about six inches of depth before the output changed, these tests were of only limited success. The model did, however, maintain depth to within the six-inch difference between maximum sensor error and commanded depth, while performing moderate maneuvers in the other degrees of freedom.

7. Double-thrusting operation. The model was tested briefly in the double-thrusting mode of operation. Forward propeller blades were adjusted for nominally $+30^{\circ}$ collective pitch and forward cyclic pitch inputs were reversed in sign. The submarine was controllable, diving and turning at command; but cable drag, lack of braking capability, and limited maneuvering space did not permit extensive evaluation of this operating mode.

8. Proportional control. In addition to the bang-bang mode, which was used for normal operation, the control system could be switched to a proportional mode with reduced cyclic pitch range. It was anticipated that the proportional mode would be suitable for precision maneuvers where large control forces are not required. However, significant control couplings were introduced and the proportional mode was judged inferior to the bang-bang mode.

5. CONCLUSIONS AND RECOMMENDATIONS

The feasibility of the tandem propeller concept for propulsion and control of undersea vehicles has been established. A program for the design and development of a self-contained, manned submersible utilizing tandem propellers should therefore be initiated.

Investigations to date have been generally limited to a single TPS design. Fundamental work remains to be done to utilize the full potential of the tandem propeller concept and to permit optimum tandem propeller designs for a variety of operational requirements. Among the more prominent investigations which will be required are:

1. A generalized propeller theory for large hub-to-tip diameter propellers with variable pitch blades should be developed. Present CAL and NSMB hydrodynamic theory should be revised and augmented for better agreement with captive test data. The resulting theory should be reduced to a form that permits optimum design of tandem propellers for specified performance indices for a range of vehicular configurations.

2. Additional captive model tests should be carried out to supplement the present data. New captive tests should be devised that include investigation of basic configurational changes in propeller and hull designs, as well as extension of test conditions in order to establish optimal blade/propeller/hull combinations for specific applications. Particular emphasis should be placed on appropriate inclusion of scaling law effects.

3. Propeller drive and pitch-changing mechanisms should be developed for various tandem propeller applications. Full exploration of the TPS concept for deep submergence operations requires early development of the inside-out wrap-around wet motor. The associated blade pitch-changing mechanisms, including the means for information and power transfer to the actuators, should be simultaneously developed.

4. Control systems for tandem propeller submarines should be analyzed for a broader range of application than has been accomplished to date. Available captive test data and hydrodynamic theory should be applied to a computer simulation suitable for the comparison of several types of control systems for TPS operation. Some types of control logic which are appropriate for TPS control, and should be included in these studies, are: fixed parameter analog, pre-programmed digital, and adaptive.

5. The acoustic properties of the tandem propeller concept should be analyzed and/or tested. Information on the noise-producing characteristics of large hub-to-tip diameter ratio propellers, particularly with regard to expected improvements resulting from low blade loading and low rotational speeds, is essential to proper evaluation of the usefulness of the tandem propeller approach for tactical submarines.

6. Vehicle controllability requirements should receive additional study. Particular attention should be given to displays and input devices in relation to vehicular configuration, application, and mission with special emphasis on compatibility with TPS mobility and maneuvering capabilities.

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