Tandem Propeller Concept of Submarine Propulsion and Control

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Under U. S. Navy sponsorship, analytical and experimental studies of a new means of propulsion and control of undersea vehicles, the tandem propeller system (TPS), have been performed. The utilization of a pair of large hub-to-tip diameter ratio propellers with collective and cyclical pitch blade control for developing independent six-degree-of-freedom vehicle motion is discussed. It is shown that the nonlinear transverse force characteristics of the propeller require formulation of a specialized control system in order to take advantage of this capability at low forward speed. Results of a free-running model test program are presented to illustrate the performance of a tandem propeller vehicle with the selected mode of control. It is concluded that the concept is feasible and that it provides a means for obtaining marked improvement in the low speed maneuverability of underwater craft.

Introduction

THE purpose of this paper is to give a brief discussion of a new concept of submarine propulsion and control and to describe the results of its application in a free-running model test program.

The technique, which is sometimes referred to as the Haselton propeller, is called the tandem propeller concept in this paper. It has been the subject of a number of analytical studies during the past four years leading to the design and construction of the self-propelled model used in the test program. The results of these studies are briefly described in Ref. 1.

Prior to the free-running tests discussed herein, the model, which was built by the Netherlands Ship Model Basin (NSMB), was used in captive model experiments by both NSMB and the David Taylor Model Basin. The results of these tests, together with results from experiments by NSMB on a single propeller model,[2] constitute the primary information on propulsion performance and transverse force-generating capabilities of tandem propellers on which the vehicle control system discussed herein is based. Special attention is given to the low speed maneuvering capabilities of tandem propeller vehicles in this paper; both Refs. 1 and 2 contain additional information on the propulsion characteristics of these propellers. It should be pointed out also that this discussion is concerned with a single hull-propeller configuration. Other designs using the concept which appear to offer improved maneuvering performance are currently under study.

Discussion

The tandem propeller concept of submarine propulsion and control is based on the ability of a propeller, equipped with suitably programable variable pitch blades, to develop useful transverse forces in addition to the axial forces that are normally obtainable from marine propellers. As shown in Figs. 1 and 2, the application of the concept utilizes a pair of large hub-to-tip diameter ratio counterrotating propellers. Propeller blade pitch is variable collectively (all blades assume the same angle) and variable cyclically (the pitch of the individual blade varies according to some periodic waveform as the blade rotates about the hull). The utilization of two propeller, one located forward and one astern of the vehicle's center of gravity, makes it possible to produce control forces in three degrees of freedom, control moments in three degrees of freedom, or combinations of these forces and moments. A brief explanation of how this is accomplished is given below.

Axial forces (thrust) are developed in a TPS propeller in much the same way as in a conventional variable-pitch screw propeller, and thrust magnitude is controlled in a similar manner by varying collective pitch angle and/or propeller speed. The associated tangential forces in a TPS, acting through long moment arms because of the wraparound propeller construction, result in the generation of a significant roll moment by each propeller. The equalization of these moments, which must be directed oppositely in the two propellers to maintain roll stability, is accomplished by counterrotation. With variable collective pitch capability only, no useful transverse forces are developed because the tangential components of the blade forces are symmetrical with respect to any set of axes in the propeller plane and therefore cancel (Fig. 3).

However, this symmetry is not maintained with the superposition of cyclic pitch variations on the collective pitch angle. In this case, both the axial force and the tangential force on each blade are modulated as the blade rotates around the hull. The total propeller thrust (the sum of the axial force components of all blades) is only weakly affected because the increases in axial force produced by some blades are counterbalanced by decreases in others (Fig. 3). Total roll moment also is influenced only slightly. The principal effect is that the summation of the tangential forces now produces a nonzero total transverse force. It is this force that provides the unique maneuvering capabilities of the vehicle.

In order to generate a transverse force in any desired direction, the cyclic pitch-changing period must be capable of being selectively phased with respect to vehicle axes. This can be accomplished in a phasing mechanism that provides independently controllable sinusoidal blade angle variations indexed

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with respect to the horizontal and vertical axes. The total blade pitch at any location around the hull is then equal to the algebraic sum of the collective pitch angle and sinusoidal and cosinusoidal cyclic pitch components.

Combinations of cyclical pitch variations can be coupled with different combinations of the collective pitch angles on the two propellers to produce three separate operating modes of varying maneuverability.

1) The double-thrusting mode is that in which the blade collective pitch angles on the two counterrotating propellers are oriented to give aiding thrusts for high forward speed. Independent control of the other five degrees of freedom is possible also, but, because of the large hull forces that can be generated at high speed with a hull angle of attack, vertical and lateral translations are performed more effectively through coupled pitch-dive and yaw-sideslip motions, in the manner of a conventional submarine.

2) The single-thrusting mode is that in which the after propeller operates as double-thrusting to produce thrust, and the blades of the forward propeller, which is nonrotating in this mode, are pitched collectively as necessary to counteract the after propeller roll moment. This mode, which resembles normal screw-propelled submarine operations more closely than the others, allows coupled pitch-dive and yaw-sideslip motions in maneuvering.

3) The counterthrusting mode is that in which blade collective pitch angles on the two propellers are oriented to give opposing thrusts. Some net thrust still can be obtained to permit moderate forward-after velocity. In this mode, independently controllable motions are available in all six degrees of freedom. The control capability in this mode is one of the major advantages of the concept.

A simplified linear theory for determining the propeller forces has been derived from blade element theory. This method neglects the effects of propeller-induced inflow, swirl, propeller-hull interactions, blade interactions, partial stall, etc. Force magnitudes predicted by this method agree reasonably well with test data, but force orientations, particularly at low vehicular forward speeds where the neglected flow phenomena are significant, are not predicted adequately by such a simplified theory. In a later section of the paper where control system considerations are discussed, various characteristics of the available propeller forces as determined by test will be described in some detail, but the point to be emphasized here is only that useful transverse forces and moments are in fact generated as envisioned in the concept. The adjunct to the existence of these forces and moments is their controllability in producing desired vehicle motions. Two hydrodynamic considerations influence controllability to a significant degree; these are instability and cross-axis coupling.

Instability is a potential problem for the TPS because streamline bodies of revolution without external surfaces are unstable at high forward speeds. However, stability may be induced in the TPS by adding motion feedbacks to the control system. A comprehensive study utilizing analog computer simulation of the nonlinear motion equations has confirmed the stabilizing effects of motion feedbacks on the TPS.

Two types of coupling are of interest: motion coupling and control coupling. Motion coupling exists when vehicle

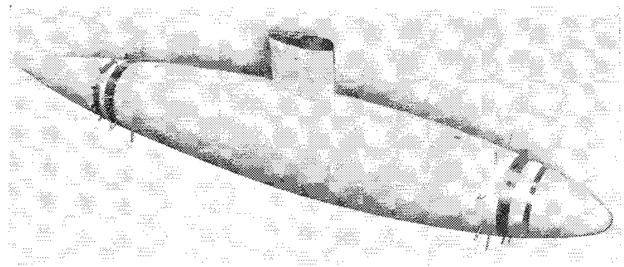

Fig. 2 $13\frac{1}{2}$-ft-TPS model.

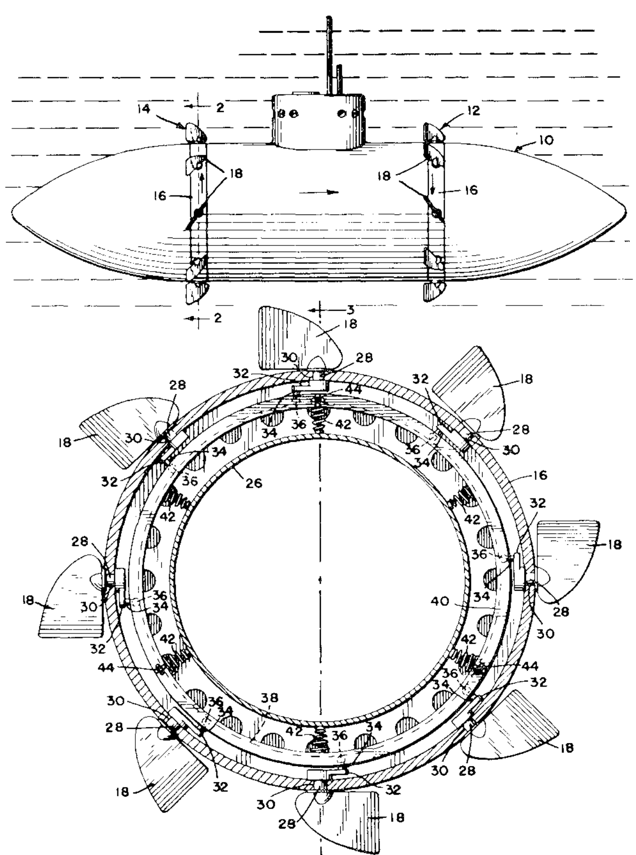

Fig. 1 Tandem propeller patent application.

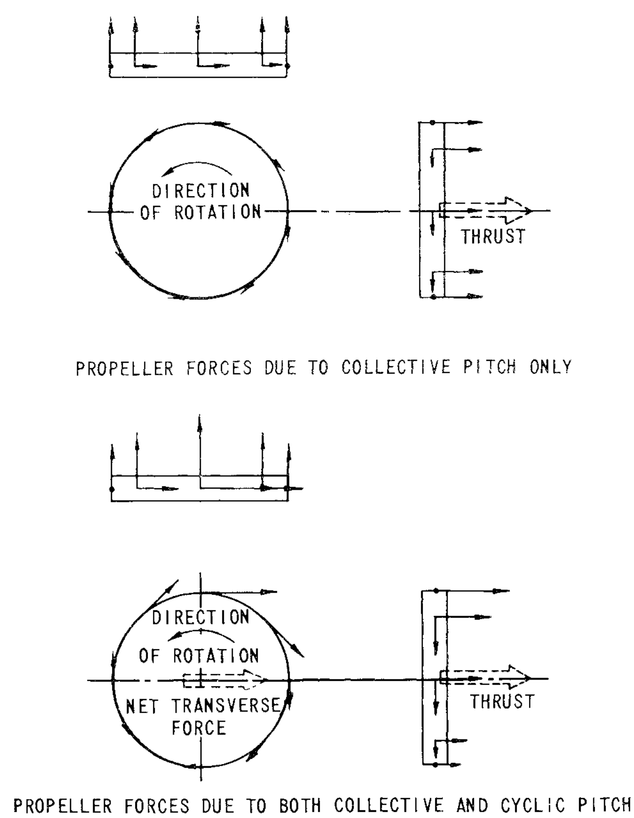

Fig. 3 Propeller forces.

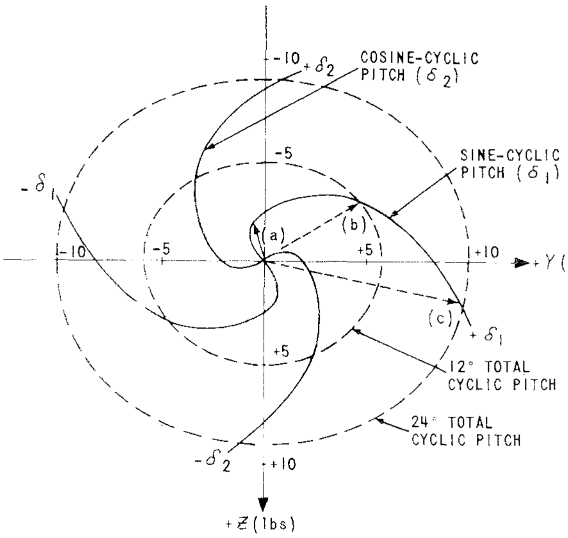

Fig. 4 Zero forward speed after propeller transverse forces.

motions in one degree of freedom induce motions in other degrees of freedom. Control coupling exists when a control command produces a force or moment along or around body axes other than the desired axis. Motion coupling does not appear to be a problem for the TPS. As mentioned in the description of TPS operating modes, the motion coupling induced by hull angles of attack can be used for improved TPS maneuverability at high speed. It is therefore expected that TPS operation at speed will be similar to that of conventionally controlled submersibles. However, if it is desirable to proceed on a course that does not coincide with the hull longitudinal axis, the TPS six degree-of-freedom control force and moment generating capability can be utilized to decouple motion couplings.

For purposes of discussion it is convenient to separate control coupling into that which exists between the two longitudinal degrees of freedom (roll and forward-after translation) and that which exists among the four transverse degrees of freedom (pitch, vertical translation, yaw, and lateral translation). Control coupling, which occurs between longitudinal and transverse degrees of freedom, is relatively minor.

In the single and double thrusting modes of TPS operation, both roll and foreward velocity are controlled by variations on the forward and after blade collective pitch angles, δ_{0f} and δ_{0a}. First-order linearized control equations are as follows:

$$X_c = + X_{\delta_0 f}\delta_{0f} + X_{\delta_0 a}\delta_{0a}$$

$$K_c = - K_{\delta_0 f}\delta_{0f} - K_{\delta_0 a}\delta_{0a}$$

X_{δ_0} and K_{δ_0} are the partial derivatives of propeller generated thrust and roll moment with respect to the propeller collective pitch angle, evaluated at a trim collective pitch angle and forward speed. Since $X_{\delta_0 a}$ is approximately equal to $X_{\delta_0 a}$ and $K_{\delta_0 f}$ is approximately equal to $K_{\delta_0 a}$, it is apparent that these equations are linearly independent of collective pitch; hence, both forward-after translation and roll rotation can be controlled independently.

In the counterthrusting mode of operation, the form of the control equations remains the same, but the partial derivatives of the thrust and roll moment for the forward propeller are evaluated for a negative value of trim collective pitch. $X_{\delta_0 f}$ remains approximately equal to $X_{\delta_0 a}$, but $K_{\delta_0 f}$ is approximately equal to $-K_{\delta_0 a}$, i.e., the sign of $K_{\delta_0 f}$ is reversed. Therefore,

$$X_c \cong X_{\delta_0 a}(\delta_{0f} + \delta_{0a}) \qquad K_c \cong -K_{\delta_0 a}(\delta_{0f} + \delta_{0a})$$

These two equations are linearly dependent on collective pitch; hence, another control input is required to provide independent control of both roll attitude and longitudinal translation. Propeller speed variation fulfills this requirement. With the addition of this input, the linearized control equations become

$$X_c = + X_{\delta_0 f}\delta_{0f} + X_{\delta_0 a}\delta_{0a} - X_{\Omega f}\Omega_f + X_{\Omega a}\Omega_a$$

$$K_c = - K_{\delta_0 f}\delta_{0f} - K_{\delta_0 a}\delta_{0a} + K_{\Omega f}\Omega_f - K_{\Omega a}\Omega_a$$

where X_Ω and K_Ω are the partial derivatives of propeller generated thrust and roll moment with respect to the propeller speed Ω.

For modest control input variations, the coefficients of these equations remain near enough constant so that proportions of collective pitch angle and propeller speed variations can be selected which essentially will produce decoupled thrust forces and roll moments.

The transverse control forces and moments generated by the tandem propellers differ in both magnitude and orientation as functions of not only cyclic pitch magnitude, but also of collective pitch magnitude, propeller location, propeller speed, and forward speed. However, the equations representing the TPS force and moment generation at high forward speed are essentially linear for small perturbations about some operating condition. The transverse moment and force generation can thus be represented, in general, by the following equations:

$$\begin{bmatrix} M_c \\ N_c \\ Y_c \\ Z_c \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} \delta_{1f} \\ \delta_{1a} \\ \delta_{2f} \\ \delta_{2a} \end{bmatrix}$$

where δ_{1f} and δ_{1a} are the forward and after propeller sinusoidal components of cyclic pitch, and δ_{2f} and δ_{2a} are the cosinusoidal components. The control coefficients a_{ij} are fixed for a given value of collective pitch and advance ratio.

All that is required of a control system to decouple these equations and provide the proper proportions of forward and after sine and cosine cyclic pitch for a desired control force or moment is to program the inverse of the coefficient matrix in the control computer. That is,

$$\begin{bmatrix} \delta_{1f} \\ \delta_{1a} \\ \delta_{2f} \\ \delta_{2a} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & b_{34} \\ b_{41} & b_{42} & b_{43} & b_{44} \end{bmatrix} \begin{bmatrix} M_c \\ N_c \\ Y_c \\ Z_c \end{bmatrix}$$

where

$$[B] = [A]^{-1}$$

At low forward speeds the transverse control forces and moments generated by the tandem propellers are not linear, and a linear transformation is not sufficient for effective decoupling of the control forces and moments. A plot of a typical locus of the transverse control force as a function of cyclic pitch magnitude is shown in Fig. 4. The coordinates are Y, the lateral force magnitude, and Z, the vertical force magnitude. The locus of transverse force vectors for fixed collective pitch and zero forward speed with fixed cyclic pitch phase angle and varying cyclic pitch magnitude are shown in solid lines that are hereafter referred to as S curves. These S curves are labelled sine cyclic pitch and cosine cyclic pitch. The locus of transverse forces for fixed cyclic pitch magnitude and varying cyclic pitch phase angle are shown by the dotted ellipses. The inner ellipse is for 12° cyclic pitch amplitude and the outer ellipse is for 24° cyclic pitch amplitude.

If the sine cyclic pitch S curve of Fig. 4 is followed out toward the right from the origin, it is seen that at about 4° cyclic pitch the transverse force a is about 2 lb in magnitude and oriented between the negative Y and negative Z axes. As the cyclic pitch magnitude approaches 12°, the transverse force b has increased to about 5 lb and has rotated past the negative Z axis. At 24° cyclic pitch the transverse force c is nearly 10 lb in magnitude and has rotated more than 90° past the positive Y axis. Although the nonlinearities are significant, the most important characteristic to note is that, within the restrictions of maximum capability, transverse forces or moments of any magnitude and orientation can be generated. It is the function of the control system to provide the proper combination of cyclic pitch angles for producing the desired magnitude and direction of these forces and moments. Three alternative control logic techniques for providing this capability are as follows: 1) a nonlinear transformation that provides the proper proportion of cyclic pitch inputs for all desired operating control force and moment combinations, 2) a feed-back control technique (perhaps adaptive) to alter the proportions of the control inputs automatically as some function of comparative measurements of vehicle motions and commanded vehicle motions, and 3) a nonlinear control system that does not require continuous control variations over the range of cyclic pitch.

Although each of the techniques has certain disadvantages, any of the three techniques, or combinations of these techniques, are suitable alternatives for a TPS control system.

For free-running tandem propeller model tests, a control system that incorporates both methods 2 and 3 was chosen largely because of its relative simplicity and flexibility. A simplified block diagram of this control system is shown in Fig. 5.

The control system components and functions are identified by number 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. 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 to provide essentially bang-bang operation. With single-valued control inputs, only two points (other than zero) on the control force S curves are used, and control system complications required to follow the curves are avoided; 4) linear decouplers that transform the control input commands into the required cyclic and collective pitch and propeller speed inputs; 5) output limiters to prevent the

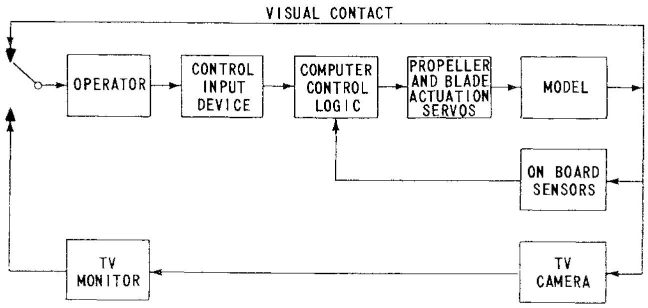

Fig. 6 Free-running model system block diagram.

cyclic and collective pitch servos from hitting the actuator stops; and 6) vehicle control inputs to accommodate forward and after collective pitch changes (δ_{0f}, δ_{0a}) up to ±10° about the nominal collective pitch (approximately 30°) sine and cosine cyclic pitch changes (δ_{1f}, δ_{1a}, δ_{2f}, δ_{2a}) up to ±25°, and propeller speed changes (Ω_f, Ω_a) up to ±40 rpm about the nominal propeller speed (normally about 200 rpm).

Since the counterthrusting mode of operation provides the best conditions for examining TPS maneuverability and controllability, a free-running model test program, with operation in this mode, was conducted in the spring of 1964. The general arrangement of the system for these tests was as shown in the block diagram, Fig. 6. The model was controlled from shore by a single operator who, for the most part, had visual contact with the vehicle although a model-mounted television camera permitted operation without direct visual contact as well. Submarine motions were commanded by means of a six-degree-of-freedom input device. Electrical signals from potentiometers on the intput device were transferred to a general purpose analog computer. The computer was programed to calculate the collective and cyclic pitch settings and propeller rotational speeds necessary to perform the commanded maneuver. The calculated values of blade pitch and propeller speed were transferred to actuator servos in the submarine model by means of a 160-ft neutrally ballasted umbilical cable, which also carried air and power to the model and signals from model motion-sensing instrumentation back to the computer.

Figure 7 shows the hovering stability of the vehicle with all command inputs and all control feed-back gains equal to zero. Note that the model is not trimmed completely, as evidenced

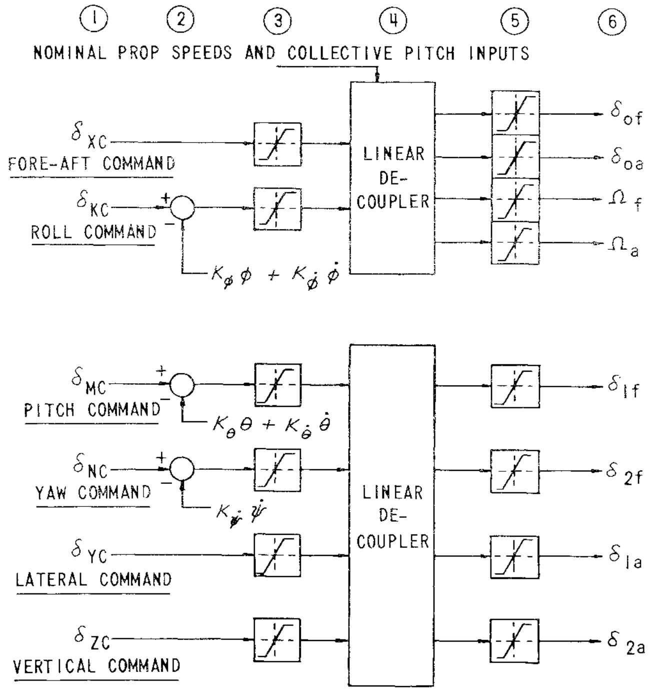

Fig. 5 Simplified control system diagram.

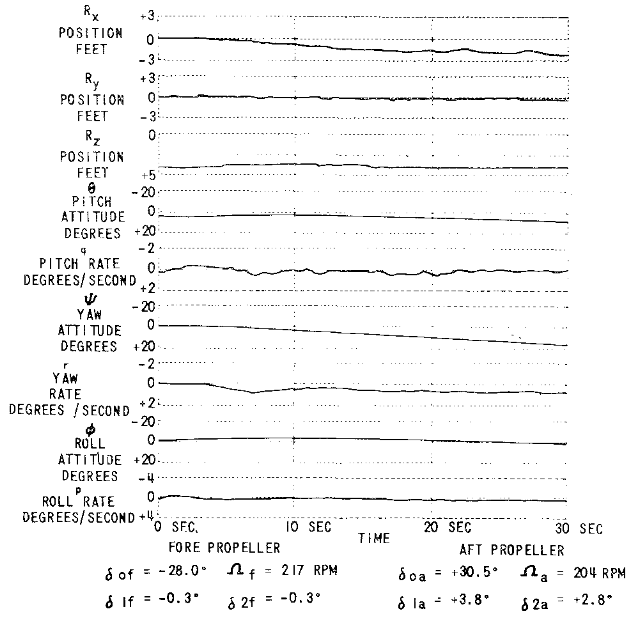

Fig. 7 Counterthrusting hover condition, unaugmented.

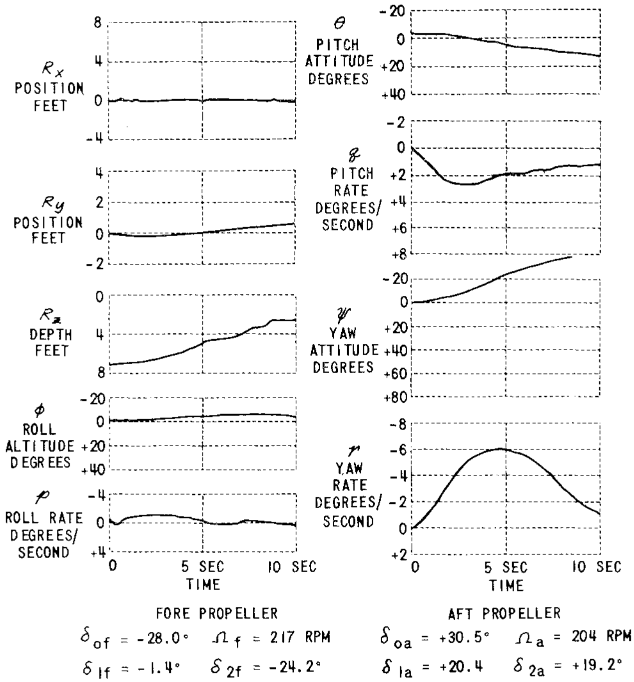

Fig. 8 Counterthrusting vertical response, unagumented.

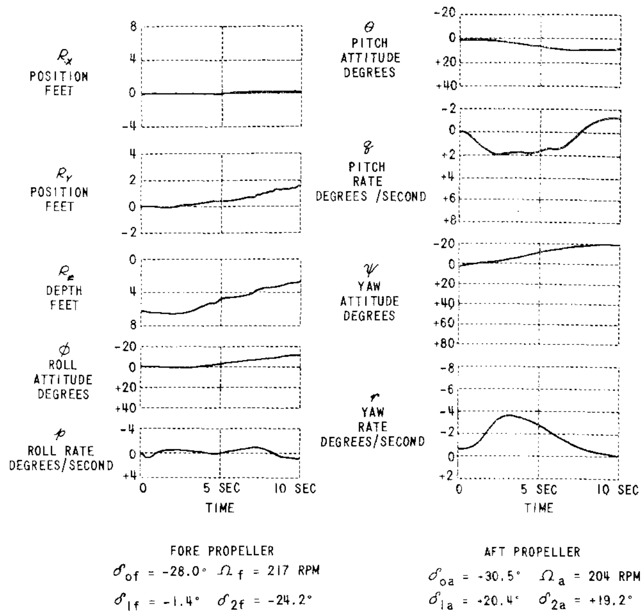

Fig. 9 Counterthrusting vertical response, augmented.

by the change in heading angle ψ and forward-after position R_x.

Figure 8 shows the response of the vehicle to a command for a step change in pure vertical velocity from the hovering condition. In addition to the desired change in depth, significant motions are experienced in pitch and yaw. The other degrees of freedom (R_x, R_y, and ψ) appear to be reasonably well decoupled.

In order to reduce the pitch and yaw couplings, pitch rate and yaw feedbacks were incorporated in the control system. Figure 9 shows the effect of these feedbacks on dynamic response. Although the amounts of feedback selected for this run were not optimum, some improvement in decoupling the pitch and yaw degrees of freedom is evident. Some adverse effect on the lateral motion coupling appears, however. Improved feed-back gain settings, based on a simple linear mathematical model for the system dynamics as derived from model response data, were later incorporated in the control for further reduction in the angular motion couplings. Feedbacks in the translational degrees of freedom could have been added also but were considered unnecessary because of the rather weak coupling that was introduced into these degrees of freedom.

Conclusions

The results of the model test program indicate that the TPS concept is feasible and has potential for substantial improvements in the low-speed maneuverability of underwater craft. The results also demonstrate the satisfactory controllability of tandem propeller-equipped vehicles by a single operator. These conclusions are based upon observations of the performance of the model with both experienced and inexperienced operators in control and on records of the transient response characteristics of the vehicle after undergoing pure-motion commands.

References

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