Tandem Propeller in Review

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The tandem propeller system (TPS) for submersible propulsion and control was conceived by the author in 1961. This paper traces its theoretical and experimental development through the most recent tests conducted at Cornell Aeronautical Laboratory. Although the initial configuration was for high-speed nuclear submarines, the emphasis in recent years has been for application to the slower, more maneuverable deep-submergence vehicles. Both configurations are discussed in detail in this paper.

ON 28 February 1961, the basic concept of the Tandem Propeller System (TPS) was formulated by the author. The genesis of a new idea is often difficult to reconstruct; however, this is not the case in this instance. An ongoing research program, the Novel Electric Propulsion System, was then being reviewed by the author. The central theme of this program was a propulsion system for nuclear submarines embodying two large-hub, counterrotating, wraparound, electrically driven propellers located near the stern. One serious deficiency of this system was that backing down involved reversing the direction of rotation of very massive propellers and driving motors. The most obvious solution to this problem was to make the propeller blades collectively variable in pitch, thereby permitting very rapid backing power. This step, however, required the added complexity of blade-changing mechanisms, which, for purely mechanical reasons, had shown little promise in the submarine Navy. Contemplation of this problem produced the thought of individual blade-pitch variation as a means of developing nonaxial (control) forces. The relocation of one of the propellers to a forward position resulted from considerations of larger control moment arms and better weight distribution and propulsion redundancy through separation. So much for the one percent "inspiration." The remainder of this paper deals with the 99 percent "perspiration."

It was recognized that TPS represented such a radical departure from current hydrodynamic practice that universal acceptance was most unlikely. There are, indeed, many aspects of TPS which demand investigation as a prerequisite to further consideration. Perhaps the most controversial aspect is the feasibility of large wraparound a.c. motors which run in a seawater environment. Serious reservations are held, and rightly so, as to whether such machines would work reliably, quietly, and efficiently. Another problem area closely tied in with the motor construction is that of the individual blade-pitch-changing mechanisms. They are envisioned as being mechanical, electrical, or hydraulic. These two problems, along with the necessary power-generating equipment and submarine internal arrangements, are grouped under the heading of hardware research and development.

The more subtle aspects of TPS included, most importantly, the hydrodynamics of large hub-to-tip diameter ratio propellers. No theory or experience existed for large-hub propellers with fixed pitch or collectively variable blades, much less for one whose blades were individually controllable in pitch. A basic new mechanism capable of producing three-dimensional hydrodynamic forces was being introduced into a field theretofore dominated by one- or, at most, two-dimensional devices. The crucial step of demonstration of a new concept by means of an operational model (Fig. 1) cannot be over-valued, for it points the way to ultimate acceptance by the required key innovator, who might not otherwise be exposed to the invention.

A problem area of twofold nature was that of how to interface this new capability machine with the human operator. He must be capable of effectively assimilating the information on vehicle motion as well as imposing his will upon the vehicle. Conventional devices (including pitch, course, speed, and depth information displays) already marginally effective with today's submarines are inadequate for a submarine capable of being controlled in the three remaining degrees of freedom of sway, roll, and heave. Similarly, the control input devices now capable of ordering pitch, yaw, and speed do not possess the inherent growth capability to permit ordering roll, sway, and heave. Clearly, these two areas required investigation.

The potential elimination all of conventional control surfaces promises to rock the foundations of hydrodynamic stability and control theory (and practice). A re-enactment of the overlapping transition from sail to steam, wherein the sails were finally abandoned through disuse, would be inevitable.

The one remaining area of concern was that of worth and utilization of the capability were it to be developed. The resulting operations analysis effort ultimately, in combination with the Thresher loss, led to shifting of emphasis from large nuclear submarine application to smaller deep-submergence vehicle (DSV)-type vehicles typified by the deep submergence rescue vehicle (DSRV). The shifting of emphasis to concentrate wholly on the maneuvering characteristics of TPS led to design modifications and optimization efforts which form the second part of this paper.

Once the scope of the problem areas was determined, it was decided that a parallel rather than serial effort would be undertaken. During the first year after the inception of the idea, teams of recognized industrial specialists were assembled. These teams met and received the simple instruction that each participating team was to remain entirely within its own discipline, assuming complete success on the part of every other discipline involved. There were, of course, some necessary artificialities introduced, such as developing a control system for a vehicle whose maneuvering characteristics were not accurately known and selecting a propeller-operating rpm permitting a specific design without knowing the inpact on the

Fig. 1 Original TPS Model.

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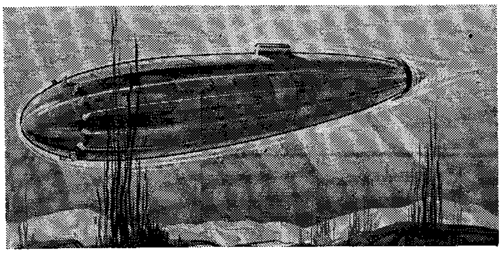


Fig. 2 Artist's concept of TPS attack submarine.

propeller hydrodynamics. There were, in fact, a reasonably large number of pseudoarbitrary constraints including hull shape (Thresher), number of blades per hub (12), location of hubs (about 20% in from each extremity of hull), blade shape (NACA 0015 rectangular planform), hub-to-tip diameter (blade tips not to extend beyond hull maximum diameter), design power at propeller hub, and single-operator control.

The program plan called for a merging of the various efforts within a year or two in the form of a free-running manned or remotely controlled, TPS-equipped Thresher model. The highlights of the various efforts are summarized herein.

The major hardware-oriented studies were conducted under the primary leadership of the Electric Boat Division (EB) of General Dynamics Corporation, which was charged with the over-all power development and utilization aspects of TPS. Because of the wet a.c. motors represented, the furthest departure from current practices, parallel but separate subcontract efforts were conducted at the General Electric Large Motor Division and at the Elliott Electric Company. Within this framework, EB was charged with over-all design responsibility with emphasis on general submarine internal arrangements and with exclusive responsibility for mechanical blade-pitch-changing systems. GE and Elliott both performed large, wet a.c. motor design studies, with GE having the added responsibility for electrical blade-actuating systems and Elliott the hydraulic blade systems. These efforts[1] culminated in the design of a nuclear submarine embodying

1) two synchronous a.c. wet motors of equal power; one located forward and one aft, as shown in Fig. 2 (a cutaway view of one of these motors is shown in Fig. 3);

2) electrically operated individual blade-pitch-changing mechanisms for reasons of reliability and quiet operations;

3) two rotating transformers to transmit synchronizing and blade-actuating power across the water gap;

4) the absence of all planning surfaces and their attendant mechanisms;

5) the addition of stern torpedo tubes;

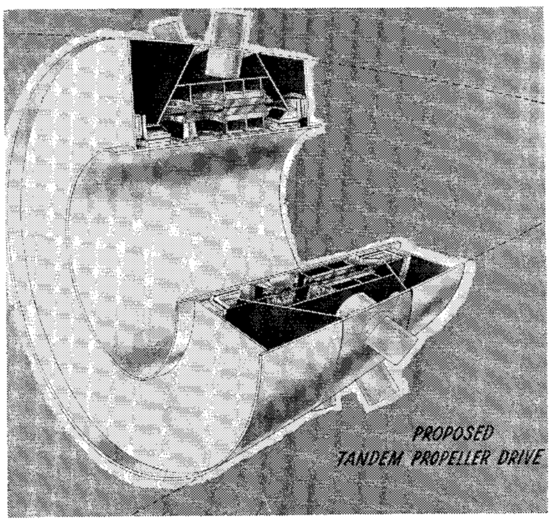


Fig. 3 TPS motor cutaway drawing.

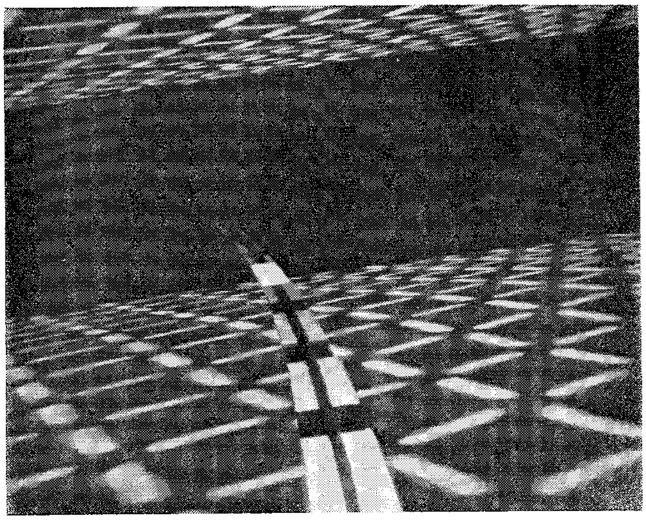


Fig. 4 CONOLOG.

6) the elimination of shaft sealing problems;

7) no increase in displacement; and

8) no significant loss of top speed capability.

The task of developing an adequate display format was assigned the Norden Division of United Aircraft Corporation. Its solution[2] was an adaptation of their newly developed contact analog display for aircraft, known as CONOLOG. The submarine version is shown in Fig. 4. It is an electronically generated perspective view of the underwater world as would be seen by the operator looking out of a window at his control station. This "inside-out" display shows the ocean surface and floor (or maximum depth limitation) as grids. By grid element shaping it may be caused to show earth-oriented directions. The ordered course and depth is represented by the "roadway." This artificially generated world is caused to move dynamically in response to the real-time vehicle motions so that the operator has the illusion of driving down a highway. He also has the freedom to drive off the highway or even down through it. The "picture" responds to all six degrees of freedom of the vehicle, thereby removing the extremely difficult integration task an operator faces when attempting to piece together his vehicle's over-all motions from information he gathers from a set of individual dials and gages. A prototype of the system was constructed for use by the control input designer as well as for use in the free-running model test phase.

The task of developing and evaluating the six-degrees-of-freedom, single-operator input device was awarded to the

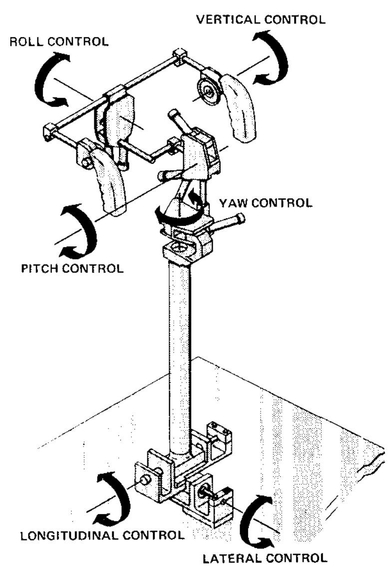


Fig. 5 TPS model control input device.

Minneapolis-Honeywell Corporation (MH). A number of input devices and combinations of devices were evaluated using CONOLOG displays.[3] Shown in Fig. 5 is the final input device, based on this work, which was used throughout the free-running model tests. MH found that such a device permitted a single operator to effectively perform strenuous maneuvering tasks in minimum time. Their study included an evaluation of "quickening" and "predictive" applications to display symbols, with the most effective combination being a quickened six-degrees-of-freedom symbol superimposed on the CONOLOG real-time world format.

One of the problems important to hydrodynamicists is that of providing artificial but adequate stability to a submersible having no rudder or stern planes. This investigative task was assigned to Cornell Aeronautical Laboratory Inc. because of their extensive experience in the aircraft stability field. Their studies[4] showed that, although the vehicle would be unstable in the absence of control input signals to the propeller, artificial stability augmentation could be applied to provide adequate stability even during severe casualty-mode operations.

The most fundamental questions regarding hydrodynamic theory development and model verification were studied by the Netherlands Ship Model Basin (NSMB). Their theoretical studies,[5–9] backed up by extensive hydrodynamic model tests, demonstrated the propulsive efficiency and control force development capability of TPS. Shown in Fig. 6 is the $\frac{1}{20}$th-scale TPS-equipped Thresher hull-form model. This model was designed with the flexibility to operate either in a captive strain-gage-mounted mode or a free-running mode, with or without shrouds mounted forward or aft and with an optional additional center section for manned free-running tests. At the completion of the extensive NSMB captive test series, this model was flown to the David Taylor Model Basin for free-running tests.

The Cornell Aeronautical Laboratory Inc. was chosen to tie together the results of all the aforementioned free-running tests conducted at DTMB. Prior to this step, it was necessary to conduct a short series of captive tests in order to determine control equation coefficients as well as to "hook" onto the NSMB data.

In addition to the hardware items developed under the various elements of the ongoing program, which included the submarine model, the CONOLOG, and the control input device, several additional elements were required to successfully free-run the model. These are shown assembled in Figs. 7–9. Not shown is the television camera that, during certain tests, was mounted forward of the fairwater, permitting the superposition of a quickened CONOLOG picture upon the real-world underwater view. The position location system embodied a keyed hydrophone on the model; its signal was received at three separated hydrophones mounted in the test tank. These signals were resolved by the conversion unit shown in Fig. 9 to give x, y, and z position information (or x and y with redundancy). The model was operated primarily in the hover mode first, in the fairly restricted circulating channel as shown in Fig. 10. Once the control system was tuned and the model accurately trimmed, operations were transferred to the explosion basin to take advantage of the deeper water and greater maneuvering room. Several weeks of operational testing followed. In addition to having a large number of people witness and perform the tests, a documentary motion picture film was prepared by the Navy Research and Development Office and released as a part of NARAD 2–64. This test series culiminated a three-year effort to demonstrate TPS feasibility for large nuclear submarines.

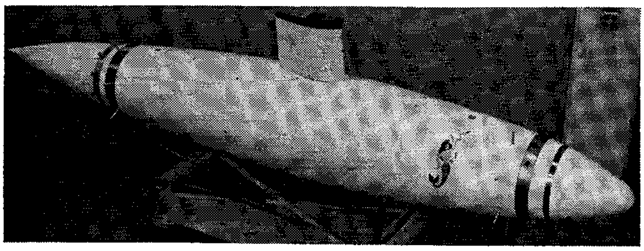


Fig. 6 $\frac{1}{20}$th-scale attack submarine with TPS.

During the latter phases of these R&D efforts on the large-submarine applications of TPS, Thresher was lost. The ensuing evolution of a new submarine rescue system requiring a highly maneuverable small craft sharpened interest in this inherent attribute of TPS. A new look was taken with the view that high speed and extreme quietness were of secondary importance whereas rapid development of large control forces at low speeds was paramount. The angled-blade configuration, with greatly increased blade area, was through most appropriate to fill these needs. Little of the theoretical and

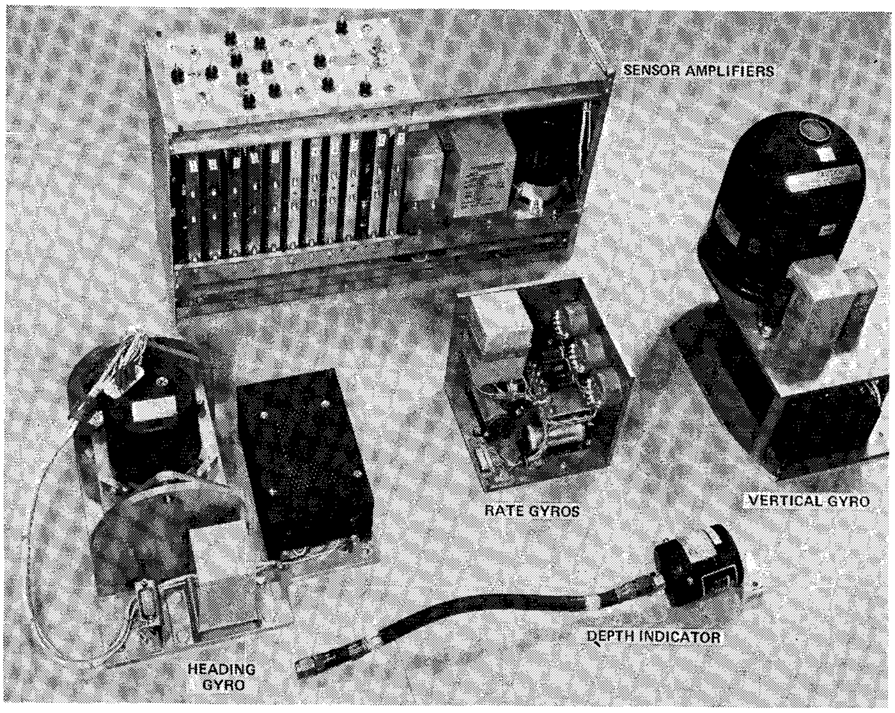


Fig. 7 CAL model-borne instrumentation.

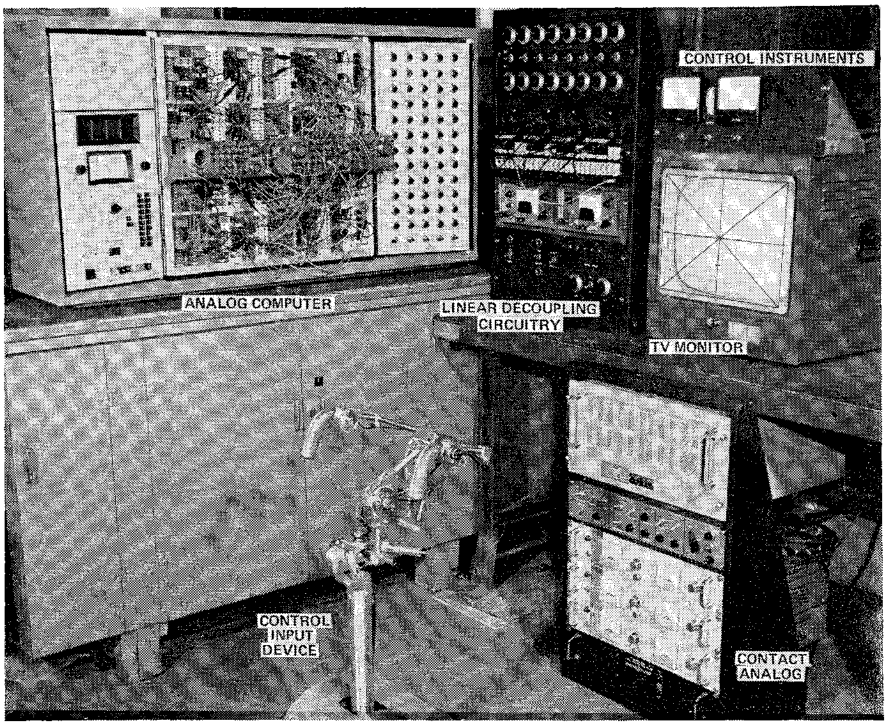


Fig. 8 CAL on-shore control equipment.

exhaustive test data derived from the Thresher model were valid for this new configuration which promised to outperform other contenders for this mission. Whereas the Thresher model developed moderate control forces in the hover mode through the expedient of collective pitch counterthrusting with superimposed cyclic pitch patterns, the angled-blade configuration promised to develop many times the same control (cross-body) forces with cyclic pitch alone, without wasteful counterthrusting with collective pitch. Additionally, the troublesome force vector rotations associated with counterthrusting promised to disappear. It was clear that a new set of fundamental experiments had to be conducted in order that meaningful comparisons might be made between TPS and other competitive schemes proffered to solve the low-speed maneuvering problem faced by the Navy. The two key questions which were in doubt were the magnitude of the control forces (pounds) developed per installed horsepower (pounds per horsepower) and the effects of cross-axis velocity upon this ratio. For economy reasons and because the TPS is inherently a balanced system, a half-body test series was undertaken.[10,11] Figure 11 shows the $\frac{1}{2}$-scale Deep Submergence Rescue Vehicle model strain gage sting-mounted on a movable carriage over the CAL test facility.

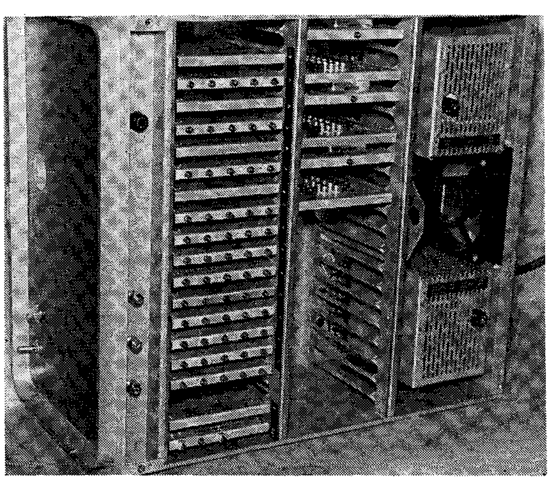


Fig. 9 CAL position location system conversion unit.

One-half of the NSMB Thresher model was modified, as shown in Fig. 12, to most economically attain the desired blade motions. Two cone angles of 35° and 25° half-angle were tested as a check on the angled-blade theory concurrently developed. Additionally, three blade plan shapes were tested in blade number combinations of 12, 6, and 4 installed on the hub. It can be seen from Fig. 13 that 6 blades produced pounds-per-horsepower ratios nearly as high as 12 blades, the operating rpm being only slightly higher. Figure 14 shows the half-chord as well as the half-span blade result for 6 blades. It is clear that swept area is the most predominant factor in determining performance, other geometry remaining fixed. The most important characteristic of TPS demonstrated by these tests is the magnitude of the force-to-power ratio. The balance was mounted on a carriage to validate the theoretical prediction that the force-to-power ratio would not appreciably be reduced in holding position against a broadside current of up to two knots. For the test setup shown, cyclic pitch was imposed only about the axis, causing forces to be developed in the direction of carriage motion. In recognition that this fairly crude carriage could not attain the velocity accuracy normally experienced, 20 equally spaced data points were obtained for each run and averaged over a timed-fixed distance. The points through which the curves have been drawn are, therefore, very accurately defined.

For the same reason that the NSMB model was accurately scaled to the Thresher hull and power, the latter tests were scaled to the predicted DSRV hull and power. The model was chosen to represent a $\frac{1}{2}$-scale DSRV and all operating

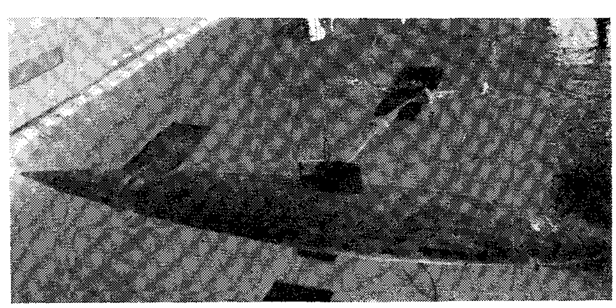


Fig. 10 TPS model in circulating water tunnel.

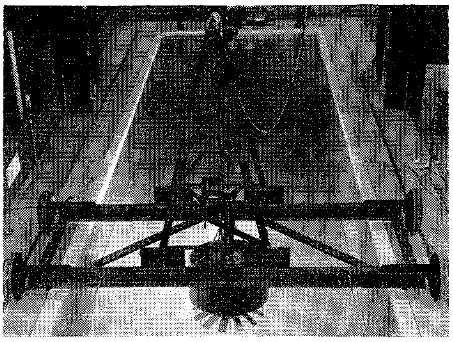


Fig. 11 ½th-scale TPS-equipped DSRV model.

conditions and results extrapolated to full scale and at a 300-pounds-per-propeller force level. This was necessary in order that comparative performance might be obtained between TPS and the ducted thruster system, which was also a contender. Figure 15 is included to show the broadside holding performance of both systems.

Another concern was control (maneuvering) power in the ahead mode. Shown in Fig. 16 is a comparison among ducted thruster theoretical and actual performance and TPS theoretical performance. No experimental cyclic pitch data have been taken with the angled-blade TPS model in axial motion. NSMB data, however, on the Thresher model follow the trend, showing a rise rather than a drop in performance with speed. An attempt has been made to check the theory at least near-zero speed by the expedient of setting up an axial flow with collective pitch. Cyclic pitch was then added. ssuming that it is legitimate to then subtract the power nsumed by pure collective pitch, the curve of Fig. 17 results. hough evidence exists to disclaim any predictions of the ne collapse of performance exhibited by the ducted uster.† In any event, the problem has been solved for this ster system by the expedient of adding a tiltable control oud for cruise yaw and pitch control.

he search at Palomaris, wherein submersibles operating r the muddy bottom caused severe visibility problems,

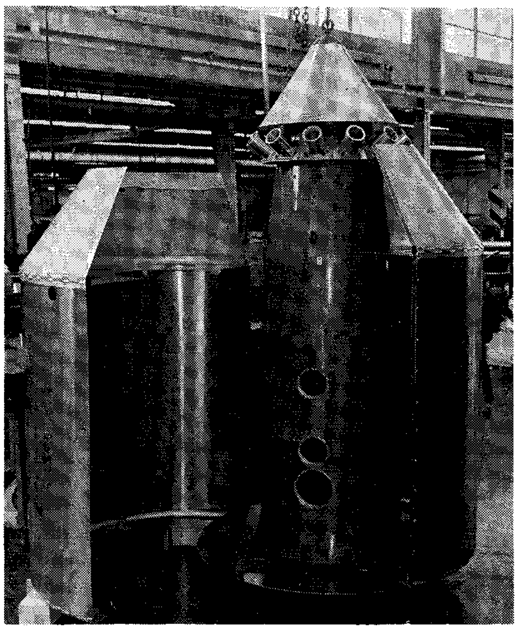


Fig. 12 Modification of NSMB model to CAL model.

† Tests conducted at the Naval Ship Research and Development Center in January 1969 confirm an increase in control force to power ratio with forward speed. Report is pending complete data evaluation.

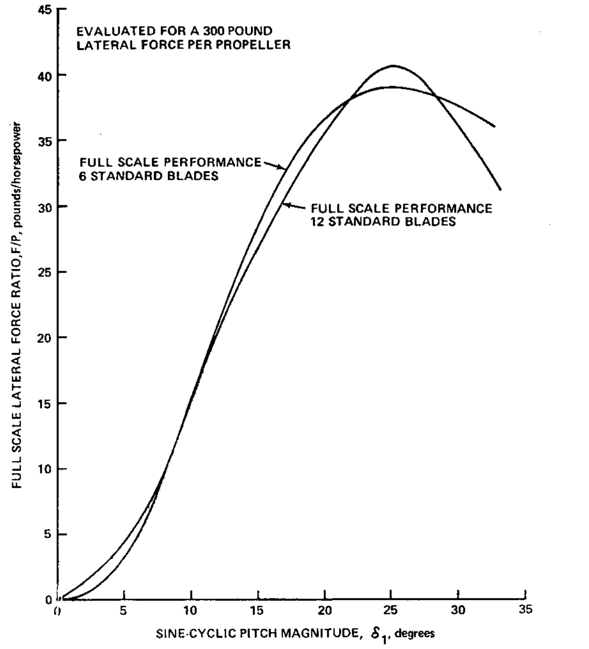


Fig. 13 Experimental performance of 6- and 12-blade configurations.

presented yet another potential advantage of TPS. It is possible, while operating near a muddy bottom, to develop control forces with greatly reduced mud agitation, through judicious balancing of collective and cyclic pitch patterns. As one example, take the case of producing an upward heave force. The upper drawing of Fig. 18 shows the water flow pattern generated with pure cyclic pitch. It can be seen that this would cause a considerable disturbance of the bottom directly beneath the vehicle, albeit less than that caused by the higher-jet-velocity ducted thrusters at an equivalent force level. However, if collective pitch is added in an amount and direction such that the blades passing nearest the bottom generate no lift, the resulting water flow in this location will be minimized. This situation is shown in the lower half of Fig. 18. It can be seen that this same technique may be applied to attain pitch motions as well. Pitch and heave are the two classes of vehicle motions which impart water reaction motions likely to cause stirring of mud. It

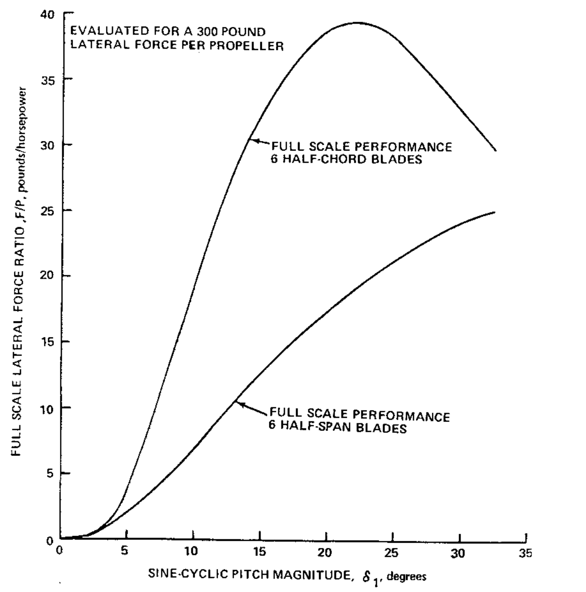


Fig. 14 Experimental half-chord and half-span performance.

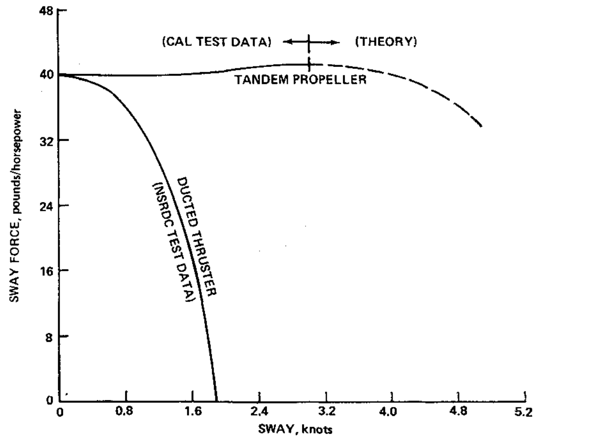


Fig. 15 Broadside holding performance of TPS and DT.

is possible to operate vertically oriented ducted thrusters in an antimud mode also, but at the expense of bias ballasting and maintaining half-power expenditure continuously. Ballast changing is particularly expensive at great depths. A series of tests to demonstrate the antimud mode has been conducted by the expedient of surrounding the model with a screen tufted to reveal water flow. In one typical test, 10° collective

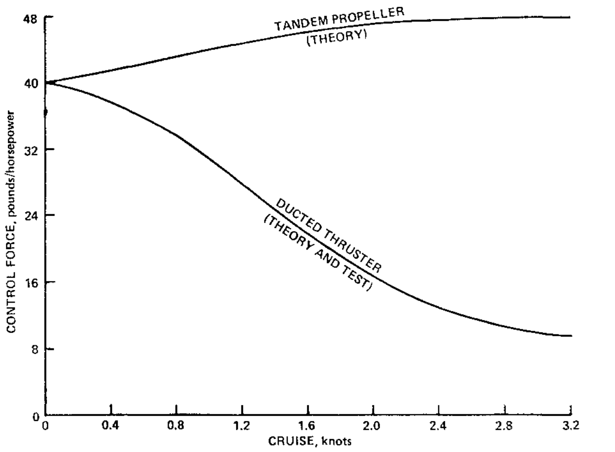


Fig. 16 Comparison between TPS and DT in control force development (during cruise).

pitch and 10° cyclic pitch were superimposed to represent a force directly away from the simulated mud bottom. Tuft activity was undetectable in a position representative of being directly beneath the vehicle, and the generated force was

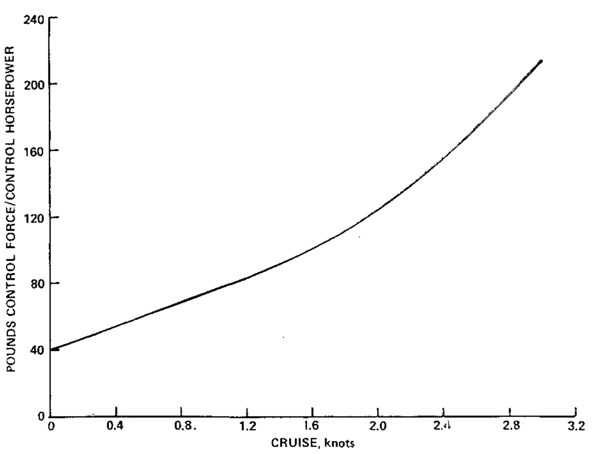


Fig. 17 Experimental TPS control force development in cruise.

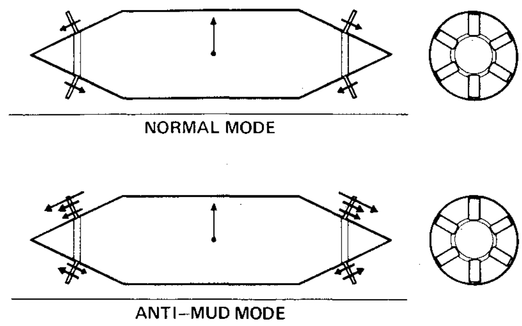


Fig. 18 Antimud mode configuration.

reduced only 30% below that attainable with 10° of cyclic pitch alone.

Roll control is attainable with TPS in three ways including dithering collective pitch or cyclic pitch on the appropriate propeller (depending upon whether plus or minus roll is desired) and stagger-blade operation. This latter technique implies the superposition of alternate plus and minus values of pitch on the individual blades in addition to the control pattern otherwise being generated. Tests have been conducted which show that stagger-blade roll control is approximately twice as effective as dithered collective pitch for the same magnitude of pitch angle. The effect is attributed to the more complete energy exchange between adjacent blades

One frequently asked question regards the accomplishmen of angled-blade actuation. Figure 19 includes, in gener form, the major schemes that have been envisioned. T choice from among these would depend upon a large numb of criteria. Figure 20 demonstrates how each might b modified for stagger-blade roll control should this mo efficient capability be desired (as opposed to dithered ro control).

During the various tests, it was noticed that, when eit collective or cyclic pitch was changed with the propel rotating and the recorder on, the delay between pitch patt change and the onset of measured body forces was extrem short. In no case observed did this delay exceed 0.1 Figure 21 is representative of records wherein a ramp func was imposed on pitch change. Measured pitch change resulting force were recorded. Additionally, oscilla pitch patterns were imposed up to a frequency of 2 cps. T model exhibits force leading characteristics below 1 cps a lag above.

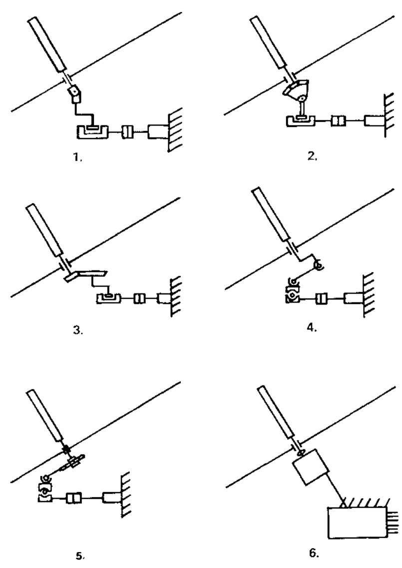


Fig. 19 Generic angled-blade mechanisms.

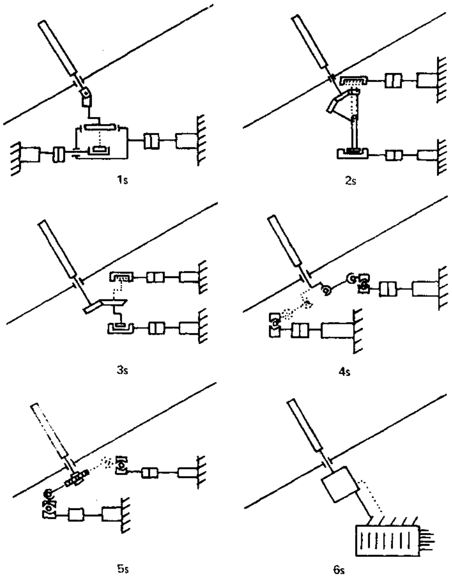
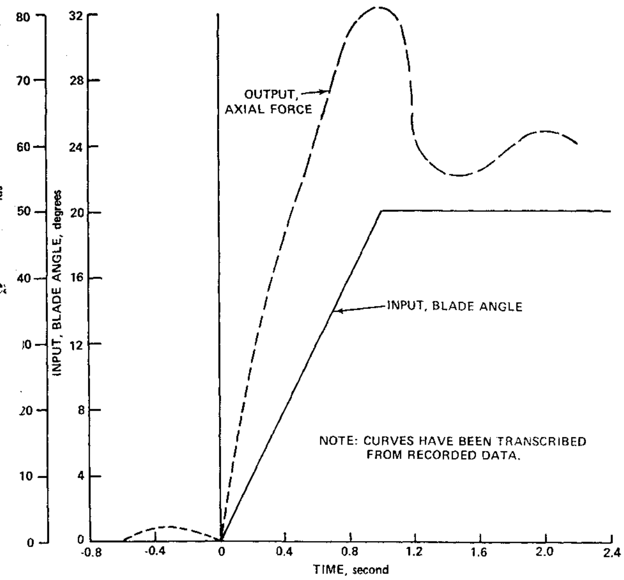


Fig. 20 Generic angled-blade stagger-blade mechanisms.

In lieu of summarizing, a few comments regarding general characteristics capabilities and problem areas are offered. Of all the systems currently known which are capable of



g. 21 Ramp control input with measured force output.

maneuvering submersibles, only the tandem propeller, in a single device, can generate forces and moments in the three dimensions. Other devices such as the cycloidal propeller are two-dimensional, at most, but most are one-dimensional. Although it is true that maneuvering capability equal to the TPS may be obtained through the utilization of a multiplicity of simpler devices, no combination of them provides a more efficient and flexible utilization of installed power. The efficiency of large lifting surfaces is well established. The uniqueness of the tandem propeller system is that it permits the ordering of all its blades to utilize these efficient forces in producing desired vehicle motions in the six degrees of freedom. It is, therefore, the first device born of the needs of the depths not being adopted from the long-established surface ship technology.

In any objective presentation the cons should be aired as well; otherwise a legitimate question might well be, "Why has not this system gained universal acceptance?" For the large-submarine case, major costly development programs would be necessary to prove the feasibility of machinery items such as the motor shown in Fig. 3. The Navy must put all things in perspective and base these costly programs upon the need for improved capability in the light of the degree of risk envolved. Utilization of small submersibles would certainly appear to be more imminent, in that this field is in its infancy, with a propensity toward low-speed, highly maneuverable craft. The Navy's continued investigations of TPS for this application lend credence to this assumption.

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