POWER TRANSMISSION OPTIONS FOR LARGE NAVAL HYDROFOIL SHIPS+

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ABSTRACT

Propeller horsepower requirements for large hydrofoil ships exceed the demonstrated capabilities of conventional right-angle geared transmissions. Ship designers have investigated improved gear technology and dual mesh configurations. Other promising concepts are electric drives, both superconductive and normally conductive. Five alternate transmission concepts are examined for application to a future hypothetical naval hydrofoil. Numerical relative merit ratings are presented for important ship performance parameters and for reliability. Safety, vulnerability, and control aspects are evaluated qualitatively. The status of technology and development timeline are discussed for each concept. Results show that electric and mechanical drives are competitive and that each exhibits advantages to be weighed for a particular ship design.

Introduction

The excellent seakeeping characteristics and speed capabilities of hydrofoil craft have been amply demonstrated by both experimental and operational platforms. The problem now facing the hydrofoil design community is the extension of the hydrofoil concept to transocean ships capable of surpassing conventional surface vessels in terms of effectiveness and overall system cost. Compared to conventional vessels of equal size, hydrofoil ships are more costly, but the promise of the equivalent effectiveness of smaller, and fewer, vessels keeps the hydrofoil concept a contender. The optimization era has arrived in terms of the best foil systems, best propulsion schemes, attention to construction costs, etc. In the propulsion category, efforts are underway to improve specific ranges, resulting in reduced fuel weight fractions and increased payload fractions by optimization of the entire propulsion train from engine through propulsor.

The highest propulsion efficiencies for transocean hydrofoils are achieved using marine propellers, as opposed to other propulsor concepts. Transmission of power to these propulsors is possible up to about 25,000 SHP using present right angle spiral bevel gear technology in dual mesh configurations. Current single mesh capability is about half this value. To extend this limit, designers have been investigating advances in gear manufacturing technology, materials, load sharing, and alternate means of transmitting power, such as electric drives. Modern high technology electric drives, both superconductive and normally conductive, offer the promise of compact propulsion pod packages, flexibility of prime mover arrangement and alleviation of the mechanical alignment problems at the strut terminations. These advantages are achieved at some small sacrifice of propulsive efficiency or increase in system weight.

Recently, studies have been made of both mechanical and electric drives under separately defined programs. Of interest to the ship designer is the comparative application of these concepts to a given ship. This paper presents the results of such an investigation, whereby a twin screw baseline hydrofoil ship was defined as to full load displacement, geometry, propulsion characteristics, foilborne prime mover selection, and major weight group values. Five alternate power transmission systems were examined, each designed to match the same foilborne engine and propeller and each capable of meeting certain critical performance parameters such as cruise speed and takeoff thrust margin. The five systems were then rated for a number of parameters and an overall merit rating established.

The candidate transmission systems were:

- Mechanical Drive with Dual Mesh Gearing and a Variable Pitch Foilborne Propeller
- Mechanical Drive with Advanced Technology Single Mesh Gearing and a Variable Pitch Foilborne Propeller
- AC Normally Conductive Drive with Fixed Pitch Propeller
- AC Normally Conductive Drive with Variable Pitch Propeller
- DC Superconductive Drive with Fixed Pitch Propeller

Performance calculations were carried out for each system installed in the baseline ship, resulting in values for:

- Foilborne Maximum Speed
- Foilborne Range
- Takeoff Thrust Margin
- Hullborne Speed (Foils Extended)
- Hullborne Range (Foils Extended)
- Hullborne Range (Foils Retracted)

The foils-retracted performance was based on the inclusion of an auxiliary power train connecting either of the main LM2500 turbines to a pair of pod-mounted hullborne propellers. This auxiliary power train was either a mechanical drive or a normally conductive electric drive compatible with the main transmission.

Reliability block diagrams were prepared for each concept, and system MTBF's (Mean Time Between Failures) were calculated.

Qualitative assessments were then made to establish the relative merits of the systems with respect to control, safety, and vulnerability.

+This study was sponsored by the Hydrofoil Program Office of the David W. Taylor Naval Ship R&D Center.

For each transmission concept, the status of technology was evaluated and system development plans were established showing the time period in which each system could be available, assuming full development and funding were authorized.

Baseline Ship

Figure 1 shows the representative baseline ship used in the study. The ship characteristics were furnished by the Naval Ship Engineering Center and consisted of dimensional information, weight statements, drag and propeller characteristics. For study purposes, the displacement of the ship was held fixed at 1278 long tons. The fuel load was variable, to be traded against the weight of the total propulsion plant. Prime movers were a pair of General Electric LM2500 gas turbines. Each transmission concept was then tailored to this ship, with detailed calculations of performance, efficiency and propulsion system weight. The lighter and more efficient systems showed better performance in terms of ship speed, takeoff margin, and range, while other systems showed advantages in reliability, availability, ease of arrangement or other subjective parameters.

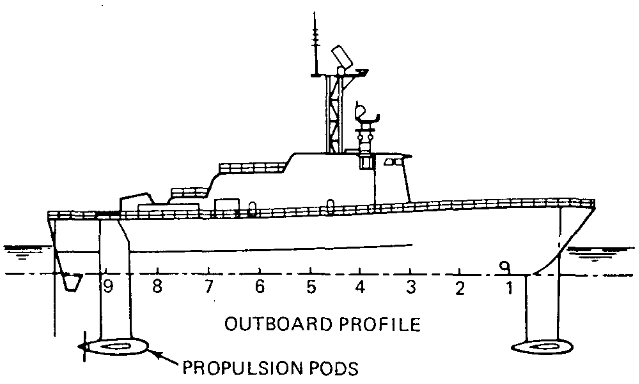


Fig. 1 USN Large Hydrofoil

The baseline ship concept provided a realistic set of constraints for comparison of the transmission concepts, although the ship does not represent any specific design under development by the Navy. In order to qualify the study results as general in nature, and not related strictly to the baseline design, performance sensitivities to critical ship parameters were investigated. Results of the sensitivity investigations showed no appreciable effect on the conclusions of the study. These conclusions are considered valid for any ship of the same approximate size which utilizes a twin LM2500 plant.

Candidate Transmission Systems

Dual Mesh Mechanical System

A schematic representing the dual mesh mechanical transmission system is shown in Figure 2. The transmission was designed using state of the art design practices and stress levels. Bevel gearbox design considered the use of both ball and cylindrical roller bearings, and tapered roller bearings. Both bearing systems were found to be satisfactory with no appreciable difference in weight or performance. An important design point is that engine RPM is maintained down to the pod where the entire speed reduction is taken in the pod mounted planetary gearbox.

Single Mesh Mechanical System

A schematic representing the single mesh mechanical transmission system is shown in Figure 3. This transmission system was designed using advanced technology design practices and stress levels. Single mesh bevel gearbox design also considered the use of ball and cylindrical roller bearings, and tapered roller bearings. Analysis showed that tapered roller bearings are the preferred choice for the single mesh bevel gearboxes. As in the dual mesh mechanical system the entire speed reduction is taken in the pod mounted planetary gearbox.

AC Electric Transmission System

A schematic representing the AC electric transmission system for foilborne operation is shown in Figure 4. The system is normally conductive and designed using presently available technology. The AC system, like the mechanical systems, requires a planetary

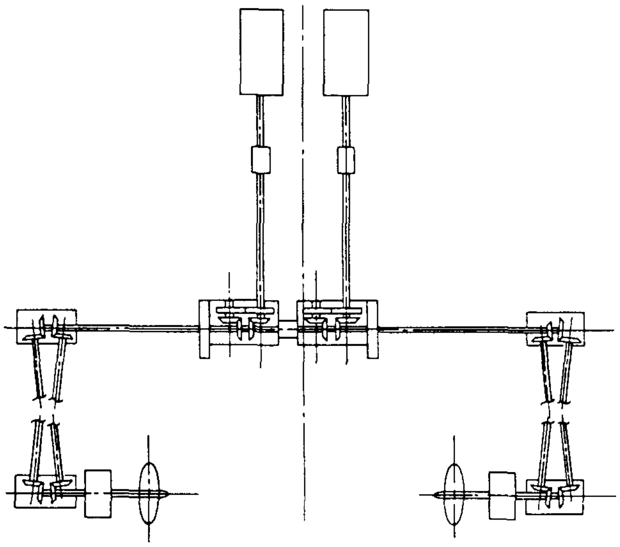


Fig. 2 Dual Mesh Transmission

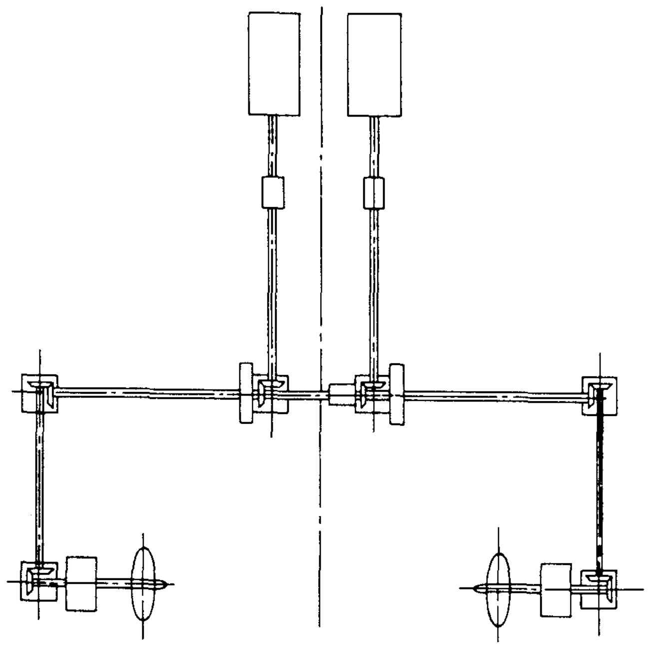


Fig. 3 Single Mesh Transmission

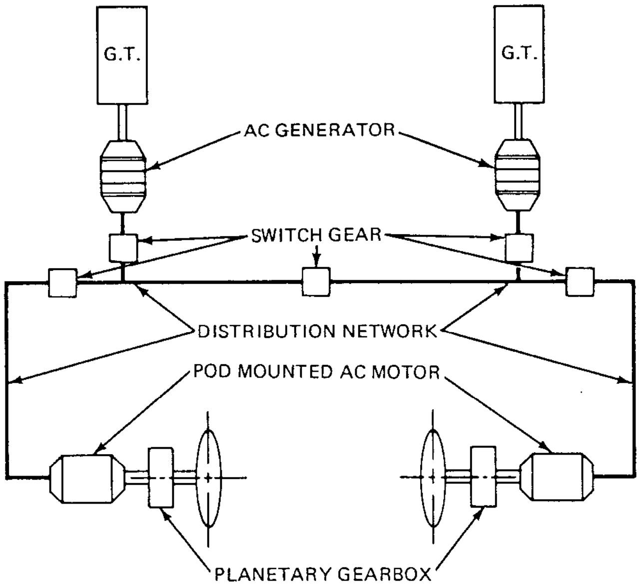


Fig. 4 AC Electric Transmission System

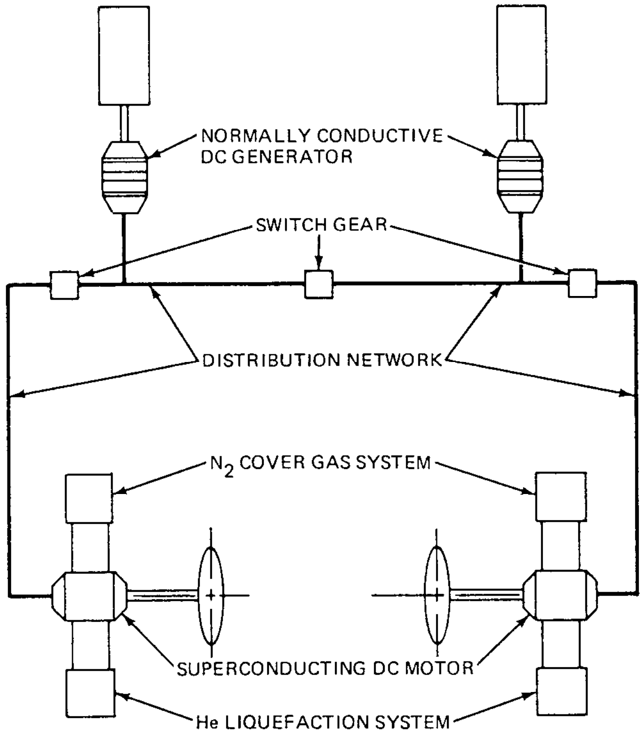


Fig. 5 Superconductive DC Transmission System

gearbox for the final speed reduction. The AC system is almost a direct analogy to a mechanical drive, in that the induction motors operate at near zero slip so that motor speed is directly proportional to generator speed, producing effectively a fixed gear-ratio system.

DC Superconductive Transmission System

A schematic representing the DC superconductive transmission system is shown in Figure 5. The pod mounted drive motor is the only superconductive element in the system, the generator being normally conductive. No planetary gearbox is needed with the DC system because the drive motor rotates at propeller RPM. The D. C. system has the advantage that generator speed is not directly related to motor speed. This allows the generator RPM-torque relationship to be tailored to the most efficient engine operating point at each speed condition. The full size system represented in the study is based upon an ongoing model development program at the David W. Taylor Naval Ship Research and Development Center.

Evaluations

Performance

Figure 6 shows the relative rankings of the systems for the performance parameters considered to be the most important for a comparative evaluation. While most of these parameters are self explanatory, the concept of takeoff margin needs to be clarified. The hydrofoil drag curve experiences a hump at takeoff, and the takeoff thrust margin is the amount of thrust available in excess of this drag at the hump speed in question. Takeoff margin, then, is a measure of the ship's acceleration capability through hump speed and at the same time provides margin for the uncertainties of takeoff drag prediction in both smooth and rough water.

Reliability

Another important parameter in the evaluation of the candidate systems was the system reliability. Block diagrams of each system are presented in figures 7, 8, 9 and 10. For each block the mean time between failures (MTBF) and the mean time to repair (MTTR), in hours, are given. The notation used is MTBF/MTTR. A note of NR indicates that the component is not repairable at sea. For the mechanical systems, calculations were made using two different MTBF's for the bevel gearboxes. This was done to determine the effect of gearbox reliability on the overall system reliability. The MTBF noted in the blocks was the expected value and the alternate MTBF represented a pessimistic gearbox MTBF.

The reliability functions used are those for a "bathtub" failure rate curve with a constant failure rate in the working life region. The reliability study resulted in a table of reliability versus time in operation and mean-time-between failures for each system. Figure 11 shows the relative ranking of the systems based on these results.

Qualitative Assessments

Of all the system parameters of interest, only the six previously displayed performance factors and system reliabilities were reducible to quantitative values. However, other questions remained relative to system control complexity, safety, and vulnerability to hostile action. These were evaluated on a quasi-subjective basis, using an A, B, C, D, relative rating system which has no numerical significance except that "A" is considered relatively better than "B", etc.

Table 1 represents the findings, which are subject to some debate. In fairness it must be noted that the superconductive drive is in a laboratory status and that the potential for superconductive machinery is so enticing in the larger horsepower range that these subjective evaluations may not be significant. It is certainly clear that an AC drive coupled with a fixed pitch propeller is an attractively simple system.

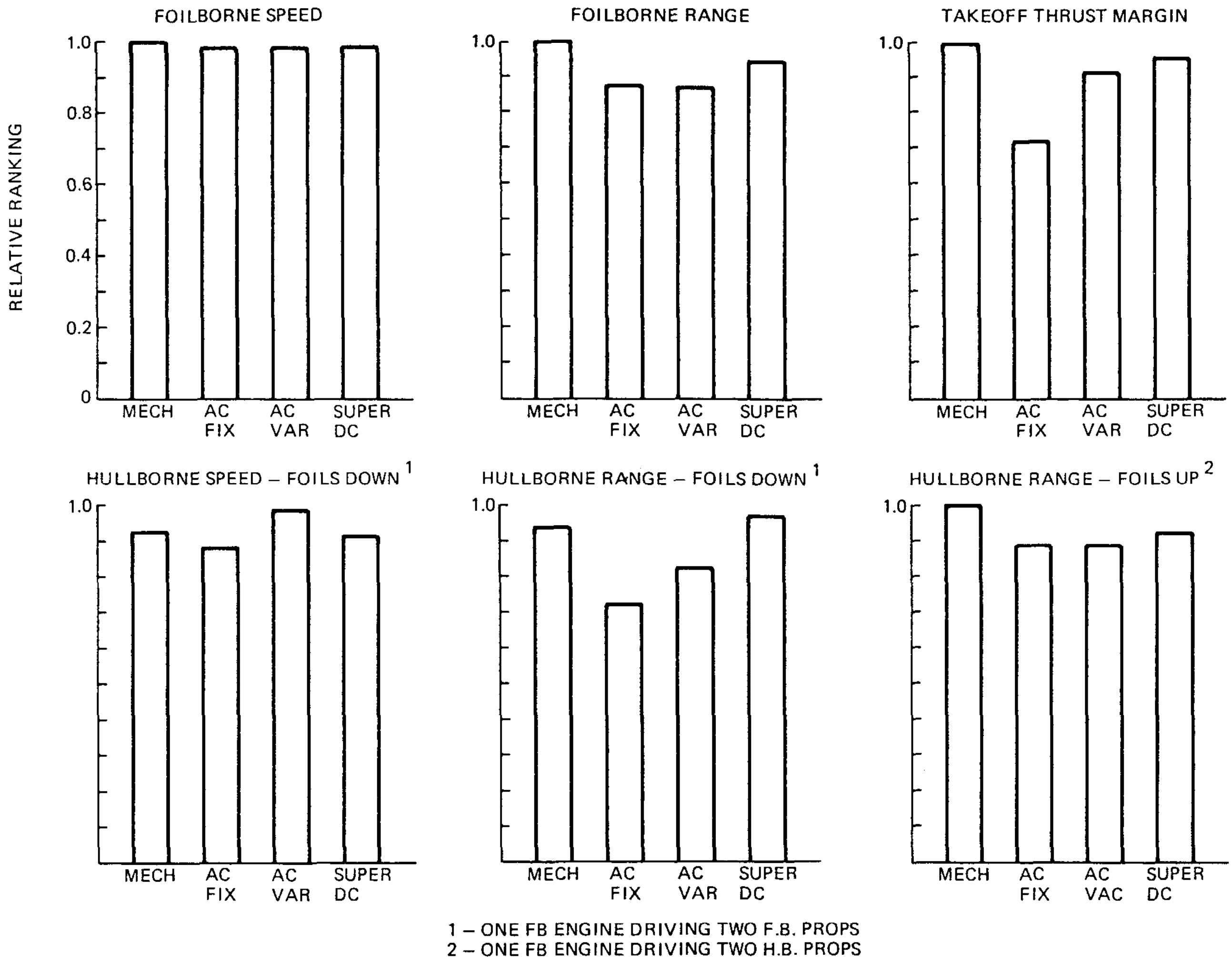


Fig. 6 Relative Merit for Each Performance Parameter

Table 1. Summary of qualitative evaluations

	CONTROL COMPLEXITY	SAFETY	VULNERABILITY
MECHANICAL TRANSMISSIONS	B	A	A
AC ELECTRIC DRIVE VARIABLE PITCH PROP	B	A	B
AC ELECTRIC DRIVE FIXED PITCH PROP	A	A	A
DC SUPER-CONDUCTIVE DRIVE	C	B	C

Systems Technology Status and Development Timelines

Technology Status

Transmission of power for ship propulsion has been achieved both electrically and mechanically for many years, at power levels greater than those anticipated for large hydrofoil ships. Shipboard installations of these systems have been relatively unconstrained by the ship's configuration. However, the hydrofoil (and SWATH) concepts require the power to traverse at least one and most likely two, right angle paths. The machinery must fit into a very confined pod with limited access for maintenance. For hydrofoil ships, the situation is complicated by the need for retraction of the foil system. Past shipboard propulsion systems do not offer much in the way of solution to these problems and it is evident that power transmission development is at least of equal importance to the eventual construction of large hydrofoil ships as is work on the foils, struts, and control problems.

Figure 12 presents a development plan timeline for each candidate propulsion system. In addition it is useful to briefly review the general state of development for each system.

Mechanical Transmissions

The weak links in the system are the spiral bevel gearboxes. Units have been demonstrated in service to about the 12 - 15,000 HP level (AGEH). There is at present no known coordinated effort on the part of government or industry to extend this range. Current interest in SES ships and VSTOL aircraft may generate the necessary need.

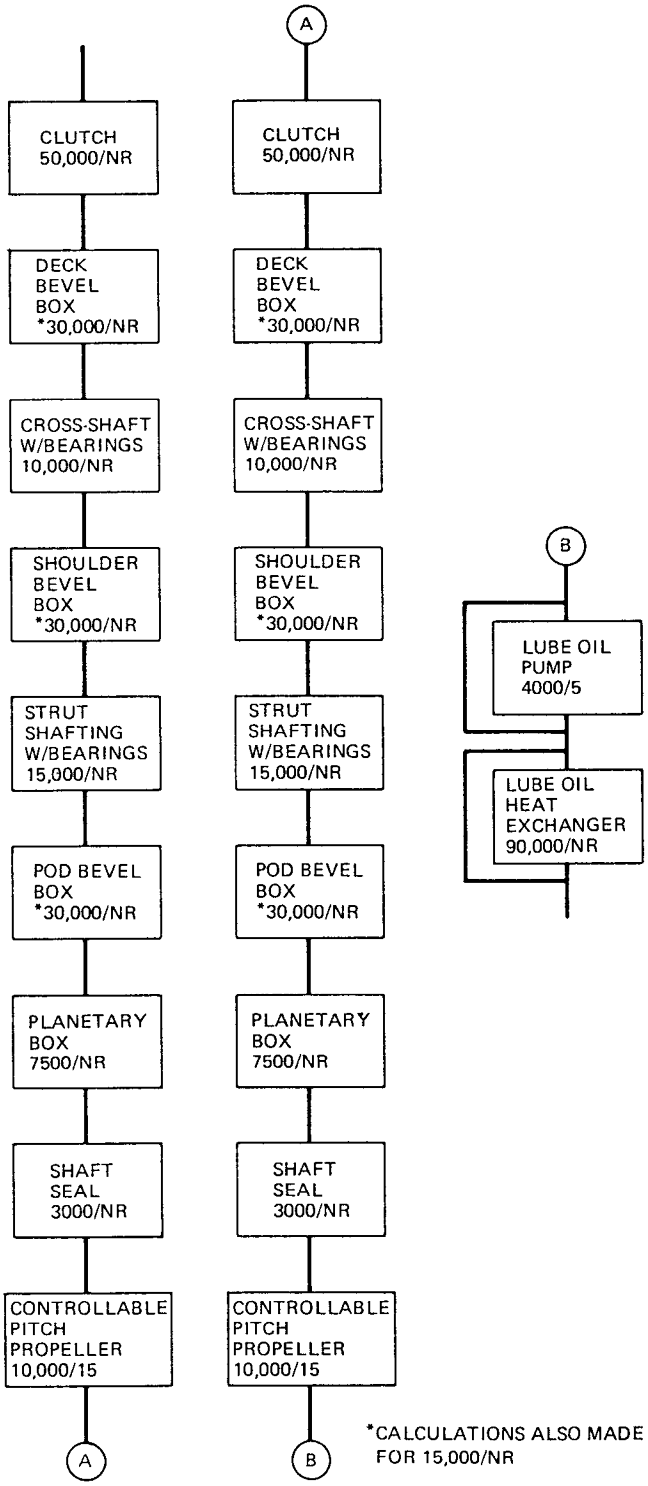


Fig. 7 Dual Mesh Mechanical Transmission Reliability Block Diagram - Foilborne Mode

AC Drives

There are no significant technology developments required to build a compact, high RPM, AC drive. The level of interest in this concept has increased considerably in the recent past with more serious consideration being given to SWATH ships than to hydrofoils. It appears that development of a ship-qualified system would entail only those problems normally encountered

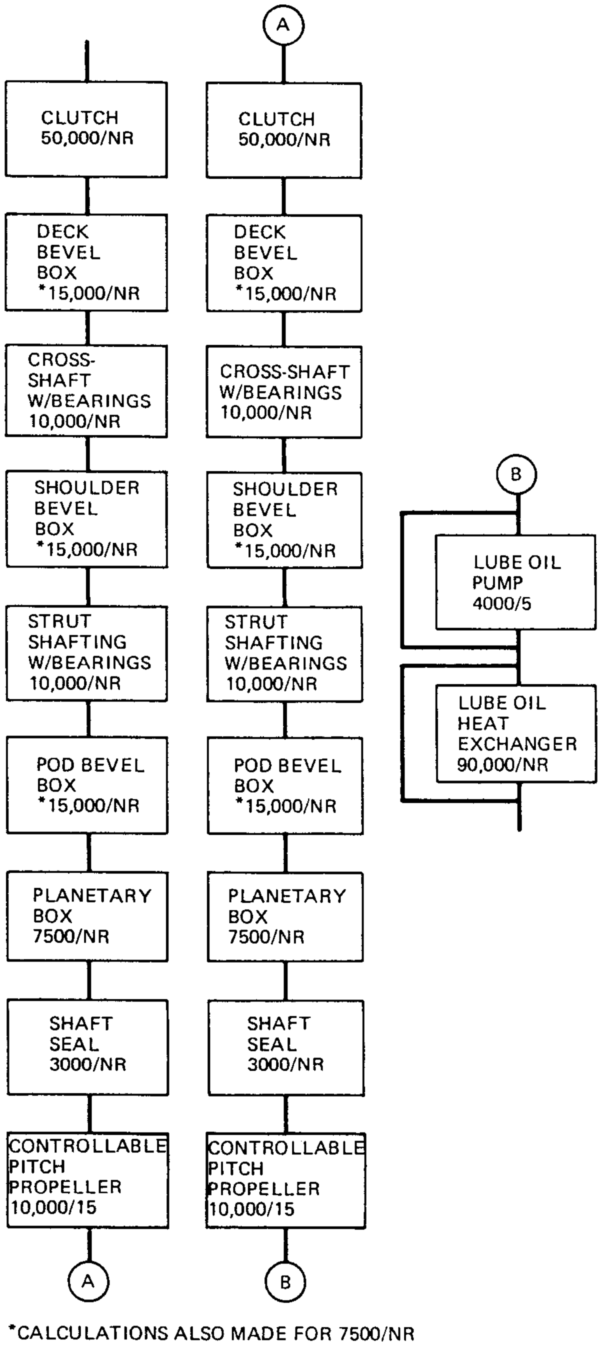
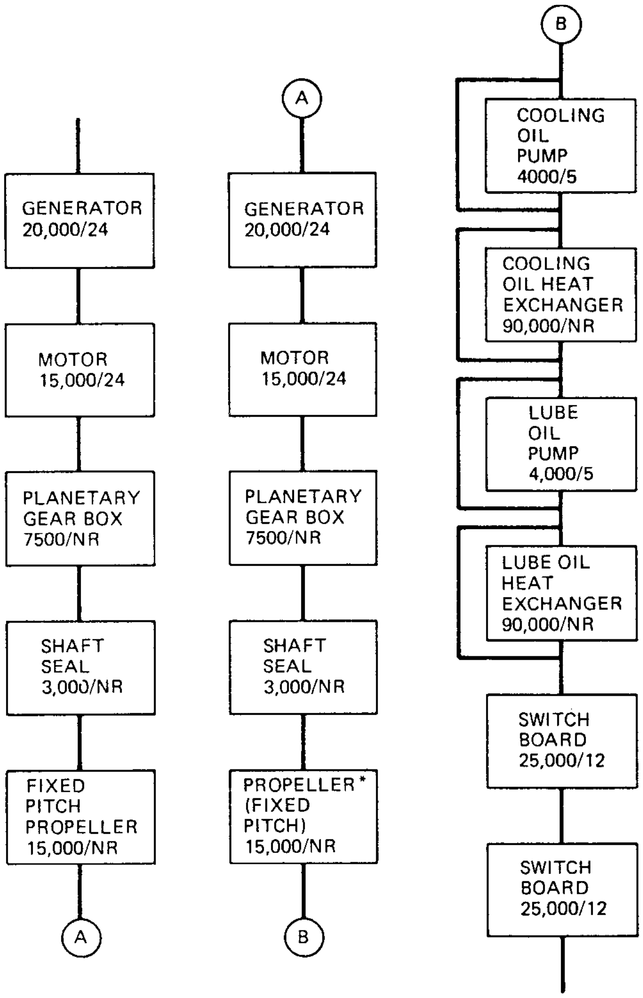


Fig. 8 Single Mesh Mechanical Transmission Reliability Block Diagram - Foilborne Mode

with prototyping. The accompanying planetary reduction gear technology is also at hand.

DC Superconductive Drive

This system requires the greatest development effort; however, it is the only one of the candidate systems receiving development funding and therefore, it has both momentum and support in its favor. The current program at DTNSRDC/Annapolis is producing laboratory-grade scale model size machinery and a true "sailor-proof" ship-qualified system is still in the distant future. The potential of this propulsion system for a very low noise signature is one of its greater attractions for future ASW applications. It becomes more



*VARIABLE PITCH PROPELLER ALSO CONSIDERED – 10,000/15

Fig. 9 AC Electric Drive Reliability Block Diagram - Foilborne Mode

attractive at the higher power levels because the supporting auxiliary machinery tends to remain of constant size and weight.

SUMMARY AND CONCLUSIONS

From the study it is clear that the mechanical and electrical drives are competitive for LM 2500 drivelines. Table 2 shows the overall relative ranking of the candidate systems along with the weighting factors used. This table, coupled with the development timelines resulted in the following conclusions:

- For a near term system the AC electric transmission system is the preferred system since it is the one closest to available hardware, development time is the shortest, it has the lowest technical risk, and the projected reliability is good.

- For noticeably increased performance with little increase in development time a mechanical dual mesh system is preferred. A lighter single mesh system is preferred if more development time is available or if higher horsepower dual mesh systems will be considered at a later date.

- The superconductive DC system shows high performance potential coupled with a promise of

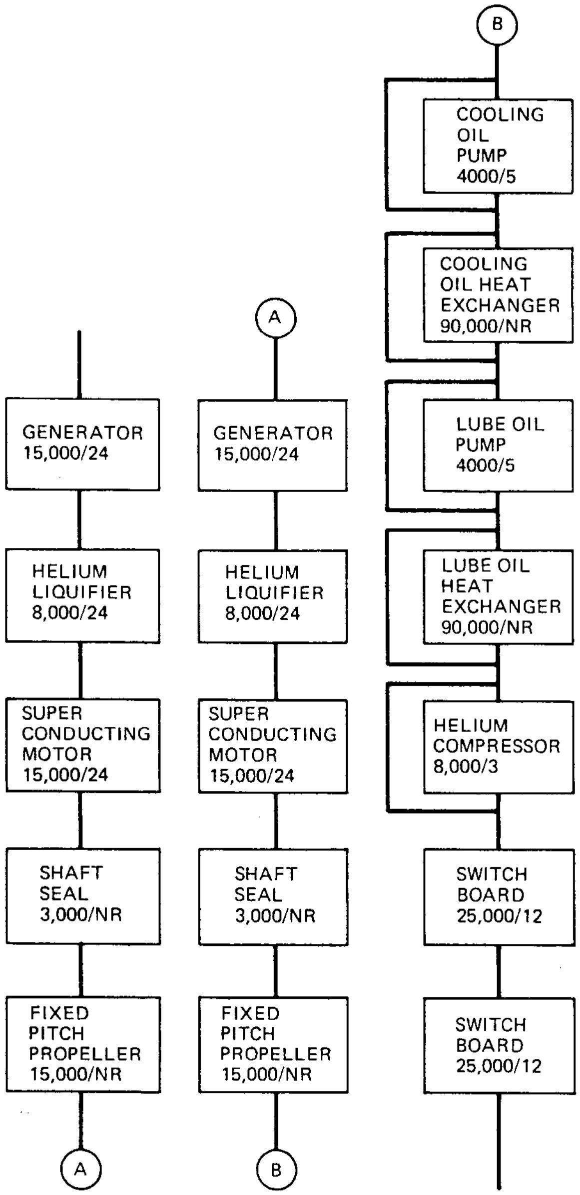


Fig. 10 DC Superconductive Drive Reliability Block Diagram - Foilborne Mode

silent operation. The system has no apparent upper limit on power level. These factors must be weighed against the longer development time required.

It is interesting to note that recent conceptual designs for large hydrofoil ships utilize mechanical transmissions, yet there is no current development program for these systems. This is in contrast to pending applications for the AC systems and an ongoing model superconductive DC program.

This difference in development effort complicates the evaluation process because all the systems are not at the same stage of development. Also, development methods differ between the systems.

The transmission system has been identified as the critical path item in development of large hydrofoil ships. In view of the timelines shown, it appears that initiation of large hydrofoil mechanical transmission development is past due.

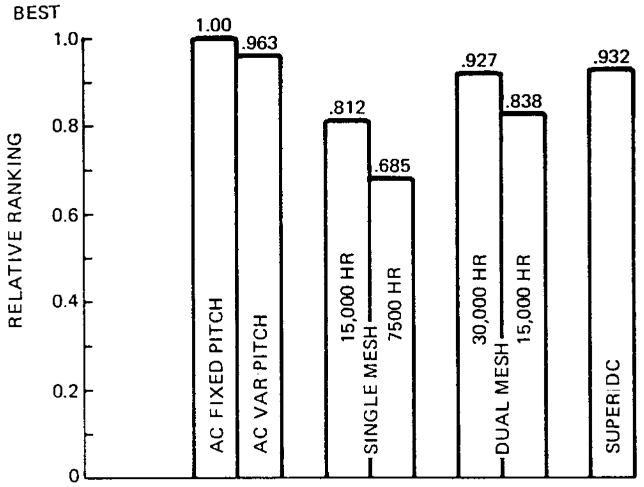


Fig. 11 Relative Merit - Reliability (Based on Estimated MTBF's)

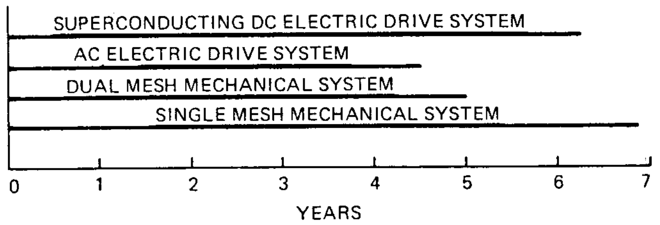


Fig. 12 Development Timelines 25,000 HP Drive Systems

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Bibliography

1. "Marine Power Plants For the 1970's," SNAME T&R Bulletin 3-26 January 1974, Section 3.3 "Superconducting Electrical Machines," pp 47-54.

2. "Navy's Superconductive Propulsion Program Reaches Hardware Stage," Gas Turbine World, March 1975, pp 12-15.

3. "Multipole Superconducting Electric Motors for Ship Propulsion," Thullen, P.; Keim, T.A.; Minervini, J.V.; IEEE Transactions on Magnetics, Vol. MAG-11, No. 2, March 1975, pp 653-656.

4. "Development of the Acyclic Shaped Field Motor," Cannell, M.; Doyle, T.; Raphael, S.; Proceedings of 1973 Workshop on Naval Applications of Superconductivity, October 1974, pp 123-165.

5. "Application of Superconducting Electrical Machinery to the Propulsion Systems of Commercial Vessels," Hicks, D.C., National Maritime Research Center Report No. NMRS-KP-115 October 1974.

Table 2. Summary of results

	SYSTEM[1] PERFORMANCE	WEIGHTING FACTOR	SYSTEM[2] RELIABILITY	WEIGHTING FACTOR	WEIGHTED AVERAGE OF PERFORMANCE AND RELIABILITY	CONTROL COMPLEXITY,[3] SYSTEM SAFETY, VULNERABILITY — AVERAGE OF SUBJECTIVE PARAMETERS
MECHANICAL TRANSMISSION, SINGLE MESH (VARIABLE PITCH PROPS.)	.97	6	.812	3	.92	A⁻
MECHANICAL TRANSMISSION, DUAL MESH (VARIABLE PITCH PROPS.)	.97	6	.927	3	.96	A⁻
AC DRIVE WITH FIXED PITCH FOILBORNE PROPELLERS	.84	6	1.000	3	.89	A
AC DRIVE WITH VARIABLE PITCH FOILBORNE PROPELLERS	.91	6	.963	3	.93	B⁺
DC SUPERCONDUCTIVE DRIVE WITH FIXED PITCH PROPELLERS	.95	6	.932	3	.94	C⁺

NOTES:
1. VALUE IS AVERAGE OF RELATIVE RATINGS FOR THE SIX SEPARATE PERFORMANCE PARAMETERS
2. BASED ON MTBF'S
3. AVERAGE OF SUBJECTIVE RATINGS WHERE A IS MOST FAVORED SYSTEM

6. "Cryogenic Systems and Superconductive Power," Hatch, B. D., General Electric Company Report No. SRD-73-022, 20 December 1972, First Semi-annual Report.

7. "Superconducting Propulsion System and Ship Interface Study - Final Report Phase II," Airesearch Manufacturing Company of California Report No. 74-10565-1, -2, Vols. 1-2, 1 September 1974.

8. "Large Hydrofoil Propulsion System Study Phase I Final Report - Mechanical Transmission (U)," Grumman Aerospace Corporation Report No. MAR-298-100-1, December 1976, Confidential.

9. "Large Hydrofoil Propulsion System Study Phase I Final Report - Summary (U)," Grumman Aerospace Corporation Report No. MAR-298-100-2, January 1977, Confidential.

10. "Large Hydrofoil Propulsion System Study Phase II Final Report (U)," Grumman Aerospace Corporation Report No. MAR-298-101-1, November 1977, Confidential.