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Combined Marine Propulsion Systems: Optimization and Validation by Simulation

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Modern Navy and Coast Guard Vessels usually have combined propulsion systems using gas turbines, diesel engines and electric motors as main propulsors. Desired operating profiles demand for individual optimization of the gear propulsion system with respect to efficiency, noise, operational flexibility and capital cost.

Combined systems are complex and therefore sensitive to dynamic excitation and resonance. To avoid unfavorable dynamic effects, it is necessary to validate candidate arrangements using modern tools like multi body simulation.

The paper describes the evaluation process for optimized combined marine propulsion systems and system validation by dynamic simulation.

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Introduction

The maritime world experiences significant changes concerning tasks and missions; global protection of trade sea ways plays an increasing role. Considering constraints with defense budgets, future Naval concepts demand a reduction in the number of vessels and, at the same time, more efficiency and flexibility of propulsion systems.

Various alternatives of mechanical and electric drive propulsion systems may be considered for future Naval ship building programs. The selection of the most appropriate propulsion system depends on the vessel platform and the intended mission profile. The most appropriate alternative enables optimum power management and minimum fuel oil consumption. A combined system using diesel engines for loitering, cruising, and –depending on vessel size and desired speed– gas turbines for sprint speed is the optimum mechanical drive system. For modern hybrid marine propulsion systems, electric motors more and more take over the role of a diesel engine for cruise speed in a combined plant, adding operational flexibility and other advantages. The heart of a combined propulsion system is a reduction gear which enables the flexible arrangement of prime movers and can thereby support various vessel missions. The following list shows examples for combined marine propulsion systems:

- CODAD (**CO**mbined **D**iesel **And** **D**iesel);
- CODELOD (**CO**mbined **D**iesel–**E**lectric **Or** **D**iesel);
- CODOG (**CO**mbined **D**iesel **Or** **G**as turbine);
- CODAG (**CO**mbined **D**iesel **And** **G**as turbine);
- CODELAG (**CO**mbined **D**iesel–**E**lectric **And** **G**as turbine).

This paper provides an overview on the engineering background from a gear manufacturer's perspective, and proposes considerations for the optimized propulsion solution. The theoretical validation by advanced calculation methods is also described.

Combined marine propulsion systems

Overview

Table 1 shows an overview of different propulsion system installations comparing hybrid mechanical and hybrid electric propulsion. Mechanical systems were continuously developed until approximately one decade ago from simple CODAD solutions to highly complex CODAG arrangements with a cross connect gear. In parallel, electric systems were increasingly accepted throughout the maritime world.

Any of the listed configurations have their specific advantages and should be considered reflecting the vessel's needs. Driving factor for the selection of a certain configuration is not only low investment cost but also life cycle cost considering specific fuel consumption, maintenance intensity and overhaul periods as well as reliability and redundancy.

The missions determine the platform, the platform determines the propulsion system and the propulsion system determines the reduction gear system. The potential prime movers in a propulsion system are given – their weights, dimensions and performance are individually selected. The prime movers can be considered black boxes. A flexibly designed reduction gear facilitates

- the matching and combining, if applicable, of the optimum prime movers with the propulsors,
- the location of the prime movers in the machinery space, and
- the optimum operation and maximum fuel efficiency of the prime movers.

Table 1. Propulsion system variants and existing applications for surface combatants

Propulsion type	Description	Installed power range, MW	Typical application
CODELOD	Combined electric motor or diesel engine	DE 5 ... 10 EM 0.3 ... 0.6	- Netherlands Navy OPV - Korean Coast Guard OPV
CODELAD	Combined electric motor and diesel engine	DE 5 ... 10 EM 0.7 ... 1.5	No reference available yet
CODOG	Combined diesel engine or gas turbine	DE 2.5 ... 9 GT 15 ... 22	- German Navy F123 - ROKN FFX
CODAG	Combined diesel and gas turbine (with or without cross connect gear)	DE 5 ... 9 GT 20 ... 36	With cross connect gear: - German Navy f124 - U.S. Coast Guard NSC Without cross connect gear: - U.S. Navy - Lockheed Martin LCS - Austal LCS
CODELOG	Combined electric motor or gas turbine	EM 2 ... 3 GT 20 ... 32	Italian Navy FREMM
CODELAG	Combined electric motor and gas turbine	EM 4 ... 6 GT 20 ... 25	German Navy F125

The reduction gear is a key determinant in developing a propulsion system that will meet the vessel's operating envelope and will fit the machinery space physical envelope. The overview presented herein provides an overview and trade-off analysis of principal mechanical drive systems and can serve as a reference and sample to identify the optimum propulsion system for a vessel. At least ten major parameters need to be considered in determining the optimum propulsion system:

- Missions
- Operating profile
- Power
- Efficiency and fuel consumption
- Weight
- Dimensions
- Maintenance and repair cost
- Location flexibility
- Survivability and redundancy
- Signature

Once the propulsion system has been selected, the final arrangement can be further adjusted and optimized to fit within the design parameters.

Operating speed profile

For decades, different prime movers have been combined to allow for flexible operation of propulsion plants. As a basis for the layout, the assumed speed profile of the vessel needs to be known. In this context, the comparison between former speed distribution assumptions and today's approach is interesting. The two graphs in Figure 1 show typical operating profiles of frigates – 20 years ago and today. The change of operational demands is obvious: With a modern frigate concept, operation in slow speed or loiter mode has almost doubled, whereas sprint speed of 30+ knots is rarely considered, the US Navy LCS is the major exception for a surface combatant with versatile mission deployments.

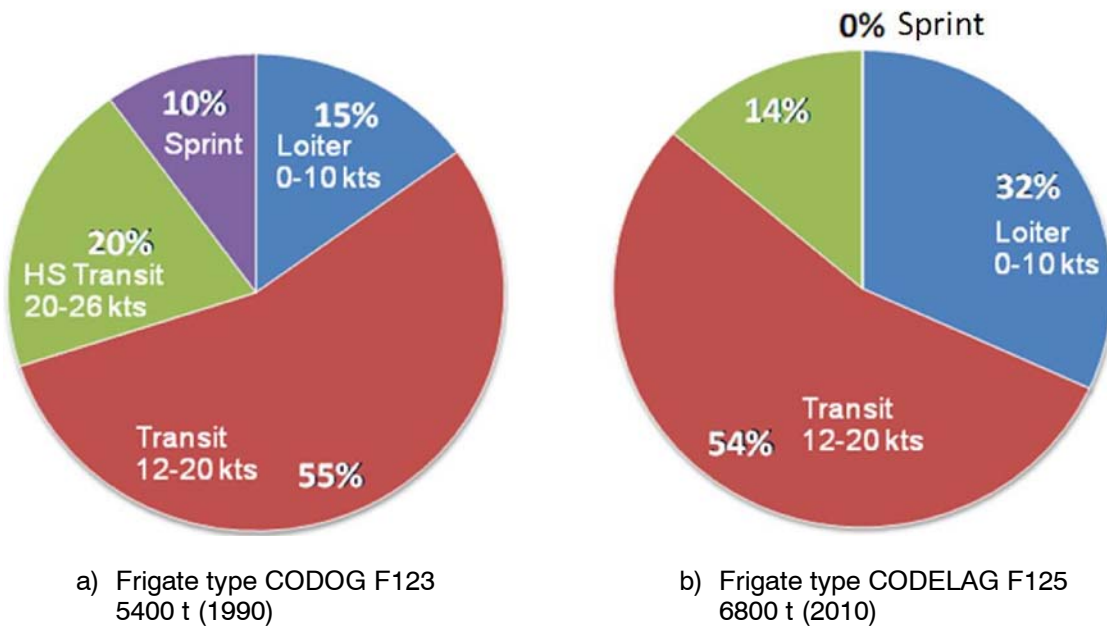


Figure 1. Design operating profile (Source: German Naval Headquarters)

Why combined propulsion plants?

A **gas turbine** is compact, light-weight and high-powered. It requires reasonable maintenance. However, when it operates at less than full or near-full load, its specific fuel consumption increases significantly.

A **high speed diesel engine** has a high thermal efficiency over a broad range of loads and accordingly maintains economic and level specific fuel consumption over those loads.

Combined systems take consideration of the above mentioned aspects for an optimized combined system.

Combined propulsion system examples

CODAG is the result of a further development in propulsion systems, mainly derived from CODOG. A perfect CODAG system integration was performed in Germany in the late 1990s. The first German Navy F124 Frigate with CODAG propulsion (Figure 2) was put in operation in 2001.

The main factors in the successful development of the F124 CODAG plant are as follows:

- Experience derived from CODOG and CODAD applications, e.g., self synchronizing overrunning clutch; light weight fabricated casings and carburized double helical gears;
- Optimized multi-disk clutch arrangement with hydraulic controls, lubrication and assembly on one common shaft;
- Ship control system and gear sub-controls following latest electronic standards are perfectly integrated using a programmable logic control unit (PLC) for operation, guarding and BUS data exchange. Local monitoring and operation is facilitated comfortably via the PLC touch screen.

The Lockheed Martin LCS monohull type (Freedom class) of the US Navy features a completely different propulsion train technology. Four water jets are driven by two symmetrically arranged CODAG systems, where the high speed combining gear and the low speed splitter gear are separately installed, linked by long intermediate shafts each, see Figure 3. Gas turbines and diesel engines can be engaged separately in cruise or higher speed propulsion modes, or jointly drive the water jets achieving a top speed in excess of 40 knots in this CODAG mode. To match with different required water jet speeds, the diesel engine inputs are equipped with two gear stages where the adequate gear ratio is selected via a multi disc clutch engagement.

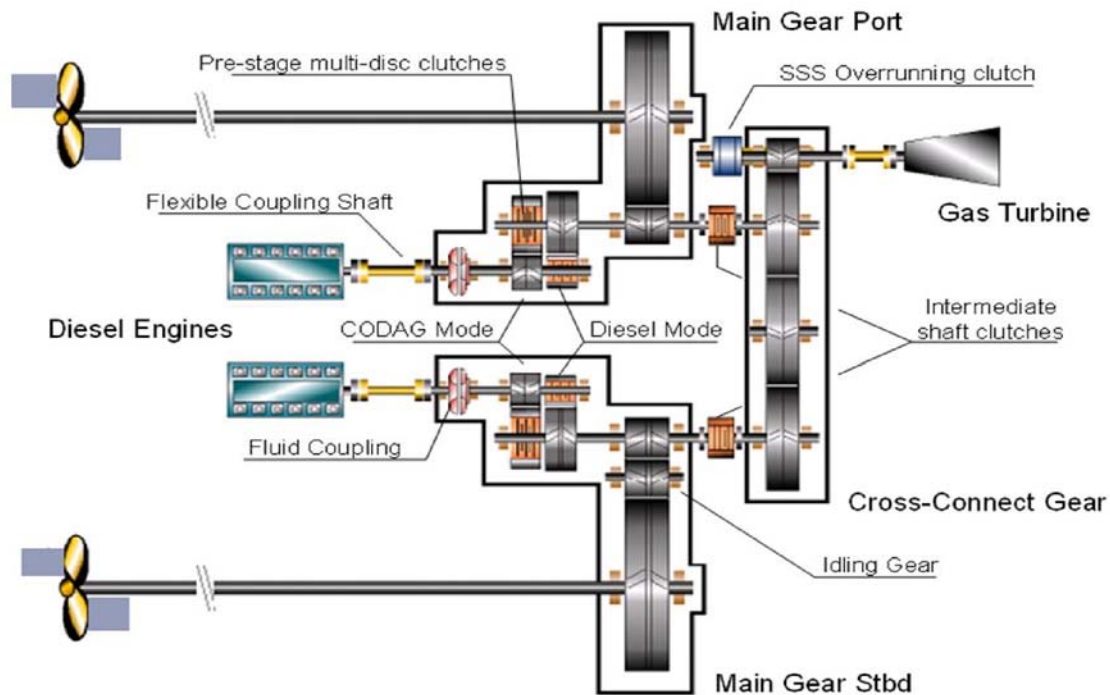


Figure 2. F124 CODAG gear plant schematic

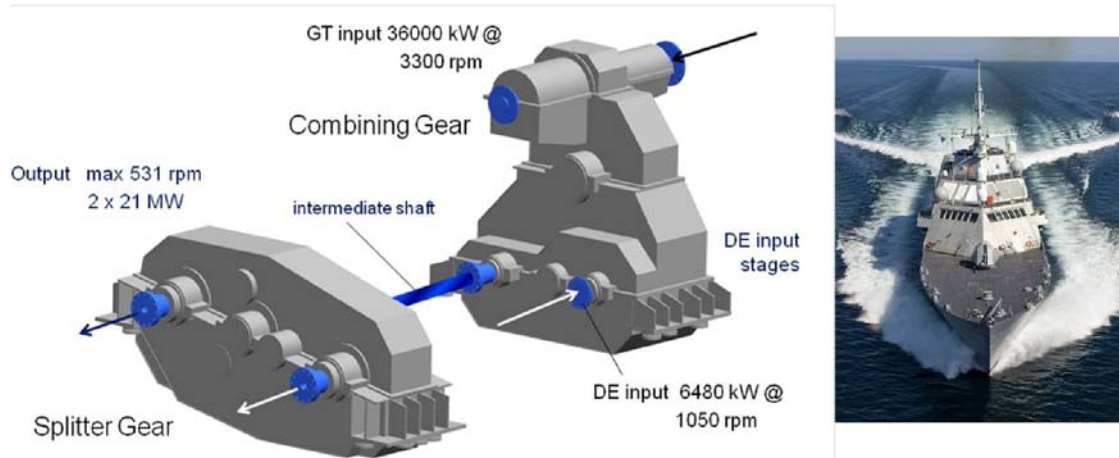


Figure 3. U.S. Navy Lockheed Martin LCS CODAG gear plant

More examples for combined propulsion are given with the variants for the propulsion system of a sample frigate in the following paragraphs.

Sample for propulsion system variants

To demonstrate variants and evaluation of suitable combined propulsion systems, a 5200 ton frigate is chosen as an example.

Mission profile and power requirement

The total required prime mover power is derived from the average power per ton of comparable Naval vessels and experience. The required installed prime mover power to achieve 29 kts for a 5200 tons frigate is approximately 40 MW. Figure 4 shows a simplified power vs. speed curve for a cubic law correlation. The frigate is assumed to operate underway approximately 150 days, i.e., 3600 hours per year.