Shafting Installation and Alignment on the USS Freedom (LCS-1)

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ABSTRACT

Construction of USS Freedom (LCS-1), the first of a new class of Littoral Combat Ships, was recently completed. The LCS class is an entirely new breed of US Navy warship. A fast, agile, and networked surface combatant, LCS's modular, focused-mission design provides Combatant Commanders the required war fighting capabilities and operational flexibility to ensure maritime dominance and access for the joint force. The 3000 ton vessel employs a steel hull and aluminum superstructure, which allow the vessel to reach speeds above 40 knots. The USS Freedom propulsion system consists of a quartet of waterjets driven by a Combined Diesel and Gas Turbine (CODAG) power plant through a complex shafting system. The two propulsion shafting systems (port and starboard) each have a gas turbine and/or a diesel engine coupled to “combining reduction gearbox”. The combining reduction gearbox drives a “splitter reduction gearbox” through a “gear coupling lineshaft”. The splitter reduction gearbox, in turn, drives two waterjets via a “boost waterjet lineshaft” and a “steerable waterjet lineshaft”. The boost waterjet lineshaft is concentric with the inboard quill shaft of the splitter reduction gearbox and is engaged via an overhanging clutch. The diesel engines, gearboxes, and gas turbines are resiliently mounted. There are four different shafting arrangements with a total of 28 support bearings, four gearboxes, two over-hanging clutches, and four axial (longitudinal) flexible couplings. The gear coupling lineshaft operates at over 1400 RPM and is supported by bearings with a relatively high bearing load influence number to load ratio. All these factors present unique challenges to the installation and alignment of the shafting system. This paper provides a description of some of the challenges and techniques employed to successfully install and align this complex shafting system.

INTRODUCTION

The lead ship of the US Navy's new class of Littoral Combat Ships is USS Freedom (LCS-1). LCS-1 is designed and constructed to operate with focused-mission packages that support missions assigned by Combatant Commanders. The mission modules allow LCS-1 to support Special Operations Forces (SOF), including deployment of manned and unmanned vehicles; high-speed transit; Maritime Interdiction Operations (MIO); Intelligence, Surveillance and Reconnaissance (ISR); and Anti-Terrorism/Force Protection (AT/FP). Speed and agility will be critical for efficient and effective conduct of the littoral missions. During sea trials, LCS-1 proved itself capable of low speed operations for littoral missions, transit at economical speeds, and high-speed sprints, which may be necessary to avoid/prosecute a small boat or submarine threat, conduct intercept operations over the horizon, or for insertion or extraction missions.

The LCS-1 class a semi-planing monohull design based on the hull form used in the 60-plus knot Destriero, which holds the transatlantic speed record. This LCS-1 design combines high-speed maneuverability with a comfortable sea keeping motion that supports launch and recovery operations, combat missions and optimal human performance from the crew. It can also turn 360º in less than eight lengths at its rated sprint speed and accelerate to full speed in less than two minutes. The 3,000 ton LCS-1 employs a high strength steel hull with an aluminum superstructure, which allows the vessel to reach speeds of over 40 knots, depending on the configuration of the mission modules. It is driven by a quartet of waterjets linked to a Combined Diesel & Gas Turbine (CODAG) power plant with a pair of MT30 gas turbines.

The propulsion shafting system design arrangement incorporates a number of features found on a variety of marine propulsion plants and combines them into one unique system to provide the required propulsive performance for this new class of surface combatant. This paper presents some of the challenges and techniques employed to successfully install and align this complex shafting system.

PROPULSION SYSTEM ARRANGEMENT

The LCS-1 has four waterjets driven by two Fairbanks Morse diesel engines and/or two Rolls-Royce gas turbines. Three drive modes are available: Combined Gas Turbine And Diesel (CODAG), Gas Turbine Only and Diesel Only.

As shown in Figure 1, the two propulsion shafting systems (port and starboard) each have a gas turbine and/or a diesel engine driving a "combining reduction gearbox". The combining reduction gearbox drives a second gearbox, the "splitter reduction gearbox, through the "gear coupling lineshaft". Each splitter reduction gearbox drives one "steerable" waterjet (outboard) and one "boost" waterjet (inboard). There are four different shafting arrangements with a total of 28 bearings:

i. 2 x Gear Coupling Lineshafts (10 bearings)
ii. 2 x Steerable Water-Jet Lineshafts (6 bearings)
iii. 2 x Boost Water-Jet Lineshafts (4 bearings)
iv. 4 x Water-Jet Impeller Shafts (8 bearings)

The boost waterjet lineshaft is concentric with the inboard output shaft of the splitter gearbox and is engaged via an overhanging clutch. When the clutch is not engaged the boost waterjet lineshaft free rotates. The diesel engines, gearboxes, and gas turbines are resiliently mounted.

The design arrangement presented many challenges for installation and alignment. The following were some of the more significant challenges:

i. High Speed Shafting: Shafting over 50' long rotating at over 1300 RPM.
ii. Splitter Gearboxes: Lineshafting connected to one input and two outputs. Over-hanging clutch on the inboard output quill shaft.
iii. High Influence Number to Bearing Load Ratio: Small changes in bearing position result in relatively large changes in bearing loads.
iv. Lightly Loaded Bearings Relative to Shaft Power: Bearing loads less than 2000 lbs supporting shafting with more than 40,000 HP.
v. Flexible couplings: Couplings designed to transmit high torque while allowing for significant axial thermal expansion of shafting.
vi. Military vibration and shock requirements: System is designed and installed to satisfy US Navy shock requirements.

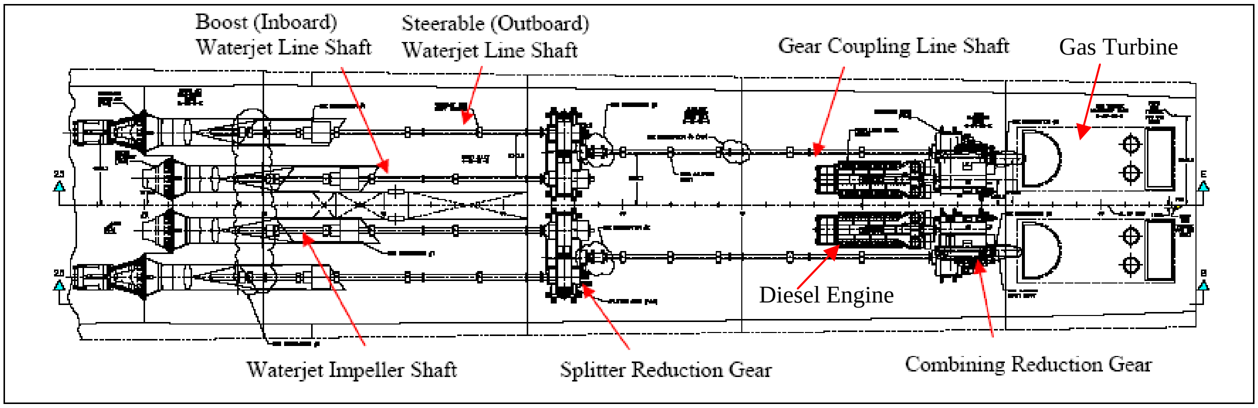

Figure 1 Propulsion System Arrangement

Photo 1 LCS 3 MPDEs and Gear Coupling Shafts to Splitter Gearboxes (Looking Aft)

Photo 2 LCS 3 Port Boost Waterjet Lineshaft, Bearing and Seal

CONSTRUCTION

The LCS-1 was constructed in a modular fashion, consistent with modern ship building. The propulsion machinery foundations were fitted and aligned using optical alignment techniques. All propulsion machinery, shafting, and bearings were installed and rough-aligned prior to launching. Specialized design features, and construction and measurement techniques were employed to ensure that final alignment with the vessel afloat would not require significant re-positioning of the machinery, in particular the gearboxes. Photos 1 to 12 show the vessel in various stages of construction.

Photo 3 LCS 3 AMR Gear Coupling Shaft Flex Coupling


Photo 4 The second of two Rolls-Royce MT 30 gas turbine engines is landed onto a hull block


Photo 7 Preparation for Waterjet Installation


Photo 5 Hull Under Construction


Photo 8 Steerable and Fixed Waterjets


Photo 6 Landing Deckhouse


Photo 9 Rolling Hull to Launch Ways

Photo 10 LCS 1 USS Freedom on Launch Ways

Photo 11 Final Shaft Alignment Conducted Afloat

Photo 12 LCS 3 USS Fort Worth Launch

THEORETICAL ANALYSIS

Finite Element Analysis was used to calculate the theoretical alignment condition for the individual propulsion shafting systems. Finite element models were constructed using beam elements for the uniform shaft sections with concentrated springs at the bearing locations. The analysis determined the theoretical bearing load influence matrix, the bearing loads, the shaft stresses, the bending moments and the shaft deflection. Alignment procedures and tolerances were developed from the results of these analyses. Four separate finite element models were developed:

i. Gear Coupling Lineshaft – Including output (bull gear) shaft of combining gear box and input (pinion) shaft of splitter gear box.
ii. Outboard Waterjet Lineshaft – Including splitter gear box output (bull gear) shaft and waterjet impeller shaft.
iii. Inboard Waterjet Lineshaft – Including splitter gear box quill shaft and waterjet impeller shaft – clutch disengaged and engaged.
iv. Inboard Splitter Gearbox Bull Gear Shaft – Bull gear shaft with over-hanging - clutch disengaged.

Figures 2 to 4 illustrate the finite element models, with the exception of the inboard splitter gearbox bull gear shaft.

Propulsion Shaftline Flexibility

The bearing load influence numbers describe the flexibility of the shaftline as load change per unit offset. Influence numbers are used to determine the tolerance for misalignment and the appropriate theoretical bearing offsets for a satisfactory alignment condition. They can be applied to both vertical and athwartships (horizontal) bearing loads.

Combining Gearbox to Splitter Gearbox

The influence numbers for the gear coupling lineshaft indicated that this shaftline was relatively stiff, such that an offset of 10 mils would result in a load change of about 70% of the prescribed static load. Therefore, the lineshaft bearings on the gear coupling lineshaft were required to be aligned within less than 5 mils of their prescribed positions. This required the use of the stain gauge alignment technique.

Steerable and Boost Waterjet Drive Shafts

The influence numbers for these shafts indicated that the shaft was relatively flexible, such that an offset of 45 mils from the straight-line condition was required to overload a bearing. Therefore, the waterjet impeller shaft bearings were required to be aligned within 20 mils of their prescribed positions. The stain gauge alignment technique was also employed.

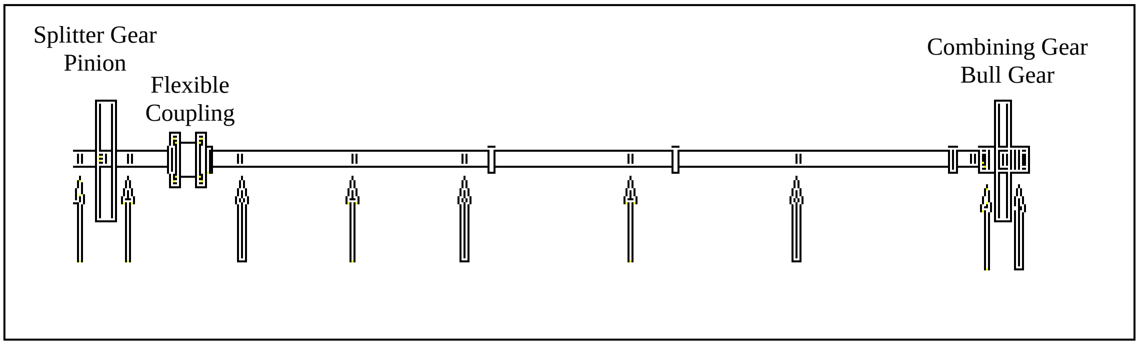

Figure 2 Gear Coupling Shaft Finite Element Model

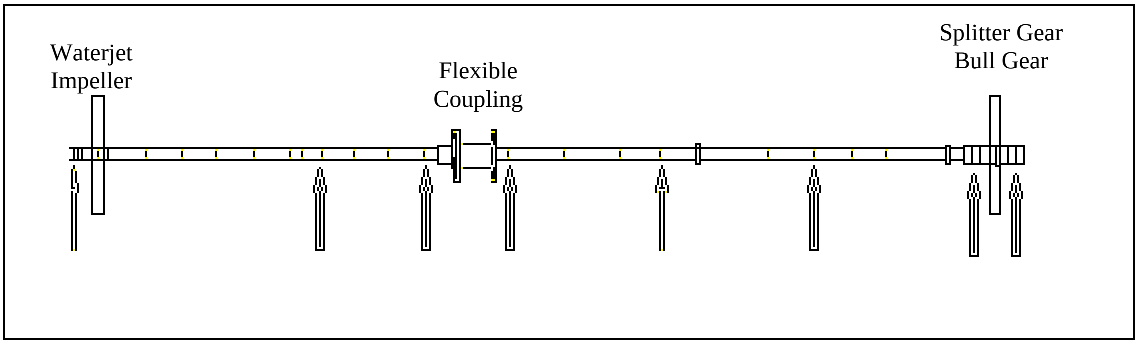

Figure 3 Outboard (Steerable) Waterjet Drive Shaft Finite Element Model

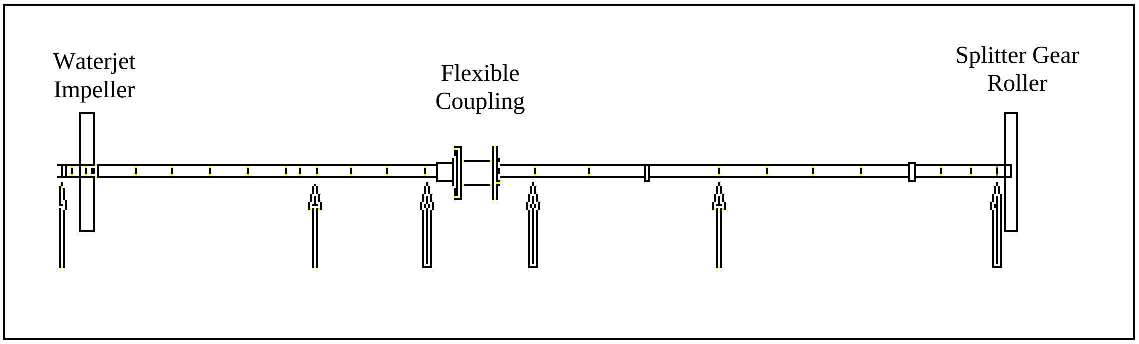

Figure 4 Inboard Waterjet (Boost) Drive Shaft Finite Element Model Clutch Disengaged

Bearing Loads

The static bearing loads were calculated under the following conditions:

- i. Straight Line: Shaft centers at the bearing locations are aligned concentric.
- ii. Aligned Cold: The bearings are offset the recommended theoretical amount for an acceptable alignment condition.
- iii. Aligned Hot: The lineshaft bearings in their aligned positions and the gearbox bearings higher due to relative expected thermal rise.

Recommended bearing offsets were determined to provide an acceptable alignment condition, with the least-cost and the most reliable method of installation.

ALIGNMENT PROCEDURE

The following three techniques were used to align the shafting systems:

i. Optical (laser / telescope): This method was used to align the waterjet transom rings to the output shafts of the splitter gearbox. It was also used to rough align the lineshaft bearings and to align the combining gearbox to the splitter gearbox.
ii. Hydraulic Jack: This method was used to provide an independent check on the strain gauge alignment results. It is useful for the vertical loads only. Reference [1] describes the technique in some detail.
iii. Strain Gauge Technique: This method was used to conduct the final alignment (horizontal and vertical) of the completely assembled propulsion system prior to final pinning the engines the lineshaft bearings, the splitter gearbox and the combining gearbox. References [2, 3, 4] describe this technique.

The primary advantages of using the strain gauge technique are:

- Accurate measurement of lightly loaded bearings.
- Measurement of athwartships (horizontal) bearing loads.
- Measurement of inaccessible bearing loads, such as bull gear, pinion shaft and waterjet impeller bearings.
- Accurate measurement of gear shaft bearing loads with the resiliently mounted gearboxes.
- Lineshafts remain connected and bearings remained sealed.
- A line of sight is not required.
- Shaft bending stresses are measured directly.
- Shaft hog or sag can be determined. Its magnitude may be estimated.
- After the gauges are installed, the alignment condition of the entire shafting system can be re-measured in a relatively short time to confirm the alignment in the hot condition, or in different trim conditions.

Combined with the results from a finite element model, strain gauge data can also provide reliable, accurate estimates of the bearing offsets. On LCS-1, the vertical and athwartships reactions were measured on all support bearings.

A satisfactory alignment of the LCS-1 propulsion shafting systems using the following sequence of events:

Prior to launching the vessel

1. Module fit up and welding was completed from the transom to one module forward of gas turbine space before the impeller shaft alignment was started and impeller ring was fitted in place.
2. The combining gearboxes and the splitter gearboxes were loaded out and aligned to one another optically.
3. The lineshaft bearing housing hold down bolt holes for the bearings between the combining gearbox and the splitter gearbox were marked using optical measurements.
4. All shafting and bearings between splitter gears and combining gears was installed.
5. The forward end of the gear coupling lineshaft was connected to the combining gearbox.
6. The flexible coupling at the aft end of the gear coupling lineshaft was made up to the lineshaft and to the splitter gearbox input shaft.
7. The gas turbines and the diesel engines were rough aligned to the combining gearboxes. Sufficient room to move engines and gas turbines in all directions for final alignment was confirmed.
8. Transom holes were cut for the transom cone assemblies.
9. The waterjet assemblies were aligned by line of sight and longitudinally to benchmark reference points and welded in place.
10. The waterjet transom rings were machined.
11. The waterjet shaft enclosure tubes and the waterjet impellers were installed.
12. All shafting and bearings between the splitter gearboxes and the waterjets was installed.
13. The forward end of waterjet lineshafting was connected to the splitter gearboxes. The waterjet impeller shafts were connected to their lineshafts.
14. The seal mounting plates were aligned and installed.
15. The machinery, equipment and shafting were secured for launching.

After Launching

1. A diver checked all waterjet impeller blade tip clearances.
2. All propulsion shafting from combining gears to waterjet impellers was aligned using the strain gauge technique.
3. The gas turbines and diesel engines were aligned to the combining gearboxes.
4. All machinery from combining gearboxes to waterjet impeller shafts was chocked and bolted down. The alignment condition was checked using strain gauge technique.
5. The diesel engines were final aligned to the combining gearboxes and the flexible couplings were installed.
6. The gas turbines were final aligned to the combining gearboxes and the flexible couplings were installed.
7. The gas turbines and the diesel engines were chocked and bolted down in place.
8. Shaft tunnels and bulkhead seals were installed.

As an independent check on the strain gauge results, vertical loads on selected bearings were also measured using the hydraulic jack/load cell method. The bearing loads obtained by this technique were in close agreement with the strain gauge results.

CONCLUSIONS

- All shafts from the waterjet hub up to and including the combining gearbox were aligned to a satisfactory condition.
- All bearing loads were within allowable tolerances.
- The hydraulic jack / load cell results agreed well with the loads obtained from the strain gauge technique.
- The flexible couplings were aligned within tolerance.
- Sea trials were conducted in July 2009. Bearing temperatures and shafting vibrations were all well below the acceptable limits. Not one component in the propulsion shafting system required service, repair or re-alignment.

OPERATIONAL EXPERIENCE

USS Freedom LCS 1 has been successfully operating with the US Navy since 2009 putting over 50,000 nautical miles under her keel. During her first deployment with the US Southern Command (SOUTHCOM) and the US Pacific Command (PACOM) she successfully conducted counter-illicit trafficking (CIT) operations. The ships performance allowed her to intercepting several high speed boats, recovering several tons of illegal drugs while operating off the Atlantic and Pacific coast of Central and South America. During this time the propulsion system performed flawlessly and there have been no reported issues with the propulsion shafting system.

USS Fort Worth (LCS 3) was launched on December 4th 2010. In February LCS 3's propulsions system was aligned using the same processes and procedures as outlined above and will begin trials in the summer of 2011.

AKNOWLEDGEMENTS

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DISCLAIMER

The views expresses in this paper are those of the authors and not necessarily of any members of the LCS-1 design and construction team.

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