NORTHWEST HYDROFOIL LINE'S HYDROFOIL SHIP "VICTORIA" GAS TURBINE MAIN PROPULSION SYSTEM

William I. Niedermair
President
Northwest Hydrofoil Lines, Inc.
Winslow, Washington 98110

ABSTRACT

The 75 passenger hydrofoil ship "Victoria" was designed for Northwest Hydrofoil Lines by Gibbs and Cox of New York and constructed by Maryland Shipbuilding and Drydock Company of Baltimore. The unique ship is equipped with General Electric twin LM100 gas turbines, transmission and gears, and flight control system. Presently the "Victoria" is in regular service between Seattle, Washington and Victoria, B.C.

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Introduction

The vessel is designed to carry 75 passengers and to fly in 8 to 10 foot waves at the designed speed of 40 knots. The fully submersible foil system with control surfaces activated by a flight control system was selected to obtain maximum vessel stability and minimum ship motion for passenger safety and comfort. The wing-like underwater struts and foils are constructed of high-tensile strength (HY-80) steel for maximum strength with minimum weight.

The all aluminum hull, designed for two-compartment subdivision (i.e., any two adjacent compartments below the main deck may be flooded and the vessel will remain afloat) is a hard chine, high deadrise forward, planing hull form selected for easy entrance, good planning surfac aft, and good re-entry characteristics for take-offs and landings. Approximately 65 per cent of the main hull is formed by extruded panels combining hull plating and tee stiffeners and is of the 5000 series aluminum material. The passenger cabin is arranged in aircraft fashion with three and four seats abreast on either side of a longitudinal aisle. The cabin is acoustically and thermally insulated and sheathed in aluminum, and the forward and after cabin bulkheads are covered with a walnut wood veneer. The passenger cabin deck is covered with an acrylan carpeting, and the reclining seats are vinyl covered and are equipped with foot rests and seat belts. The cabin is complete with water dispensers, overhead racks, and two lavatories, one fore and one aft, are located in the main passenger cabin. All materials of construction, including curtains, are fire-proof in accordance with U.S. Coast Guard rules and regulations.

The vessel is fully automated and is operated from the Flight Deck Control Center. The Flight Deck, located forward, has an unobstructed 360° visibility, and is equipped with duplicate steering controls for the Captain and First Officer.

Passenger and crew spaces are fully heated and ventilated by means of a hot air system, and air conditioning is optional.

The displacement drive compartment, auxiliary machinery space, fuel oil tanks, electronic compartment and baggage-freight compartment are all located below the main deck.

The two 1000 HP propulsion gas turbines are located in watertight sponsons outside the main hull and drive through a single train right angle reduction gear system consisting of a reduction gear, upper and lower spiral bevel gear pairs, vertical shafting and non-reversing main propellers.

A Foil-Borne Control System is provided to automatically maintain the stability of the "Victoria" in the foilborne condition and provides height, heel, trim and heading control and power steering.

A 100 HP Harnischfeger light weight displacement-drive diesel engine is provided with a Hydro-Drive retractable right angle drive unit mounted through the stern of the main hull to facilitate easy maneuverability in docking, undocking, and is retracted during normal flight.

The starting, stopping and operations of the main turbines and auxiliary diesel engine is remotely controlled from the Flight Deck. The remainder of the auxiliaries are remotely controlled from the control area aft of the main cabin.

The "Victoria" is provided with a 24 volt DC electrical plant with power source from two (2) 500 amp, 30 volt aircraft type generators, one driven off each main turbine. Emergency power is provided by a separate auxiliary battery to serve illumination and instrumentation services in the event of loss of ship’s service power. A second independent auxiliary power source is provided by a 300 amp generator driven off of the displacement diesel drive.

A Carbon-Fiber-Foam (CFRP) fixed flooding fire fighting system is installed to protect compartments below the main deck and the gas-turbine sponsons. A sea water fire main runs the length of the "Victoria" with two fire stations located so as to reach any point in the vessel with a 25 ft. hose.

Four (4) twenty-five man self-inflating life rafts of the latest type are provided, as required by the U.S. Coast Guard. The life rafts are completely equipped with self-inflation equipment; distress signal equipment; first aid kits; emergency water and rations; and is further equipped with survival manuals, leak repair kits and anti-seasick pills.

The "Victoria" is fitted with complete navigational aids and communications equipment, including radio telephone, a radio direction finder, radar, depth and forward looking sonar, electric horn and compasses.

MAIN PROPULSION SYSTEM

Engine Description

The vessel uses two LM100 marine gas turbines.

The LM100 turboshaft engine is a small, lightweight, two-shaft power plant in the 1000 shaft-horsepower class. The engine consists of a gas generator, which produces a high pressure hot gas flow and a mechanically independent power takeoff which converts the gas flow to useful mechanical shaft energy. The power plant weighs less than 400 pounds and consists of five major sections: compressor section, combustion section, gas generator turbine section, power turbine section and accessory drive section.

The basic engine assembly employs two (2) independent rotor systems. The gas generator rotor system consists of the compressor rotor, two gas generator turbine wheels, connecting shaft, and three bearings. The power turbine rotor system consists of an integral power turbine wheel and shaft, and two bearings.

(Figure 1)

The compressor section includes the front frame, compressor rotor, compressor stator, and rear frame. Ambient air enters through the front frame and is directed to the compressor inlet, passes through ten stages of compression and is discharged into the rear frame. The compressor, at maximum power, develops a pressure ratio of 8:1 and air is discharged from the compressor at the rate of 12.5 pounds per second.

The combustion section is that portion of the engine in which fuel is added to the compressed air and ignited, thus causing a rapid expansion of gases toward the gas generator turbine section. The combustion section of the engine includes the outer casing, combustion liner, outer deflector, and various fuel system components.

The gas generator turbine is a two-stage type, employing blades that utilize both the impulse and reaction principles, to extract the required power from the exhaust gases to drive the compressor.

The power turbine section, flange-bolted to the gas generator turbine casing, consists of the exhaust casing assembly, power turbine rotor assembly, and power
turbine governor drive system.

The engine accessory section is composed of those components that sustain the functions of the basic engine. They include the accessory drive gear casing assembly, main lube pump, main fuel pump, gas generator governor and gas generator tachometer-generator.

The accessory drive gear assembly is mounted at the bottom of the engine front frame assembly and transmits power to drive the engine accessories. This power is taken from the compressor rotor shaft, through the accessory drive gear assembly, via radial shafting and right angle gears.

The accessory drive gear housing houses the engine oil filter, relief valve, filter bypass valve, magnetic drain plug, bearings, and gears. (Figure 2)

**Systems Description**

The lubrication system is a dry-sump positive displacement type providing lubrication for the accessory drive gear components, gas generator bearings, power turbine bearings and power turbine governor drive gear components. (Figure 3)

The fuel control system regulates the flow of fuel that is sprayed into the combustion system of the gas generator. The gas generator speed is controlled by the fuel control, which in turn is controlled by the combined outputs of the gas generator and power turbine governors. In addition, the system, independent of the governor demand, schedules fuel to the engine for starting, acceleration and deceleration within safe limits to prevent stall, excessive turbine inlet temperature or flameout. (Figure 4)

The control of the gas turbine propulsion system is semi-automatic. The operator may set the throttle at the Start position, turn a switch and expect the turbine to reach the selected speed and then indicate attainment of that speed by an indicator light or other instrumentation. He may than select Idle or subsequent cruising speeds at random being guided by the indicator lights on the control panel. If conditions are not appropriate for operation, the engine will not start or will shutdown if already started and a fault light will indicate the reason for failure.

Each of the gas turbines has its own electro-mechanical control system. They are separate systems with the exception that at each of the two throttle stations, a pair of throttle controls are mounted in tandem for the convenience of the operator.

The system consists of a control panel and instrument panel instrumentation mounted in the control panel.

The control panel contains most of the devices for remotely starting, stopping and monitoring the propulsion gas turbines. It has been specifically designed to fit into the boat's control console.

The Instrument Panel contains all the remaining components of the control system that aren't located in the Control Panel or are not in the nature of a sensor or display indicator. (Figure 5)

**MACHINERY ARRANGEMENT**

The gas turbines are located outboard of the main hull in watertight sponsons and drive single-shaft right angle drives.

Engine mounting provisions and shaft power connections are such that harmful effects are not imposed upon the engine. The engine mounting arrangement accommodates radial and axial thermal expansion of the engine. It also isolates the engine from objectionable vehicle deflection and vibratory inputs.

Engine mounting is accomplished by use of a rigid tube bolted to the rear flange of the power turbine and an inverted "U" support member connected to the compressor front frame.

This mounting scheme, with the rigid support tube fastened to the power turbine casing, allows for thermal growth of the machine by use of flexible plates incorporated in the front support and a spherical bearing incorporated in the front vertical mounting bracket located at the top of the compressor front frame.

The power shaft mates with the power turbine shaft coupling and provides for misalignment between the turbine and the drives equipment, thermal growth of the rigid support tube, etc.

The approximate heat radiation and convection in the engine compartment from the engine hot surfaces is 40,000 BTU per hour.

The gas turbine engine is connected by a high-speed floating-shaft type flexible coupling to a single reduction gear box. This unit reduces the output speed of the engine from 10,500 RPM to 3600 RPM, and also serves to drive ship's accessories. The oil-tight high-speed coupling guard also serves as a torque tube and as the rigid support for the exhaust end of the gas turbine engine.

The output torque of the single reduction gear box is transmitted by means of a flexible coupling to an upper bevel gear box. The upper bevel gear box consists of a horizontal input shaft and a vertically downward output shaft. In addition to changing the direction of the power transmission, the upper bevel gear unit reduces the input speed of 3600 RPM to an output speed of 2080 RPM. This unit also contains a brake which is used to restrain the torque of the free power turbine of the engine at idle speed.

The downshaft couples the output of the upper bevel gear unit to the input of the lower bevel gear unit. It is approximately 112 feet long and is supported by bearings which are flexibly mounted so as to allow the shafting, during operation, to follow the deflection of the strut in which it is mounted.

The lower, or pod-mounted, bevel gear unit is flexibly coupled to the downshaft and serves to change the direction of power from vertical to horizontal. This gear box also reduces the speed from an input of 2080 RPM to an output of 1200 RPM which is the rated speed of the propeller.

The hydrofoils transmission system was designed to obtain an optimum routing of the power path and to fit within the space envelope as permitted by the ship's structure. Designed for minimum weight, the ship's transmission system, consisting of the port and starboard units, weighs approximately 3000 pounds.

**Maintenance Features**

In addition to the inherent maintenance features of the gas turbine engine a number of special maintenance devices were provided for use on the hydrofoils.

Due to the location of the engines within the totally enclosed sponsons, outboard of the main hull, routine cleaning of the axial compressors would prove difficult. To facilitate cleaning the internal engine parts, a solvent applicator and water wash rig were provided for permanent installation in the craft.

External connections are provided either as part of the ship's routine maintenance or as indicated by a decline in engine performance.

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Initial Operation Problems and Solutions (Maryland Shipbuilding and Dry Dock Co., Baltimore, Maryland)

The gas turbines were installed in the H.S. Victoria hydrofoil in late July of 1965. On July 29, 1965 the official launching took place, but following the ceremony the vessel was hauled from the water and returned to its construction cradle where engine installation and alignment was completed.

Approximately one month later, the first engine check run occurred after the automatic engine control system had been calibrated and checked out. Numerous adjustments were required on the engine controls to obtain the correct starting temperature and idle speeds. The idle speed of the power turbine could not be checked or adjusted until the hydrofoil was in the water, which was required to load the power turbine.

Approximately seven hours operation of the engines on the dock were required to check out and adjust the hydraulic system and lube system for the gearing. Because the shipyard was not, at the time, equipped to handle the aircraft-type systems of the hydrofoil, both the hydraulic and lube systems were plagued by dirt and required complete disassembly, filtering and refilling.

The Victoria was placed back into the water on January 21, 1966 for dock trials. Open water operations was delayed for almost a month due to autopilot and system problems. First operation in displacement mode was accomplished on February 15, but was cut short due to autopilot, prop brake, and auxiliary diesel engine problems. On February 18 the Victoria made her first foilborne "flight" for a total of fifteen minutes and attained a speed of twenty-five knots with no engine problems. The next run was made in Chesapeake Bay on February 28 for a duration of almost four hours with only three minutes of foilborne operation due to marginal weather conditions.

The next run down the Bay occurred on May 17. The run lasted about eight hours of which approximately four hours were spent on foils. Engine operation was excellent with no problems. It was necessary, during the return to port, to reduce speeds due to overheating of the port upper bevel gear box.

Several runs on the foils were completed in July with more gear box problems as well as autopilot and foil adjustment problems. After several runs in August, with recurrence of the same problems, the hydrofoil was removed from the water to correct the upper gearbox overheating problem. Fitting of internal splash plates and oil baffles proved an adequate solution to this problem.

The H.S. Victoria completed official trails on October 19, 1966 in good condition. An additional one and one-half hour endurance run was still required by the U.S. Maritime Administration due to fires incorporated in the gearboxes. The only engine problem encountered during all these runs was a starting difficulty on the port engine. In restart, the engine would overheat unless cooled down to a maximum of 150°F by either motoring over with the starter or using the engine cooling blowers before attempting restart.

Further difficulty was encountered on July 16, during a return trip from Victoria, when both of the gas turbines began to consume lube oil at a very rapid rate. When all lube oil had been consumed the engines automatically shutdown. It was necessary to tow the vessel into port.

The long period of inactivity had no effect on the basic integrity of the vessel. This was physically proven in July of 1968 when the craft struck a three foot diameter log while running in foilborne between Seattle and Victoria, B.C. The shock caused shutdown of the port engine (apparently due to vibration), but resulted in no apparent damage to the craft.

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Inspection of the turbines disclosed cracks in the power turbine bearing sumps of both engines and extensive cracking of the port engine exhaust casing. Repair of the starboard engine was accomplished on site while the more severely damaged port engine was sent to the overhaul shop for repairs. A spare engine was installed in place of the port engine. Although engine repair was rapidly accomplished, additional time was consumed to replace seals and repair a number of pumps and hydraulic system components that had proved fairly troublesome.

Commercial Operation Problems and Solutions (Northwest Hydrofoil Lines - Seattle, Washington)

The H.S. Victoria arrived in Seattle in March of 1968 to begin commercial operation between Seattle and Victoria, B.C. In May, 1968, after nearly one year of inactivity, the hydrofoil was put into the water for machinery checkout and crew familiarization. Despite elaborate precautions taken to prevent machinery deterioration, the long lay up and trip from Baltimore to Seattle as deck cargo on a freighter resulted in a number of system malfunctions. Although generally of a minor nature, the malfunctions caused considerable annoyance during the initial days of operation. Malfunctions encountered were: 1) corrosion of the control valve input shaft resulting in a lack of throttle response, 2) corrosion of the starting motor engagement mechanism resulting in occasional "no start" conditions, and 3) corrosion of the idle hold actuator piston resulting in erratic operation and inconsistent idle speeds. Replacement of the malfunctioning hardware reestablished normal operation of the offending systems.

Continued operation of the vessel uncovered additional problems such as drying out of seals and hardening of "O" rings which resulted in hydraulic system leaks and faulty operation of pumps and actuator pistons.

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The ship was returned to service on July 28, 1968 and since that date as provided highly reliable operation. Cause of the earlier double engine failure has not been determined. Comprehensive investigation is still being carried out by the manufacturer to determine the cause. Pending the results the vibration survey and system analysis (which have been conducted) the ship is continuing to operate at reduced power levels. Sacrifice in the hydrofoil's speed has been very slight and has resulted in the addition of only a few minutes to the scheduled two hour run between Seattle and Victoria, B.C.

To date the gas turbines have operated more than 3000 hours since entering commercial hydrofoil service.

Future Potential

While the H.S. Victoria is a prototype vessel, she continues to operate like a well developed production piece of machinery. Problems encountered to date have, for the most part, been very minor. Solutions of the few outstanding problems appear eminent. Material improvements and advances in component design (especially in the area of resistance to long-term storage damage in a marine ambient) will help to realize greater system reliability.

It appears evident that there will be more hydrofoils in the near future and the LM100 lightweight gas turbine seems uniquely qualified by design and experience for this kind of propulsion. Problems have been identified, improvements are being incorporated and even more power is on the way.

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Figure 3 Lubrication System Schematic

Figure 4 Liquid Fuel System Schematic
Figure 5  Pilothouse Instrument Panel