Jet-Boat Design Considerations

This document explores design considerations for the successful application of marine jet drives. This is a compilation and summary our experience, the experience of various boat builders and jet manufacturers, various technical papers, and other sources. It is offered as a guide only. We recommend you review the specific designs and needs of your boat with your boat builder, a professional naval architect and/or marine engineer.

"The Physics of Planing"

"Most maritime operations professionals spend quite a bit of time skimming along the water in some type of planing craft — whether it be a high-speed interceptor, rescue RIB or even a water jet propelled personal watercraft. I am sure, however, that few people give much thought to the actual workings of how their craft is able to rise up out of the water and move at speeds that, until recently, were unheard of.

The interaction of forces on a planing hull are actually very complex in all but a flat sea. At every instant in time, there is a different combination of buoyancy, dynamic lift, engine thrust, frictional resistance and gravity working on the boat. To complicate matters even more, the boat is moving along a boundary layer between water and air that just happens to be moving almost at random. All of this creates a dynamic system that is far more complex than even that of a fighter aircraft. In fact, even with today's computer technology, it is impossible to fully model this system in anything but a rudimentary manner."

J. L. Mitchell, COMBAT CRAFT magazine

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Introduction

A successful marine jet drive application involves four crucial elements, all of which need to operate in harmony, as a system, for the vessel to perform as desired. These elements are:

The Mission

The Hull

The Power Source

The Propulsor (Waterjet)

1. **The Vessel's Mission**

   A full understanding of the vessel's mission is extremely important to the success of any propulsion system, including marine jet drives. This understanding begins with good communication between the naval architect, boat builder and the boat owner when the boat is being specified and quoted. Simplified, the mission is the boat's primary tasks, where used, when used, and who will be operating the boat.

2. **The Hull**

   There are many papers and opinions on the resistance and performance characteristics of various hull forms. The power developed by the power source and delivered as propulsive thrust by the propulsor is intended to overcome the resistance of these hulls and move the vessel up to a speed at which the propulsor thrust and hull resistance are in balance.

3. **The Power Source**

   The power source is often a diesel engine in commercial revenue-producing craft and larger pleasure boats. Modern diesel engines are complex machines with many components and sub systems. In most instances, these engines will reliably deliver the stated torque and speeds given the correct fuel quality and temperature, air temperature, turbo boost pressure, exhaust temperature, cooling system, alignment, and engine room temperature. Gasoline engines and gas turbines may also be used with jet propulsion. It is important to consider the appropriate engine rating, and to decide if the optimum boat performance is required at full or at cruise throttle setting.

4. **The Propulsor**

   The propulsion system is to convert power from the engine to the thrust that will propel the vessel. The thrust is then opposed by the dynamic hull resistance. In the case of waterjet propulsion, the conversion of power to thrust is performed by the most simple element in the propulsion system. A waterjet comprises an intake, an impeller housing, a nozzle, and the steering and reverse deflectors. The only moving parts involved in generating the thrust are the drive shaft and impeller. Impeller technology can provide an accurate prediction of the torque required at the drive shaft to produce a given thrust.

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Planing Monohulls

The most common use of production jet drives is on planing vessels normally operating at cruise speeds of 20 to 40 knots. Jet drives are a little lower in propulsive efficiency compared to propellers optimized for similar boat speed, however, this is offset by lower hull resistance of a jet boat due to the absence of underwater propellers, shafts, rudders, struts, etc. Craft with jet drives do not have this appendage drag, therefore, the overall efficiency can be equal or greater than propellers at boat speeds greater than 20-25 knots. At slower boat speeds, the resistance of these appendages has less impact and propeller drives may be more efficient.

- **Monohedron Planing Hulls**
  - A typical monohedron hull form has the chine parallel to the keel line creating a constant deadrise angle from approximately mid-waterline to the transom.
  - A monohedron hull suitable for jet drives will have a constant deadrise angle (from mid-waterline to the transom) in the range of 8 degrees to 25 degrees with most common being in the 12 degrees to 18 degrees range.
  - Deadrise angles less than 8 degrees can be used with jet drives in some applications.
  - The hull resistance increases with larger deadrise angles (deep-vee hulls), however, sea keeping and ride improves.
  - Lower deadrise angles provide lower resistance than deep Vee hulls and the ability to plane at higher speeds but with a less comfortable ride on all but the most calm seas.
  - Monohedron hull forms with moderate deadrise angles are generally suggested when cruising speeds greater than 30 knots are required.
  - The location of the LCG is important to achieve optimum planing trim and best hull efficiency. Chine flats can also add lift and reduce resistance.
- **Warped Planing Hulls**
  - A typical warped hull form has a decreasing deadrise angle along the waterline length towards the transom.
  - Warped hulls with jet propulsion offer better sea keeping and good load carrying capability compared to the monohedron hull form.
  - Warped hulls offer less hump resistance so therefore will plane easier with less power. Warped hull forms are generally suggested for cruising speeds in the 20 to 30 knot range and when the ability to operate in a variety of sea conditions is required.
  - Warped hulls tend towards a flatter boat trim, especially as boat speed increases. The flatter trim increases the wetted surface of the hull thereby increasing resistance and limiting boat speed.
  - The location of the LCG is important to prevent the stem being driven into the water causing bow steering and the potential to broach. LCG is measured as a percentage of waterline length from mid-waterline or the transom at the static waterline. Chine flats can also add lift and reduce resistance.
  - Some warped hulls have very low deadrise and minimum draft at the stern. This combination may result in insufficient immersion of the jet for initial priming.
- **Stepped Planing Hulls**
  - Stepped hulls typically used in high speed boats with propeller or stern drive propulsion are generally not recommended for waterjet propulsion. The air cushion created by the steppes may be drawn into the jet, causing ventilation and loss of thrust.

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Other Hull Forms

Jet drives are suitable for use in semi-planing and displacement hulls when the attributes of jets are required for the operation and mission of the vessel. These attributes include low draft, avoidance of propeller repairs, excellent low speed maneuverability, low noise and vibration levels, safety for personnel and aquatic mammals in the water, low maintenance, simplicity, and durability.

- **Semi-Planing Hulls**
  - This type of hull is common on fishing, work, and pleasure boats built in the Northeast, Atlantic States, and Florida. In the Northeast, this type of hull is known as a Downeast-style.
  - Semi-planing hulls typically cruise in the 15 to 25 knot range with the top speed being determined by the installed power.
  - Semi-planing (more commonly referred to as semi-displacement) hulls typically have a full or partial keel, a deep forefoot, a deep Vee entry at the bow tapering back towards amidships and a relatively flat deadrise at the stern. These boats are also typically wide of beam at the stern.
  - Some semi-planing hulls have very low deadrise and minimum draft at the stern. This combination may result in insufficient immersion of the jet for initial priming.
  - At first glance, these hulls may not appear appropriate for jet drives, however, some jet drive manufacturers, including Ultra Dynamics, have introduced hull-specific drives that suit the shallow immersion at the stern, and the overall arrangement of the hull.
- **Displacement Hulls**
  - Displacement vessels operate at speeds determined by waterline length and displacements. Hull shapes are typically for moving through the water (displacing water) rather than planing on the water surface.
  - Jet drives designed for planing craft are generally not the best solution for displacement craft. Displacement craft with missions requiring attributes of jet drives can use jet drives specifically designed to provide high thrust at low boat speeds, such as some UltraJet models or the tractor-style jet drives with large diameter, multi-blade (or vane) impellers.
- **Catamarans**
  - Twin and quad engine/jet arrangements (two engines and jets per hull in larger catamarans) are a common form of propulsion for catamarans.
  - Multi-hulls tend to have a high length to beam ratio making for a relatively efficient movement through the water.
  - Catamaran hulls with underwater profiles similar to the monohedron and warped hulls are common with jet drives. Symmetric hulls with deadrise in range of 10 degrees to 18 degrees are best for jet drives.
  - Be cautious with some asymmetric hull shapes as these may not be conducive for waterjet installation, especially if the jet intake is on the tunnel side of the hull. Air from the tunnel may be drawn into the intake as the hull rises with increased boat speed.
  - Nacelles have been used with some catamaran hulls to ensure the jet intake is always in non-aerated water.
  - Hulls that use air as a cushion or lubricant to reduce friction between the hull and water may be unsuitable for waterjet propulsion. Aerated water at the intake will cause ventilation resulting in reduced thrust. Ventilation will cause an increase in engine speed, similar to the effect of a slipping clutch in an automobile. This will limit the ability to utilize the available power and will may result in lower than expected boat performance.
- **Nacelles**

- Nacelles are pods are containers for the jet intake and unit. Use of nacelles often permits use of waterjets in hulls initially unsuitable for waterjet propulsion. Refer to separate UltraJet document on nacelles.

Preparing The Hull

Some considerations when designing or preparing a hull for use with waterjet propulsion:

- The forward and aft ends of the jet intakes must blend with the bottom of the hull and have no bumps, steps, ridges, gaps that might create turbulence ahead of the intake. There should be laminar flow over the intake opening when planing with the jet consuming only the water needed for propulsion.
- For single jet applications, the intake will be on a flat surface fitted across the Vee and blended forward into the Vee hull with a triangular section.
- A Nacelle is an alternative to clipping the Vee hull for the jet intake. See separate UltraJet document on Nacelles.
- A skeg keel might be considered to aid directional control in following or quartering seas. These have been successfully use by some boat builders. Consult the jet manufacturer and a naval architect for suggestions regarding keels on your hull design.
- For single engine applications, the aft end of the skeg should be trimmed so that the aft end is no closer than 5 feet (1.5 meters) from the forward end of the jet intake. The aft end of the skeg should be faired similar to the trailing edge of an airplane wing so that there are no low-pressure areas ahead of the jet intake.
- There should be no through-hulls, water intakes, or other appendages any closer than 6.5 feet (2 meters) in front of the jet intakes.
- Underwater engine exhaust system should not be located anywhere in front of the intakes due to the risk of exhaust gasses being drawn into the intake and ventilating the impeller, with a resultant loss of thrust. Ideally, underwater exhaust should be placed beside the jet intake, aft of the midpoint of the intake.
- Transom mounted engine exhaust should be above the waterline. Underwater exhaust in the transom may cause the exhaust gases to be carried under the hull and into the jet intake when in reverse. This will ventilate the impeller and result in a loss of thrust in reverse.
- The transom flange of jet drives can range from 90 to 102 degrees relative to the jet intake. If the transom is at another angle, rectangular or round insets sized to fit the jet flange will need to be welded or molded into the transom to accommodate the transom flange of the jet drive. Ultra Dynamics provides templates to prepare the openings in the transom for UltraJet drives.
- Some jet drives are mounted to the transom. These tend to have more of the jet outboard and transmit thrust to the transom. Other jet drives, including UltraJet drives, do not transmit thrust to the transom when correctly installed.

Static Balance and Dynamic Trim

Consider the following points static balance to help achieve optimum dynamic trim when planing:

- For planing monohulls, the suggested starting point for the longitudinal center of gravity (LCG) is approximately 40% of the water line length (LWL) from the transom at the waterline. The location of optimum LCG will vary by hull type and shape and center of buoyancy when planing. Consult the hull designer for optimum LCG location for the selected hull.
- Catamarans typically run with a flatter boat trim so the LCG may be 40 to 50% of waterline length from the

transom. There is a wide range of catamaran hull shapes so contact the hull designer for optimum LCG location for the selected hull.

- Fuel tank(s) should be located close to the LCG so that the dynamic trim is not significantly changed as fuel is added or consumed.

- Engine and gen-set (if installed) should be located near the LCG. If possible, leave room to move the engine fore or aft along the stringers in case moving the engine(s) is required to optimize the balance and dynamic trim after sea trials.

- Allow for the additional weight of the jet drive plus the weight of the entrained water within the jet when computing the weights and moments. The water volume within the jet will be carried by the boat when planing.

- Allow for the planing surface area lost to the jet intake when computing the hydrodynamic support of the hull when planing.

- Consider the differences in propulsive thrust vectors of the jet drives (horizontal near the waterline level) compared to the thrust vector of a propellers (at an angle to the hull and further below the waterline). The jet drives may have a lower tendency to lift the bow resulting in a flatter trim and lower boat speed if the LCG is not moved aft to compensate.

- The use of trim tabs should be closely examined. If trim tabs are required to get quickly on plane it may indicate the weight and balance of the vessel is less than optimum for jet drives. If trim tabs are to be used, ensure they are positioned out of the reversing thrust.

- If additional lift should be required aft to get "on step" planing surface extensions of the hull under the jet drives have been utilized by some boat builders. The extensions add lift without the drag associated with trim tabs. Planing extensions may be fixed or have variable deployment by means of hydraulic or electric actuators. Consult the jet manufacturer and your naval architect for advice and see separate UltraJet document on trim tabs and planing extensions.

- A detailed weight and moment calculation is imperative as the successful planing hull cannot have a little ballast added here or there as an afterthought. Also consider the probable weight and location of the personal gear to be brought on board by the owner, A weight and moment calculation worksheet (Excel) is available from UltraJet,

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The Engines

- UltraJet marine jet drives may be powered by petrol (gasoline) or diesel engines in the range of 150 to 1,800 bhp each.
- The power absorption of UltraJet impellers is rated in kilowatts (kW) and brake horse power (bhp). Some manufacturers of diesel engines for pleasure boat applications state horsepower (hp) but note at bottom of page that hp = metric hp while the commercial versions of the same engine are rated in bhp. This is to give the impression of higher power for the pleasure boat market.
- If you plan to have a marine transmission between the engine and jet drive, most engine and transmission manufacturers also list shaft horsepower (shp) being the power at the transmission drive flange. Shaft hp is typically engine power less 3% to 4% to allow for power lost to heat within the transmission.
- When estimating the power to the waterjet take into account the power demand for hydraulic pumps, water pumps, larger alternators, air conditioning compressor, and engine room ventilation fans. If one or more of these are installed they will consume marginal power that is then not available to the waterjet(s) for propulsion.
- With waterjet propulsion, the thrust is transmitted to the integral thrust bearing and then through the intake case to the hull. The thrust is not transmitted via the drive shaft to the engine, or marine transmission if fitted. Thus, the engine (and transmission) may be mounted on vibration absorbing mounts.
- With UltraJet drives, no propulsive thrust is transmitted to the transom.
- It is suggested that the engine mounting system allowing the engine to be moved fore or aft throughout a distance limited by bulkheads, fuel tanks, etc. in order to adjust the dynamic trim, if required in the first of a boat type. See preceding comments on LCG.
- There are links to the web sites of most diesel engine manufacturers at the UltraJet web site page www.ultradynamics.com and click menu item “Diesel Engines, Trans. & Shafts.”

The Transmission(s)

- Due to the inherent forward, reverse, and neutral thrust capability of waterjet propulsion, a marine transmission is not mandatory. Many jet powered commercial vessels, especially fishing boats, operate without transmissions to save weight, initial cost, and maintenance.
- The decision whether to use a marine transmission with a jet drive is typically determined by the mission, skill level of operator, and type of engine.
- The mission of the vessel, the variety and skill level of operators, and the environment in which the boat will operate should be considered when deciding if to use a marine transmission.
- Having a transmission with a neutral position (or a clutch) will permit operation of the engine for tuning, servicing, power generation, battery charging, etc. without residual disturbance of the water at the dock.
- A marine transmission will permit the jet to be "back-flushed" by engaging transmission reverse. Back-flushing of the jet enables clearing larger obstructions from the jet intake grill when operating in contaminated waters, such as rivers and estuaries, or where there may be large amounts of seaweed near the surface.
- A transmission will be required when the waterjet is used with high-speed diesel and petrol engines in order to permit the engine to achieve the rated rpm and for the waterjet to operation at optimum rpm.
- The engine to jet speed reduction ratios for diesel engines are typically in the range of 1:1 to 1.4:1. Rotary engines or petrol (gasoline) piston engines may require engine to jet speed reduction ratios in the range

1.4:1 to 2.0:1.

- There are links to the web sites of most transmission manufacturers at the UltraJet web site page www.ultradynamics.com and click menu item “Diesel Engines, Trans. & Shafts.”

Drivelines, Couplings, and Shafts

The design and selection of the drive shaft between the engine and jet drive (or marine transmission and jet drive if a transmission is used) is extremely important for long term trouble-free operation. An incorrectly installed or out of balance driveline will, over time, affect the bearings, seals, engine mounts, and even the housings of the engine, transmission and/or jet drive. An incorrectly installed or out of balance drive shaft may also result in premature failure of the universal or constant velocity joints causing the drive shaft to flail. Should this occur, there may be collateral damage to the hull, engine, transmission, jet drive, and other equipment in the area of the propulsion drive line. Some recommendations and suggestions are:

- As propulsive thrust is not transmitted via the drive shaft to the engine (or marine transmission, if installed), the drive shafts may be canted at slight angles to facilitate alignment of the drive between the marine transmission and the jet drive.

- Universal joints, constant velocity joints, or flexible couplings, are suggested to accommodate minor misalignment and/or movement of the engine on the engine mounts. There are links to various driveshaft and coupling suppliers at the UltraJet web site (http://ultradynamics.com/sections/educational/marine.asp).

- If universal joints are selected for the driveline, without a marine transmission, a flexible coupling or similar device is required at the engine flywheel to absorb torsional vibration.

- The angles formed by the centerline of the drive shaft relative to the centerlines of the jet drive and engine and/or marine transmission shafts must be equal at the driving and driven end of the universal drive shaft.

- Driveshafts with constant velocity (CV) joints may have unequal angles, however, the bearing life of the joint with the larger angle will be lower.

- Optimum is for the centerlines of the engine crankshaft and impeller shaft parallel with each other. If a marine transmission is used, the centerline of the transmission output shaft should be parallel with the centerline of the engine crankshaft.

- Unlike heavy road vehicles using universal joint drive shafts, for waterjet propulsion the torque load for on the universals increases exponentially (cubed) with increasing rpm. On-highway trucks are near the lowest torque with highest rpm (flat road), therefore, automotive or truck universals may not be suitable for waterjet applications.

- If the drive shaft of the jet drive is at an angle to the hull when installed, certain alignment practices are required to ensure the angles at the driven and driving end of the shaft are equal.

- The maximum angles of universal joints are relative to the torque and rotational speed (rpm) of the driveline. The maximum angles range from approximately 3 degrees at 5000 rpm to approximately 8 degrees at 2000 rpm. Consult the shaft supplier for recommended maximum angles for the intended torque and rpm.

- Compound angles formed by jets with inclined shafts and the hull deadrise (typically for twin jet installations) require certain procedures. Discuss the requirements with the jet and driveline suppliers.

- Consult the drive shaft manufacturer for limitations in torque capacity, alignment, balance, etc. Also request a torsional vibration analysis to include mass moment of inertia data from the engine, transmission, coupling(s), driveshaft, and impeller and impeller shaft. The analysis is typically performed by the coupling and/or engine supplier.

- If the engine is well forward in the boat, the driveline may require two sections and a center bearing support. Please consult the driveline manufacturer for recommendations.

- Additional guidance on the selection and application of drivelines with universal and constant velocity joints may be obtained from the Society of Automotive Engineers (SAE) Recommended Practice, Document SAE J901 MAR95.

- There are links to the web sites of most shaft and coupling manufacturers at the UltraJet web site www.ultradynamics.com and click menu item “Diesel Engines, Trans. & Shafts.”

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The Jet Drives

- Selecting the appropriate jet drive is based on a variety of factors including available power, the loaded and normal operating displacements of the craft, the shape of the hull, planing trim, the power to weight ratio, and the intended use. We must also note that these factors also apply to other methods of marine propulsion.
- Matching the engine power and jet drive is related to the boat speed achievable with the power to weight ratio. Some jet drive literature lists maximum power per jet but are not always clear in stating that this power absorption is only possible at higher boat speeds.
- Additional guidance on the selection and specification of waterjet propulsion is available a the UltraJet web site www.ultradynamics.com and click menu item "Jet Specification & Selection."
- Jet drives benefit from the movement through the water to help "prime" the jet intake. Therefore, the maximum power absorption of a particular jet drive (without cavitation) increases with boat speed. Conversely, reduced power absorption will be experienced in a boat with lower maximum boat speeds.
- To select the appropriate jet drive for a particular application, determine the anticipated boat speed using industry-standard methods based on power to weight ratios or thrust versus resistance calculations. Then select a jet drive that is capable of absorbing full engine power without cavitation at that boat speed. If a marine transmission is to be used, be sure to use the shaft horsepower (shp) to determine power available to the jet drive.
- The impeller is then selected based on whether maximum jet thrust (boat performance) is required at full throttle or cruise rpm. The jet manufacturer will assist with this selection.
- Many jet drives, including the UltraJet range, mount to an aluminum intake block in the hull. Stainless steel studs, washers, and nuts will clamp the jet to the intake block. All forward and reverse propulsive thrust will be taken through the jet intake, to the intake block, and then distributed through the hull and stringers.
- Waterjet units should be installed so that the static waterline is at least to the centerline of the impeller shaft when boat is at rest. This immersion is required for initial prime when the jet is engaged.

Prepared and offered to promote the successful installation and operation of waterjet propulsion, regardless of the make of waterjet selected.

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