THE BASICS OF JET PROPULSION

An engineer talks in plain language about the physics of jet propulsion and why jets may soon challenge propellers for popularity

BY ROBERT T. DEVAULT

Jets are becoming more popular. They used to be only for the "California Hot Dogs," but now they're getting into family boats. Why? Basically for four reasons: 1) simplicity—the power goes right into the water without going through gears, right-angle shafts, clutches, or gear shifts—that means lower cost, lower maintenance, more reliability; 2) safety—no danger to swimmers under the stern of the boat; 3) shallow-water operation—no prop to bend; and 4) easier launching, retrieving, and trailering.

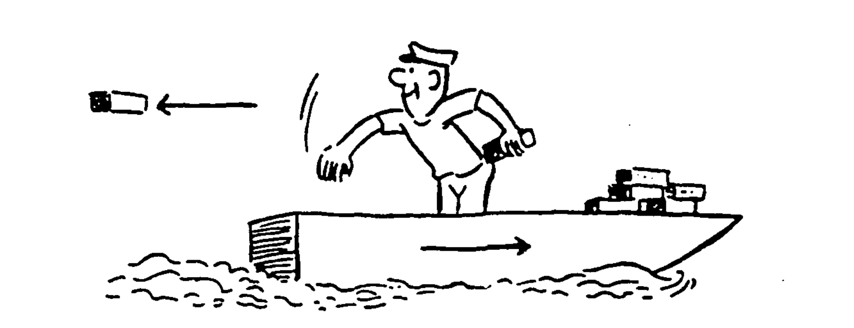


FIGURE 1

WHAT IS A JET?

Functionally, it's just a prop inside of a pipe. It looks more complicated, but all it does is squirt water out the back, reassuring us that Isaac Newton's ideas about action and reaction are still valid along the information highway.

If you've forgotten your high-school physics, I'll go through the basic stuff here, because there seems to be an almost total lack of understanding of the very simple, basic, physical laws.

Consider brick propulsion. You're standing in a boat with a pile of bricks, throwing them, one by one, over the back of the boat (see Figure 1). Everytime you throw a brick, you give the brick an impulse, and that same impulse goes into the boat, through your feet, and pushes the boat ahead. If the brick weighs 10 pounds and you throw it at a speed of 100 feet per second—you're damn strong—the impulse is 10/gx100 or 31 pound-seconds.

You have to divide the brick's weight by "g," the "acceleration due to gravity," to get the "mass" of the brick, since mass is what counts when you're accelerating things. As Einstein pointed out, gravity and acceleration are equivalent. When you stand on the bathroom scale, it indicates the force produced by your mass accelerating at 32.2 feet per second—this is the value of "g" in the English system of units. (This "English" system of units is an ancient nightmare that even the English have abandoned. Until voters get the metric system in, you'll have to try to understand this revolting mess.)

Now, if you throw one brick per second, you get a thrust of 31 pounds. If you throw two bricks per second, you get 62 pounds, and so forth. Not much thrust is it? The average V-8-powered jet can produce around 1000 pounds of thrust, so it's like throwing an equivalent of 31 bricks per second.

Now suppose you have the boat zipping along at a speed of 100 feet per second (68 mph), but you've run out of bricks. You notice lots of bricks floating (floating?) on the water, so you reach over and start picking them up. Every time you pick one up, you've put the same impulse (31 pounds per second) into the boat, but in the wrong direction. So now, if you pick one up per second, you have an additional drag (momentum drag) of 31 pounds, so you have to throw the brick twice as hard to end up with the same net thrust. This is why the net thrust of a jet, or a prop, decreases rapidly with speed.

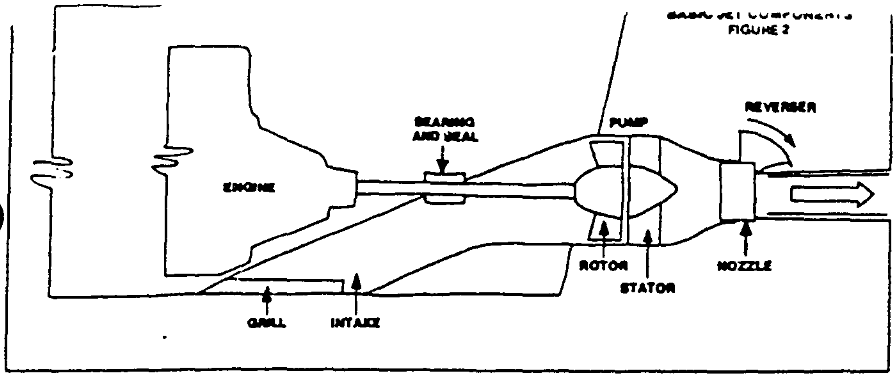
The engine (or you) produces the same maximum power regardless of boat speed. In the case of a jet, it has to pick up stationary water, bring it up to boat speed, then squirt it out faster than boat speed to get positive net thrust. If the boat travels 68 mph with 300 hp, you must accelerate the intake water to 68 mph before you can expel it. If accelerating this water to 68 mph takes 300 hp, the boat has reached its top speed. If you have a 400hp engine, you have an additional 100 hp to accelerate the water even further, which will result in a higher boat speed. (As long as you have a supply of bricks on board, you have the rocket system; i.e., the propulsion "fluid" is carried with you, and you're forced to accelerate its mass as well as that of you and the boat.) A jet sucks air (or water) from the surrounding environment and expels it to create thrust.

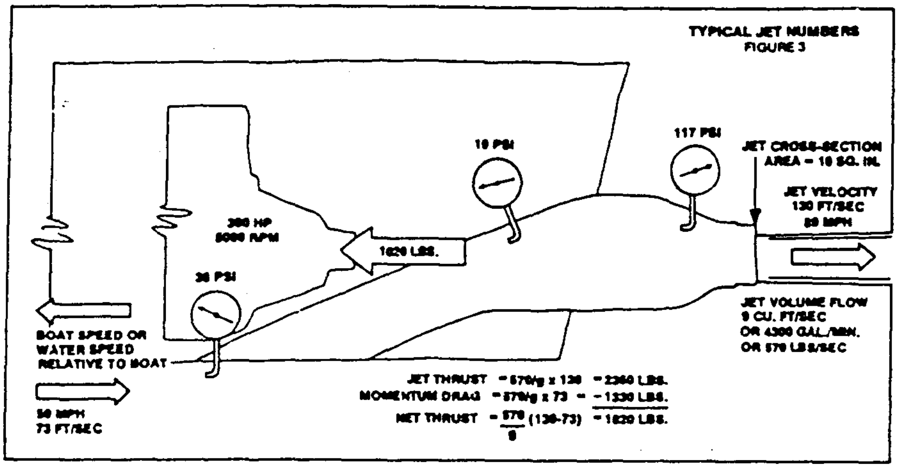
Enough of that! Let's look at the parts of the jet shown in Figure 2 (on page 34).

Intake Section

The intake is a hole in the bottom, which has the job of picking up the water and delivering it to the pump with minimum pressure loss. There is usually a grill across the intake to separate the water from the beer cans and plastic bags. The energy in the water, measured in terms of pressure, increases as the square of the relative speed. The density of water is about 2.0 in the English system, so that the water pressure measured by a pitot tube and indicated by the speedometer is about: p (in pounds per square foot) + V^2 (in feet per second squared) i.e. $p=V^2$. So, at V=100 feet per second, p=10,000 pounds per square foot (psi), or about 70 psi. (The typical numbers for a jet are shown in Figure 3, while plotting maximum obtainable thrust against speed gives the curve shown in Figure 4.)

The average intake is only about 50





■ *Figure 2 illustrates the major components of a typical marine jet. Note the grill at the bottom of the intake valve. The grill is necessary to keep foreign debris from cluttering up the intake's channel and from damaging the rotor or impeller. The impeller comes in various pitch sizes ranging from A to D. Using the formula $p = V^2$, Figure 3 demonstrates the number that would be found on a 300-horsepower jet.*

percent efficient, so that, if you put a pitot tube just ahead of the pump, it would read only 35 psi. Thus the pump will have to supply at least 35 psi just to get the jet speed back to 100 feet per second, at which point you still have only zero net thrust.

Pump Section

The common boat jet uses a pump design borrowed from the farmer's deep-well pump, and it works fine. (This writer put a stock deep-well pump on the bottom of a 50-horsepower Mercury outboard in 1959 and it worked nicely, but the world wasn't ready for it.)

Pumps are classified by the way the water goes through them. There are three major types:

1. **Axial pumps.** Here the water goes straight through, parallel to the axis. An example is the Hamilton (the grandaddy of all jets). The Hamilton uses up to three sets of blading on the same shaft to get the pressure required. A set of blades, called a "stage," consists of a rotating part (the impeller or rotor) which takes the swirl out of the water that was put in by the rotor.

2. **Radial or centrifugal pumps.** Here the flow spreads out radially as it goes through the pump. It is usually brought back in to the axis. This design has been adapted to the outboard engine, but results in a small loss of efficiency.

3. **Mixed-flow pumps.** This is the common jet pump. As the name indicates, the flow is a compromise between axial and radial. Examples are Berkeley, Jacuzzi, and Dominator.

Nozzle Section

Here the pressure is released and the water accelerates to the jet speed. This section usually includes a swiveling feature that allows the jet to be directed sideways for steering, and sometimes up or down for trim control.

Reverser

Rather than shift gears to obtain reverse rotor rotation, jets deflect the water forward, which is effective and cheap. To avoid the boat's transom, the stream of water must be deflected down as well as forward. If the jet hits the transom, that push nullifies the reverse force. The downward direction of the jet results in an up force at the transom. If you give a jet full power reverse while traveling at high speed, you will amaze and delight your friends—and get all wet as the stern goes up and the nose goes under.

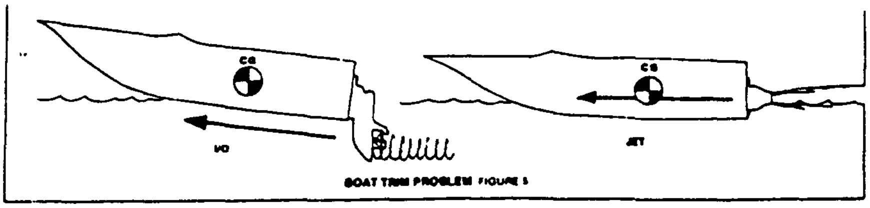
PERFORMANCE

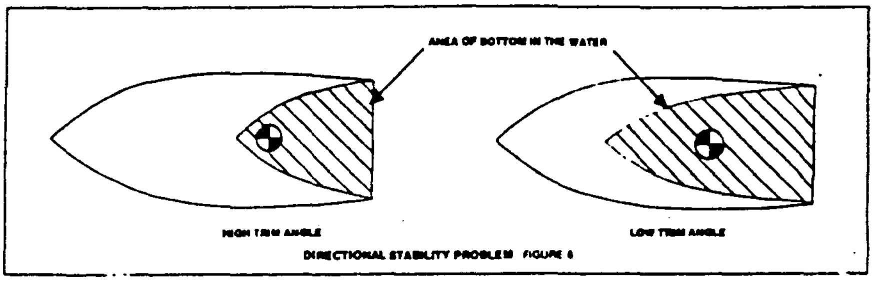
So how good are jets? Or, if you're feeling negative, how bad are props? In the first place, the two are similar as I've noted. To generalize, a jet handles less water than a prop and pushes it faster. A prop produces a jet stream behind it, of course, though it usually isn't visible unless there's enough tip cavitation to outline it. For equal power input, most thrust is obtained by pushing a large amount of water gently. At high speeds, blade friction and cavitation losses force optimum prop size down to typical jet size, so their respective efficiencies are similar.

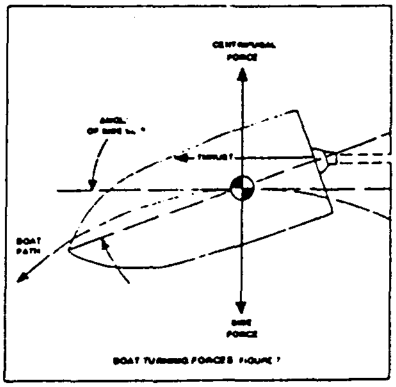
At low speeds, there's the old cavitation bugaboo. Cavitation is, simply, a boiling of the water produced by near-vacuum pressures around the front and/or tips of the propeller or rotor. The resultant vapor cavities in the fluid cut the efficiency, and usually unload the engine, so that it over-revs. Air sucked into the region ahead of the prop produces the same effect. In this case, it's called ventilation, and it's the reason for the big, flat "cavitation" plate across the top of the prop.

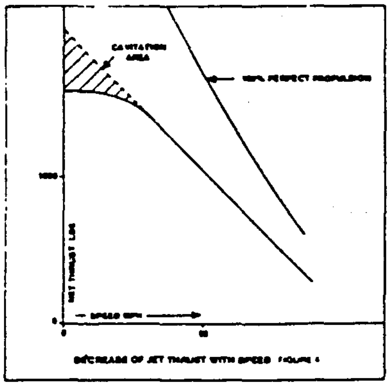
The curve labeled "100 percent Perfect Propulsion" (Figure 4) shows the best you can do with any propulsion system using the 300-horsepower assumed in Figure 3. The jet performance shown will be hard to beat with a prop at speeds over 50 mph. If we want a good 20mph jet, however, we will have to design a new jet with a much larger nozzle area to handle a higher volume flow and lower jet velocity.

Another significant difference between a jet and a prop is the speed range of efficient operation. A jet offers a much wider range of efficiency and is affected less by boat speed. In general, it should be possible to design a prop for a given speed that will be more efficient than a jet at that speed. The losses at other speeds may make the prop less attractive, however. Certainly, a super tanker will always be best with props, but jets may well take over most other applications. Even tugboats are using a form of jet, the Kort nozzle or ducted prop. In racing, prop cavitation and ventilation are inevitable, so we have the super cavitating









■ ***The 100% Perfect Propulsion chart of Figure 4 shows the best you can do with any propulsion system utilizing the 300-horsepower engine assumed in Figure 3. Figure 5 demonstrates that the thrust line on an I/O may be 2 or 3 feet below the center of gravity, producing a strong nose-up moment that causes a trim problem. I/O hulls are designed to capitalize on this moment for optimum performance. However, in jets the thrust line comes out so close to the center of gravity that practically no moment occurs, causing the same hull to cruise along at low angle with high drag. Figure 6 pictures the high and low trim angles that result from the problems discussed in Figure 5. A high trim angle has less hull in contact with the water while the opposite is true for a low angle. The forces on a turning boat illustrated in Figure 7 demonstrates that in order to turn a hull must produce a side force equal to the centrifugal force of the turn.***

and surface-riding props. With more research and development on intakes, jets could move right in here.

INTEGRATION PROBLEMS

If you install a jet in a boat, and it works perfectly the first time, you're just plain lucky. That's because the hull you have wasn't developed for a jet, but for an outboard, I/O, or V-drive. And you've probably installed a lot more horsepower, too, which may thrust you into a strange area of hydrodynamics.

By looking at the trim problem illustrated in Figure 5, you can see that the thrust line on an I/O may be 2 or 3 feet below the center of gravity, producing a strong nose-up moment. The boat hull has been developed to use this moment to produce the best trim angle for optimum performance. However, with a jet, the thrust line comes out so close to the center of gravity that practically no thrust moment results, and the same hull will plow along at a low angle with high drag. Frequently, hulls have hooks molded into them to keep the nose from getting too high. In this case, grinding off the hook will get the nose back up, and the speed with it.

Now, by looking at the directional stability diagram shown in Figure 6, you can see that a boat running at low trim angles has a lot of keel in the water ahead of the center of gravity; this is destabilizing. As the keel length ahead of the center of gravity increases, the boat becomes directionally unstable, and it will swap ends. This doesn't hurt your wash and wear (unless you're in saltwater), but it may produce a negative effect on your ribs. Running at too high a trim angle also produces impacts on the fundamental part of your anatomy, which, however, doesn't bruise as easily.

HANDLING CONTROL

Low-speed handling of a jet may take a little learning, but it can be fun. A jet can be made to go forward, backward, sideways, and rotate in about its own length in either direction.

In looking at the forces on a turning boat illustrated in Figure 7, you can see a hull must produce a side force equal to the centrifugal force of the turn. To do this, the boat must be put into a sideslip, so that the hydrodynamic forces on the keel, strakes, chine, and bottom add up to the side force required. The sideslip is obtained by deflecting the jet, or turning a rudder, so that the boat rotates around its center of gravity. With a flat-bottom boat, it may take alot of sideslip to get around a turn. Some jet-drive flat bottoms will run along at 20 degrees sideslip all day without actually turning. Note that it doesn't matter how big the rudder is or how much the jet is deflected; if the hull won't produce side force, the boat won't turn. Skegs or fins on the bottom near the center of gravity will help get such hulls around a corner.

What happens when the water isn't flat? A lot. You get oscillations about all three axis: pitch, roll, and yaw. The pitching motions are usually most important, because they make the conditions shown in Figure 6 change rapidly. A normally stable boat may become unstable as it pitches down, burying a lot of keel ahead of the center of gravity. Some boats will spin out beautifully if you start a fast turn and cut the power suddenly.

So far, it seems that jets can be used successfully in any hull that works well in the speed ranges the jets will produce. There are no basic physical laws that prevent the jet from giving good service in anything from five horsepower on up. The status of boat jets is reminiscent of the aircraft jets of 40 years ago. The boat jet is still in its infancy; it just doesn't have the tremendous technological development force behind it that the aircraft jet had. So it's going to take a few years before the real potential of the jet becomes as obvious as a 747 taking off over your house.