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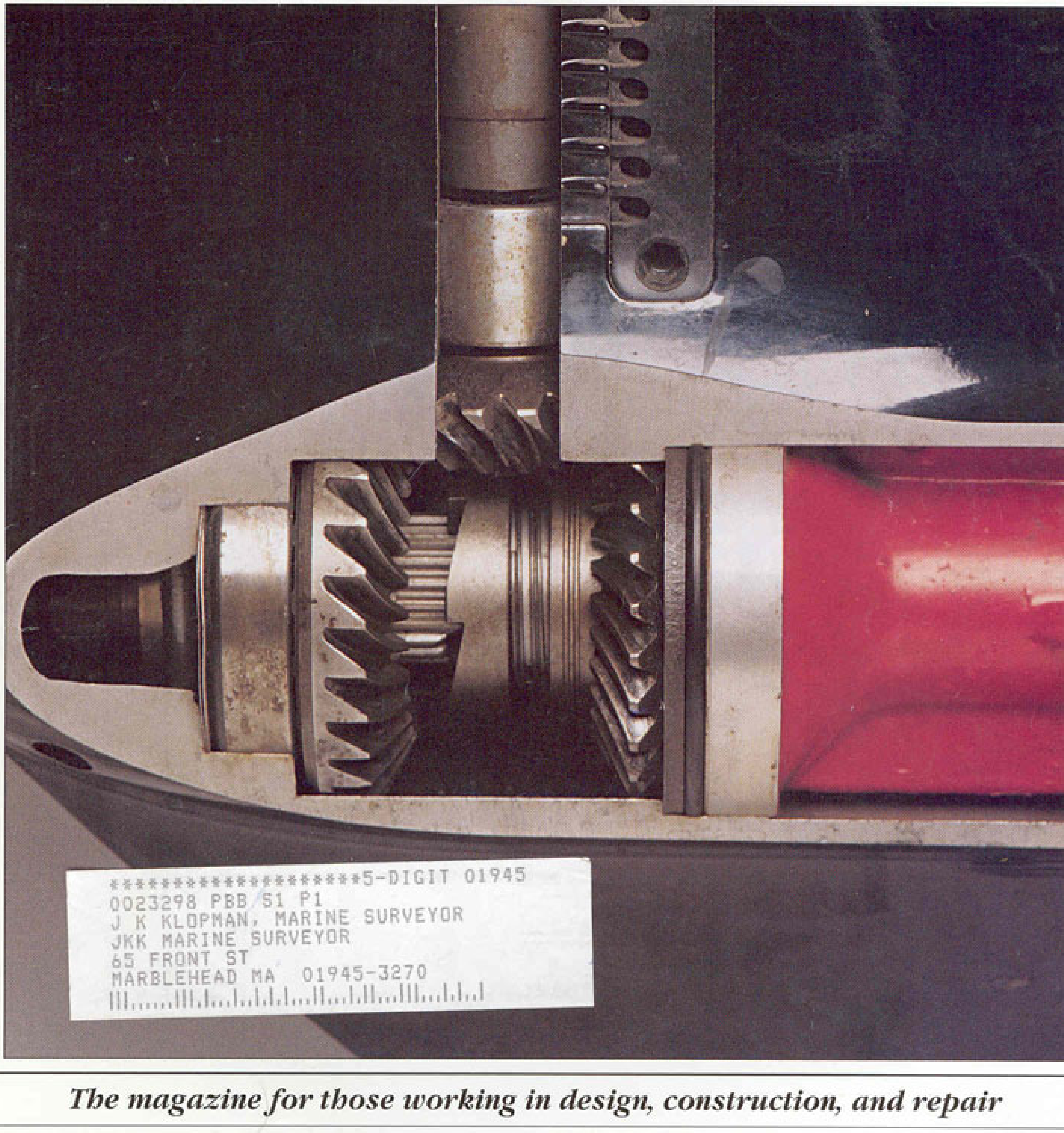

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ANALYZING STERNDRIVE FAILURES
LIGHTWEIGHT INTERIOR JOINERY
SETTING UP A 24-VOLT DC SYSTEM
THE EDUCATION OF A NAVAL ARCHITECT

Sterndrive Failures

The biggest obstacle to accurate damage-analysis could be your own preconceptions.

Text and photos by Jonathan Klopman

The split pinion gear pictured here is from an outdrive that struck an object, and was rebuilt without the gear's being replaced. The impact had caused a hairline crack in the gear at the root of one of the teeth. The crack started the fatigue process, which ended in the gear's failure a year later.

Marine claims offices are flooded by the ubiquitous "struck submerged object," or SSO, claim during the summertime. The uninitiated surveyor on a damage assignment may find his first demolished-outdrive claim an undecipherable metallic mess. With an informed and methodical approach, though, a surveyor can usually accurately reconstruct the events that lead to a failure's root cause. Success depends on understanding basic operating principles, recording the conditions surrounding the failure, and accurately reading fracture surfaces to establish the sequence of failure.

"The Leg Bone's Connected to the Knee Bone..."

The popularity of modern outdrive systems belies the somewhat shaky service record of earlier units. In fact, the history of drive systems is itself an evolution of refining the same basic parts in order to iron out recurrent problems. A solid understanding of the assembly's design and manufacture is crucial when determining loading and the possibility of progressive failure. Specific design elements create general categories of inherent problems. Consider the following:

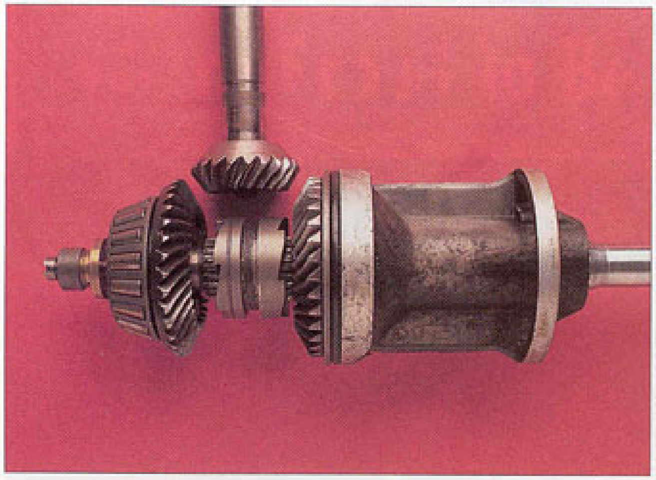
Weight distribution. The primary function of any sterndrive system is to relocate the inboard power as close as possible to the transom. Shifting the center of gravity (CG) aft improves performance and planing characteristics, but you pay a considerable price for cramming all these components into a small engine box in the back of the boat.

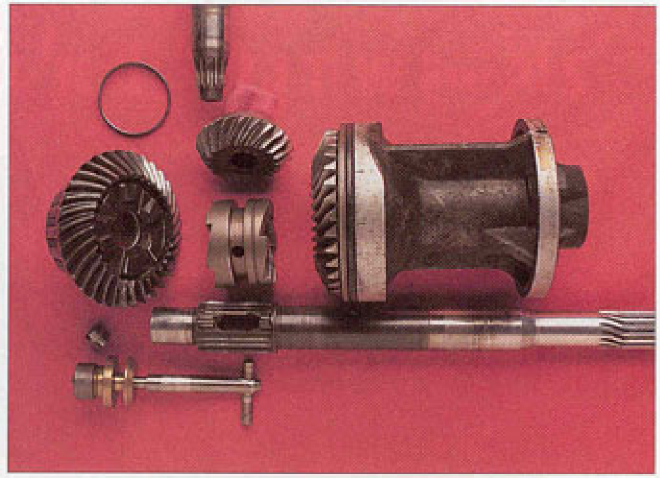
The exhaust system is typically a serpentine affair of castings and connecting hoses. Even with flapper valves and cast-iron risers, most installations remain perilously close to back-flushing. Aggressive valve overlap in some modern heads can exacerbate the problem.

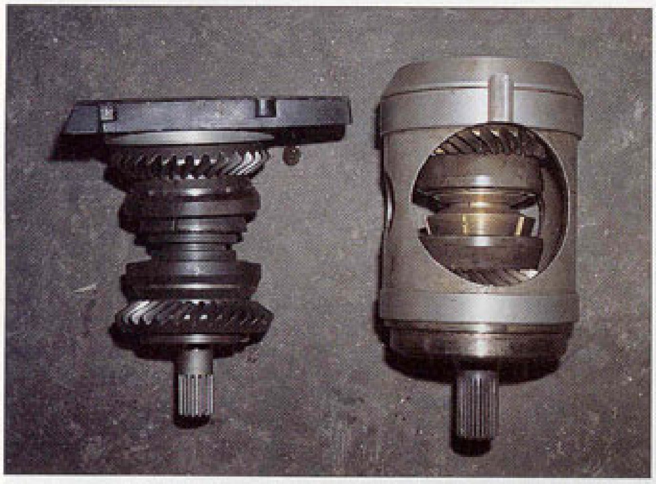
Just as the risers and top of the engine are often too close to the water, the bottom of the engine is usually too close to the bilge. More manufacturers are upgrading to cast-aluminum oil pans, but it's not unusual to see thin steel automotive pans that are corroded and pitted. Inspecting the entire pan is difficult at best, and it takes just one pinhole to drain the block of lube oil.

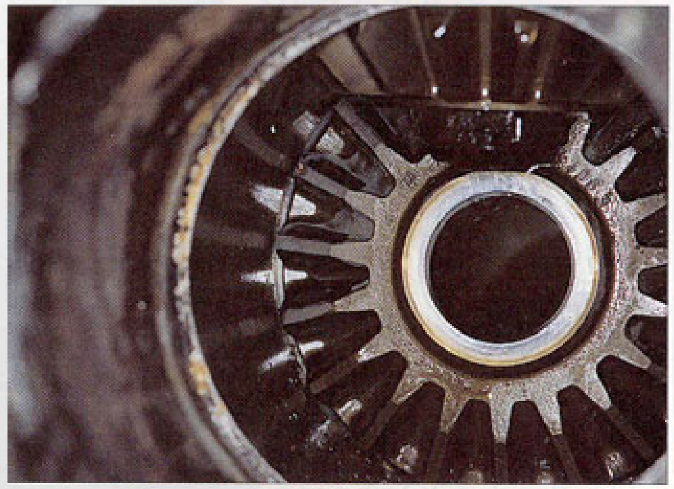
Poor engine alignment is a common problem, as well. The coupler on most I/O systems is a splined female fitting machined from aluminum, while the outdrive-input shaft is hardened steel. If the engine shifts over time, the input shaft will erode the aluminum coupler splines until they finally shear off.

Shafting. Power is redirected









Top photos, left to right—*The lower-unit drive assembly showing the pinion gear on the vertical drive shaft mated to the forward gear (left) and reverse gear (right), with the clutch dog between the forward and reverse gears; the same parts disassembled. The second photo shows that the unit shifts by sliding the clutch dog along the horizontal prop shaft so that it engages either the forward or reverse gear. The teeth on the clutch dog are not subject to impact damage, but will wear from shifting.* ***Above, left***—*A MerCruiser Bravo cone clutch (left) and an OMC assembly (right). The cone works on friction, and so is prone to wear.* ***Above, right***—*Detail of lower-unit gears on a MerCruiser Bravo drive. The teeth are straight cut and the gears are forged, making them particularly rugged.*

through the outdrive by a series of three shafts connected by two sets of bevel gears. The shafting acts as a "drop center" to place the prop in clean water below the transom. Any mechanical complication that alters the thrust can be a potential weak link. Whether due to sudden overload or premature failure, torque problems tend to concentrate in the junctions between shafts and gears.

The converse would be true of surface drives such as those produced by Arneson Industries (San Rafael, California). Since these systems don't need to drop the prop below the transom, the shafting is direct. The result is an inherently simple and rugged drivetrain that in some ways handles the torque of high-performance or diesel engines more easily than conventional systems.

Transmission. When you jam an engine into an engine box that is itself jammed against the transom, there's no room for reduction gear and a transmission. Combining a transmission with the drivetrain can add a host of complexities and failure points.

When MerCruiser (Stillwater, Oklahoma) developed its first high-output outdrive, the company, realizing the potential for failure, chose to keep a conventional BorgWarner hydraulic transmission mated to the engine. That way, the sterndrive shafting would not have to accommodate any shifting interruptions. MerCruiser's resulting TRS drive is renowned for its simplicity and bulletproof design, though at the expense of enormous size and weight.

Today's sterndrive transmissions rely on either clutch dogs or cone clutches. The former is merely a sliding collar in the lower unit that engages the prop shaft with the forward or reverse gear. The technology comes straight from lower units on outboards. While simple, the system is relatively crude. The shifting process involves little more than slamming the toothed clutch dog into a spinning gear. Properly adjusting the shift linkage can be tricky, especially given cable stretch. At the same time, the system requires an interrupter switch to momentarily "blip" the ignition off so the clutch dog can be disengaged.

The fracture surface of this broken skeg shows distinct chevron marks pointing back toward the initiation site on the leading edge.

If, or when, the little switch fails, you're stuck in gear as you hurtle toward the dock.

Volvo (Göteborg, Sweden) held the patent for cone-clutch outdrive transmissions for years, but now the system is incorporated into MerCruiser's Bravo sterndrives. As opposed to the clutch dog, shifting takes place in the upper unit. Instead of a toothed cog, the clutch is a tapered bronze cone that slips into a cup-shaped receiver on the back of either the forward or reverse gear. Shifting is much smoother and the linkage more direct than in a typical clutch-dog transmission. But, cone clutches work solely on friction, and require precise fit and assembly of the upper unit, making the system more costly than the clutch dog.

Neither transmission system is subject to damage from impact, yet both tend to show signs of long-term wear.

Articulation. Any sterndrive system must allow for side-to-side (steering) and up-and-down (trim and tilt) movement. The geometry and design of castings in the transom assembly can vary considerably from one manufacturer to the next. A critical look at the relative design strengths and weaknesses of this part of the system may explain failure during impact or regular service.

Identify the Unit

Record the serial number and gear ratio of the sterndrive. Serial numbers should match corresponding secondary numbers found on the valve covers or flame-arrester cover on the engine. If the unit does not have a serial number, then it may be a replacement part. The point here should be obvious: the serial number is a crucial link when confirming the unit's history. If the boat's owner reports that he has never replaced the sterndrive, nor had any major work done on it, what are you to say if the serial number doesn't match the secondary number on the engine?

If you're working with only one set of numbers, it's still possible to trace the serial number back through the OEM warranty department. They should be able to tell you the year the sterndrive was made and which boatbuilder received delivery of the unit.

The gear ratio can be an equally important identifier. Let's say you're working on a boat fitted with a MerCruiser 190-hp 4.3L V6 engine; the Alpha One outdrive's upper unit should be marked "1.84R." If it's marked "1.47R," then that unit was meant for a *V8* engine. Are you looking at the correct outdrive?

One of the easiest ways to learn the guts of an outdrive is to review exploded diagrams. It's difficult to tell how and why something broke if you don't know that the left-handed widget mates to a splined whatzit. In short, know what you're looking at, where it came from, and what goes in it.

Gearcase Damage

When investigating sudden overload, start by recording exterior damage at the lower-unit case. While it may seem painfully obvious, the lower unit's skeg usually bears the evidence of initial impact. Closely inspecting the fracture surface should reveal clues that are consistent with a single blow from the proper angle of attack.

The cast-aluminum case should show evidence of ductile failure along the break, and have a dull and woody texture. In many instances, the fracture will show arrow-shaped chevron marks pointing toward the initiation site of the failure. Although it's certainly possible for the outdrive to strike several rocks in quick succession, it's not typical. The most common break is a single, significant chunk taken out of the bottom of the skeg, with all the clues from the fracture surface pointing toward an initiation along the leading edge.

The point of this exercise is to notice skeg fractures that are *not* typical. The following would be considered highly unusual: many small chunks taken out of the skeg; a bent or broken trailing edge with a perfectly clean leading edge; impact directly from the side; or one or more of the types of damage cited above, combined with no damage whatsoever to the prop. Anomalous external clues should prompt you to take a much closer look at any internal damage you discover during the rest of your investigation.

It's most common to see the initiation of impact on the lower tip of the skeg, but there are certainly cases where the boat owner "catches the brass ring" and plants the nose of the lower-unit gear housing directly into a rock. The geometry of the obstruction determines whether the impact is a glancing blow or a square hit. A dented aluminum nose cone can be tricky to inspect. Although aluminum is remarkably ductile, the grain structure is somewhat more brittle because the part is cast. When in doubt, carefully clean the surface and test with dye penetrant, available through welding-supply shops. (This technique works best on clean, smooth surfaces. Any irregularities in the part such as

The shift plate on a MerCruiser Bravo drive. The plate is subject to wear, as shown here.

This Volvo lower unit took a direct hit to the nose of the case. The inset photo shows oil weeping out of the case through a crack caused by the impact. The case is probably beyond repair.

gouges, scratches, or valleys can cause the ink to puddle, making the part extremely difficult to clean prior to applying the developer. In short, don't expect this test to be as quick and easy as it normally is when spraying between gear teeth or inside gouged depressions.)

An impact to the nose that causes a hole in the case, or cracking into the oil reservoir, is cause to condemn the entire case. Although virtually any material can be welded, it's difficult to find a qualified welder who will be keen about repairing an aluminum casting that has been exposed to 90-weight gear oil and salt water. More often than not, the material is compromised just outside of the weld site, and will crack at a later date.

Consider the kinetics of what's going on here. We're talking about the force of thousands of pounds of boat, probably traveling at better than 20 knots, concentrated into an impact area of several square inches of aluminum. That's one helluva bang. A fancier term might be "unintentional deceleration trauma," but somehow this phrasing hasn't caught on in boatyards.

The value of pausing to make an initial, careful examination is twofold. First, you gain a greater respect for the real strength of the casting. Second, you realize that it's extremely difficult to recreate this level of damage ashore. I'm aware of incidents in which someone tried to smack a lower unit with ordinary tools in order to make it look like the boat struck a rock. *It doesn't work.* Invariably, the person learns that it takes more than a 24-oz (.7kg) framing hammer to craft the same single, massive blow in an effort to defraud the insurance company. I am immediately suspicious of multiple dents or blows that strike the case off the fore-and-aft axis.

Direct impact to the gearcase can transmit a significant amount of force throughout the entire outdrive. In such occurrences, you may find cracked castings in the transom assembly. With experience, you learn that certain outdrive models exhibit "weak links" that tend to fail predictably in the transom assembly.

Propeller Damage

A propeller damaged from striking a hard object typically leaves clear gouging, or entrance marks, along the leading edge of the blades, followed by bent or broken blade tips. Due to the speed of the revolving propeller, several or all of the blades show signs of damage.

The ductile nature of aluminum props means that they deform quite easily to show the direction of the blow. Obviously, the direction of the blow should match the events as reported by the boat owner. Imagine a situation where there is a dent in the nose of the case and the prop tips are bent forward. Did the owner run his boat over the rock, stop, and then back up into it again to make sure?

Stainless steel props can create several unique problems in impact situations. The stainless steel used for yachts and small-craft propellers is a precipitation-hardened grade with ex-tremely elevated tensile strengths to achieve the thin blade cross-section nec-

A MerCruiser lower-unit case with a crack at the top, near the web. First, the inset photo shows that debris has had time to collect in the crack. Second, the crack opens up on the outside of the case. It's most likely that the outdrive was left on during winter storage; the case filled with water and froze, and then cracked when the ice expanded.

Above—*Drive shafts from MerCruiser Alpha drives. The shaft at the top is broken at the O-ring groove at the upper splines. The middle shaft's lower-end splines are broken off. The bottom shaft is the most recent model, the MerCruiser Alpha Gen II. The lower-end splines have been reinforced significantly, and there is no O-ring groove machined at the upper splines.* ***Right***—*A detail of the failed lower spline. Here is a good example of a ductile material that failed in pure torsion. The fracture is perpendicular to the axis of the shaft, and the surface is smooth.*

essary for high performance. But, the material shows a relatively low percentage elongation when stretched. So, although the blade may bend conventionally if struck, it can develop cracking when someone tries to straighten and recondition the prop.

The same strength properties that keep these blades from flexing at high speed can cause significant internal damage in an accident. In an impact situation, the material's super high-yield strength causes the propeller to transmit the force of impact through the propeller shaft and into the gear train in the milliseconds before the prop itself begins to deform and absorb the blow. As a result, you may find severely bent prop shafts and fractured gear teeth upon disassembling the lower unit. Also, some technicians argue that the shock of impact with a stainless prop can cause hairline cracking in the forward and/or pinion gears even though these may look unaffected.

Shaft Damage

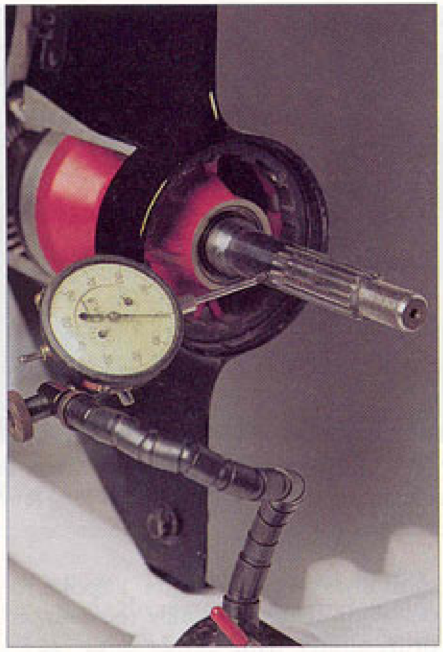
Any significant impact to the propeller, especially if it's stainless steel, will usually bend the prop shaft. The easiest way to check for shaft run-out is with a dial indicator on a flexible arm. (Take the reading from the inboard end of the prop-shaft splines.) Manufacturers generally allow for .003″ to .005″ (.07mm to .13mm) run-out off center.

Many propeller shops are outfitted with the equipment to straighten sterndrive propeller shafts. I spoke to one shop that will readily recondition prop shafts with bends over .125″ (3.2mm), though I consider this a bit too much. I've been told by several repairers that stainless prop shafts have a memory, and will return to the original bend after reconditioning, but there's no technical basis to support this claim.

In general, the austenitic stainless steels used in the marine industry are remarkably ductile, so the material will generally yield prior to ultimate failure. The normal loading on prop shafts is torsion. Momentary torsion overload at the end of a shaft causes twisting at the splines. Record the direction of the twisting to confirm the direction of rotation on the engine

Left—*Failed upper drive shafts on an older OMC stringer drive.* ***Right***—*End view of the failed shafts. The same parts failed due to the same weak links. The fracture surfaces of both shafts show signs of long-term fatigue.*

A dial-indicator setup measures shaft runout on an outdrive.



and you can tell whether the accident occurred while the prop was spinning in forward or reverse. The easiest trick for recording the rotation is the same one you would use to identify the threads on a bolt: if you can superimpose the letter "Z" over the twisted splines it is right-handed, while an "S" means it is left-handed.

Outright shaft failure generally doesn't occur unless it's in combination with a design discontinuity. This can be either the shaft necking down to a smaller-diameter set of splines, or an O-ring groove. In situations where torsion overload leads to the shaft snapping (once again, in the ductile material), the fracture will be a relatively flat surface perpendicular to the shaft.

Note that the same design discontinuities that lead to failure in overload can also initiate long-term fatigue failure. Carefully inspect the surface for signs of hemispherical "beach marks," also known as progression marks. *[For more on this, see "Analyzing Failed Metal Parts," PBB No. 58, page 56—Ed.]*

Prop and drive shafts that show signs of torque overload can fail from either an internal or external problem. Consider the action in slow motion. As the prop strikes an object, it stops for an instant. If the engine does not stall immediately, then the drivetrain must absorb the torque output, and the shaft yields by twisting. The problem is at its worst with powerful high-performance engines, and is rare with small engines under 200 hp. Wave jumping, or more accurately the shock of re-entry, can result in twisted shaft splines in the outdrive—a combination of too much horsepower and too little common sense.

Gear Failure

To a great extent, the heart of any outdrive is the gear train's design and manufacture. As noted, it is the critical element in redirecting thrust through a multiple driveshaft system. Outdrive gears are subjected to constant contact stress in service, and are hardened by a nitride process for a wear-resistant finish, yet retain a tough, ductile core.

Most outdrive gears are helical-cut, allowing for smoother, quieter engagement. Helical gears also spread the load somewhat because multiple teeth are engaged at any given instant. Nevertheless, for the same diameter and gear ratio, it's possible to engineer more tooth-contact area into a straight-cut, or spur, gear. The problem with straight-cut gears, though, is that abruptly engaging the gear teeth makes for a noisy outdrive.

A pinion gear, with pitting at the pitch line of the gear teeth. The gear had been running in contaminated oil for a long time before it failed. Another clue to water damage is the black splotches on the surface.

Compare gearing between different units and especially modifications made in newer production models. For example, the 30-year-old MerCruiser R-drive and the company's more modern Alpha Gen II are identical in terms of basic parts and operation, yet the latter outdrive has much deeper helical gear teeth. When it came time to design a new high-performance outdrive, MerCruiser engineered the lower unit of its Bravo drive with forged straight-cut gears. In the field, it's not unusual to see long-term failure in the gear teeth on an older design mated to higher-horsepower engines—gear teeth that are relatively fragile in the event of impact. On the other hand, Bravo gears have a reputation for being extremely rugged.

Unlike prop shafts, the hardened steel in gear teeth will not show signs of yielding prior to failure. Failure on impact will overload only those teeth that were engaged at that instant (normally one or two teeth on the forward gear and two teeth on the pinion). The fracture starts along the root of the tooth, digs deep into the ductile core, and generally sweeps back up to the root of the following tooth. It will appear as though the entire tooth were scooped out of the gear.

Loose debris inside the case causes further damage to the gears if the owner continues to run the engine, but this accelerated wear usually chips or burnishes the tips of the other teeth. It would be very rare for the resulting damage to completely obliterate the fracture surface of the telltale missing-teeth observation noted above.

A general pattern of gear damage

Lack of lube oil in the upper unit of a MerCruiser TRS drive caused the gear and bearing assembly to overheat. The bearing cage got hot enough to flow out from under the bearings. Severe bluing of the steel indicates that the metal reached red-hot temperature.

common to *all* teeth should signal a problem prior to ultimate failure. Often, this is a sign of improper gear shimming. For example, if just the outer tips of the forward gear teeth are broken off, it's almost certain that you'll find corresponding wear on the inside tips of the pinion gear that mates to it.

Normal gear wear includes tooth-face burnishing, and possibly very small pits along the pitch line. (Also termed the "dedendum," the pitch line runs across each tooth midway up. It's the point of primary engagement with the tooth on the opposite gear.) With age, the pits can grow in an inverted triangular pattern up toward the tip of the tooth. This is normal wear and does not compromise strength.

Another type of pitting that concentrates on the face of gear teeth can lead to tooth failure. If the lower-unit gear lube is contaminated with water, then the gear teeth can corrode. The oxidized surface of the hardened gear wears away along the pitch line, digging pits into the face. Eventually, the pit breaks through the hardened tooth case and creates a stress riser that initiates cracking. One of the clues to prior exposure to water is that the normally silvery face of the gear will be discolored with black splotches.

Lubricant Problems

Water contamination is a fairly common cause of outdrive failure. There are numerous ways for water to get in the oil, but few can be seen by

The driven gear from an Alpha upper unit. While the bearing under the gear appears to have been running in oil, the gears had been run dry. Continued operation of the softened gears led to plastic deformation and massive adhesive wear failure.

visual inspection alone. Someone who maintains his own outdrive might overlook a minor leak as he annually changes the oil. The only way to be sure about the case's integrity is with a pressure/vacuum gauge set. In the meantime, the water that sits in the case causes the gears and bearings to gradually deteriorate and pit.

Prop-shaft seals are particularly vulnerable to in-service wear, or to drying out during long-term storage. Inspect the prop shaft at the precise point where it leaves the seal. Old prop shafts may show burnished and grooved wear rings where the same seal has been riding for years.

Fishing line can wrap around the prop shaft and damage the seal, as well. Typically, the monofilament welds itself into a dense ring that works back into the seal. The damage should be noticeable. Precision seals, such as the one here, are no place to save money. I heard of an incident where a repairer had disastrous luck with inexpensive aftermarket seals delaminating.

Lack of adequate lubricant can lead to severe overheating. Because outdrives run in a non-pressurized bath of oil, maintaining the proper oil level is critical. Gravity makes the upper gearcase most vulnerable to oil starvation. In many circumstances, bearings exhibit the first signs of overheat failure. While the tapered rollers themselves are extremely hard, the stamped steel cage that holds them is not. When run dry, the heat in the rollers and race cause the cage to get red-hot and deform. As the cage begins to distort, the rollers tear loose and seize the outdrive.

Note that overheated gears turn red-hot, and then cool to a dark blue. Overheating the gear teeth destroys the hardened nitride coating and softens the steel. Along with discoloring, another sign of overheating is adhesive wear on the contact surfaces. In severe cases, plastic deformation causes mating gears to melt and strip off all the teeth.

Any form of failure analysis is valid only so long as it is based on the evidence and conforms to a logical chain of events. While kinetic energy transmitted through an outdrive explains how shock-loading damages internal parts, it does not justify an "anything goes" attitude when establishing causal links. For example, say an incident is reported as a conventional grounding, and yet upon disassembly the fractured pinion gear reveals unmistakable signs of fatigue cracking. The fact that there is a fresh chunk taken out of the skeg does not mean the gear failed immediately upon impact.

Theory and study aside, there's no substitute for hands-on experience in the field, and no better way to see how sterndrives fit together—or fly apart when they fail.

I owe a deep thanks to the mechanics who have been kind enough to share their time, knowledge, and hordes of broken parts. PBB

About the Author: *Jonathan Klopman is a NAMS-certified marine surveyor based in Marblehead, Massachusetts, and a contributing editor of* Professional BoatBuilder.