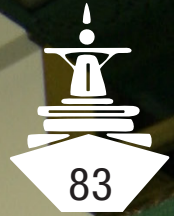




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Feature Article

Frigate Propeller Manufacturing in the Nation's Capital



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FEATURE ARTICLE

Manufacturing Propellers in the 21st Century

By Claude Tremblay and Slobodan (Bodo) Gospodnetič



Figure 1: HMCS *Calgary* - Halifax-class Frigate

A great many things are made in Ottawa: Legislation, software, propellers ... *Propellers?* Yes. As in frigate propellers. Who would have thought?

When the *Halifax*-class Canadian Patrol Frigates (CPF) (Fig. 1) were being built starting in the late 1980s, the Department of National Defence (DND) acquired the proprietary rights from the original propeller manufacturer to allow spare propellers to be manufactured from a third party of DND's choice whenever needed. A recent competitive contract to make two sets of spare frigate propellers (10 right-hand blades, and 10 left-hand blades) was won by a small high-tech firm in Ottawa: Dominis Engineering Ltd.

Dominis Engineering uses high-precision computer numerical control (CNC) milling machines to manufacture large and small propellers and waterjet impellers, with the help of technology developed at Canada's National Research Council a few years ago. CNC machining is fairly common these days, but machining ISO 484/1 Class S (the finest of ISO tolerances) noise-reduced propellers to final form is a rarity in North America. Refer to Table 1 for a summary of the ISO 484/1 & 2 Class S tolerances.

Measured propeller blade parameter	ISO 484/1 Propellers of diameter greater than 2.5 m
Tolerances for class S	
Surface roughness, R_a	less than 3 μ metre
Thickness	+ 2%, max. of 2 mm - 1%, min. of -1 mm
Chord length	$\pm 1.5\%$, min. of 7 mm
Local pitch	$\pm 1.5\%$
Mean pitch of each radius	$\pm 1.0\%$
Mean pitch per blade	$\pm 0.75\%$

Table 1: Class S Tolerances per ISO 484/1

Propeller Blade Design

A propeller is more complex than it seems. Its shape is driven by the principle of lifting surfaces, the same principle aircraft wings use; however, the rotational movement of a propeller adds a new level of complication. The surface speed through the water increases with the diameter of the propeller, thus producing higher lift. In order to keep the lifting force relatively constant throughout the propeller blade, the pitch needs to be changed and adapted to the changing diameter. Years of research have refined the shape of propeller blades to reduce drag, push cavitation inception farther up the speed curve, eliminate vibration and resonance (otherwise, they would sing like mermaids!), reduce wake disruption and noise reverberating through the hull, and improve efficiency, which we understand better as fuel savings.

When the resulting propeller blade design is put on a drawing, it is surprisingly simple, comprised of a table of numbers, and not too many of them at all. Hydrodynamicists calculate the shape of the propeller blade as it goes through the water. Since it rotates, the surface that touches the water at constant speed is found at a given cylindrical section (Figure 2). To visualize this, imagine a cylinder centring on the shaft and cutting through the propeller; the resulting intersection on the blade thickness is a cylindrical section.

The designer will take that section and “unwrap” it to get a two-dimensional shape (Figure 3). That 2D shape will look very much like a cross-section of an aircraft wing. Once they apply their lifting surface theories and modern calculation techniques, the resulting shape is divided into sections. One reference line called the chord line, or pitch helix, runs longitudinally, while a series of perpendicular lines cross the two blade surfaces – one being the face or pressure side (PS), the other being the back or suction side (SS). If the reference zero is on the chord line, the $\pm$ distances of the two faces are the data found on the propeller drawing offset table.

The propeller blade is usually made of 10 to 20 cylindrical sections (Figure 2), from 0.3R (30% of full radius) to 0.95R and 0.975R (the tip being 1.0R). With reference to Figure 4, each of the sections is listed with an associated pitch angle (since it changes throughout the diameter). Additional features are skew (the whole section is moved back along the chord line to reduce noise), and rake (induced by the skew, or added or removed for design efficiency). The design is then complete, and the hydrodynamicist goes home

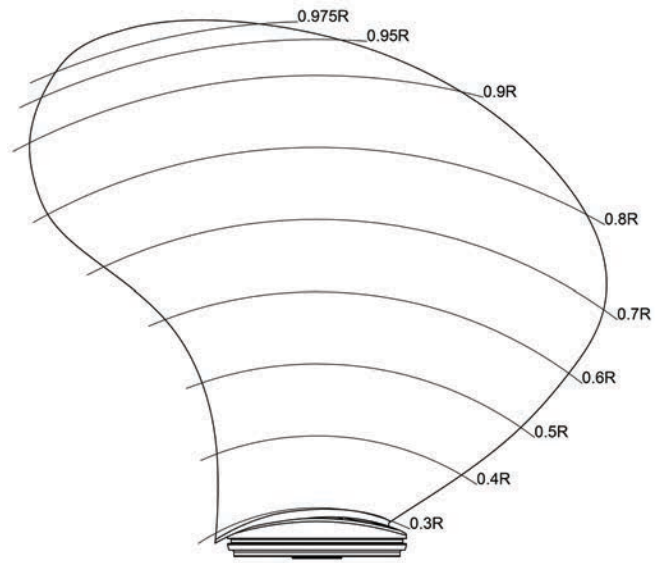


Figure 2: Propeller with Cylindrical Sections Superimposed

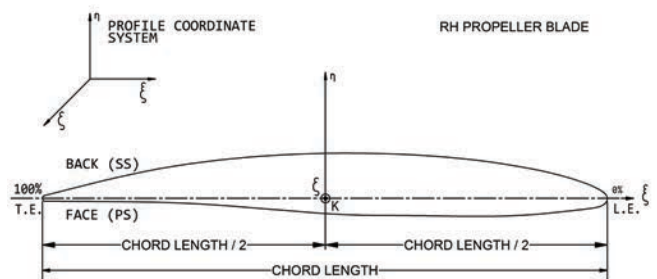


Figure 3: Unwrapped (2D) Propeller Blade Section

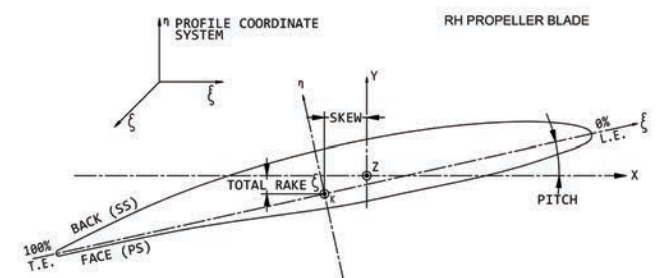


Figure 4: 2D Propeller Blade Section Adjusted for Pitch, Rake, and Skew

(in a simplistic world, since model testing and various other tests are required). The challenge is to now accurately machine this design to full scale.

Propeller Blade Manufacturing – The New Era

Traditionally, propellers are made by hand. Well, sort of. Skilled craftsmen build propeller patterns, manufacture templates, and produce wooden shapes to use for imprinting the mould for the castings of the rough propeller. They use mathematical transformations to wrap, pitch, skew, and rake the 2D model of the drawings. Once cast, the rough propeller is usually installed on a drilling machine; for controllable pitch propellers, individual blades are mounted on a dummy hub that is then turned to design pitch. The drilling machine will drill holes whose depth will be at the exact position of the surface of the finished propeller in accordance with the offset table. Once the guiding holes are completed the craftsmen then start grinding off the excess material around the holes until they disappear, which means that the desired surface has been reached. Since the drawing only identifies a limited number of cylindrical sections, there are large gaps between sections. That is where the skills come into effect; the extra material is ground off until the whole surface of the blade is smooth as felt by hand from one section to the next.

This is very exacting, time-consuming work, and skilled workers are hard to find these days. CNC milling machines can do the work much faster, but can they replace the expertise of skilled workers? That was the challenge Dominis Engineering Ltd set for themselves to solve, and they succeeded.

The initial step was to build a 3D computer model of the entire propeller geometry, not just the cylindrical sections. Since a limited number of points are provided by the designer, an accurate interpolation method was required to compute any undefined point on the propeller surface. Dominis Engineering uses proprietary in-house software to interpolate and check all propeller blade sections provided in the table of offsets for smoothness. The software is used to identify bumps and discontinuities (Figure 5), and correct them (Figure 6) to improve the blade section and, eventually, the propeller blade's performance. The corrected blade section is used to improve the computer model.

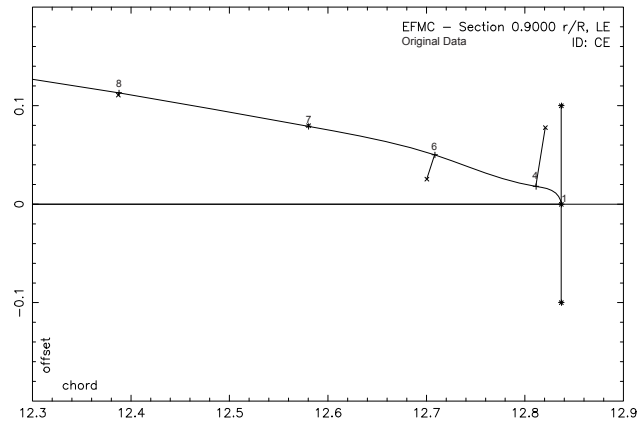


Figure 5: Original Data before Smoothing of a Sample Blade Section

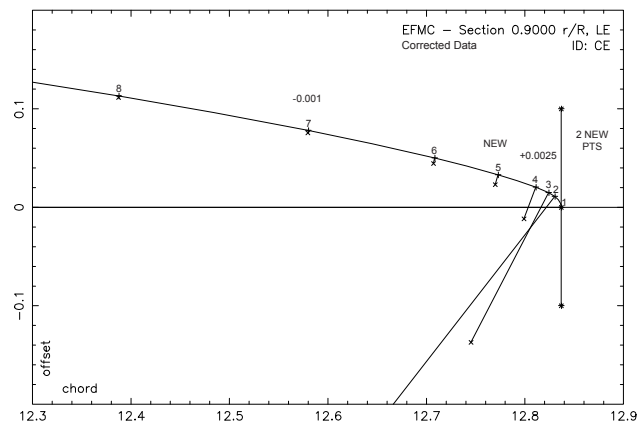


Figure 6: Data after Smoothing of a Sample Blade Section

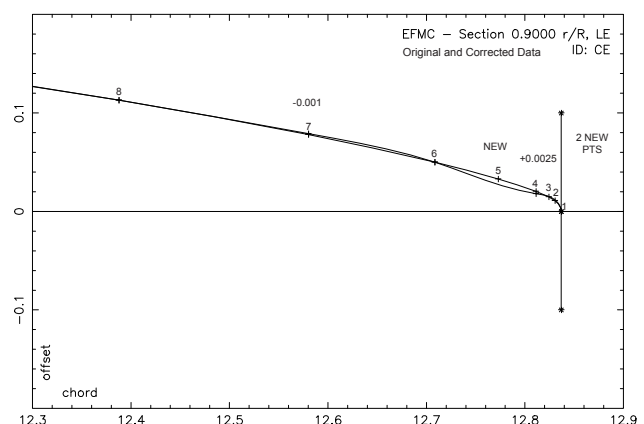


Figure 7: Original and Smoothed Data of a Sample Blade Section

Figure 7 shows the overlap of the sample blade section before and after smoothing with Dominis Engineering's in-house software. The smoothing process is iterative and requires looking at all the blade sections. In some cases, new interpolated blade sections are created to improve smoothness between sections. A smooth propeller blade is not just important for performance, but also for the ability to machine it, as a bumpy surface can wreak havoc when creating a CNC machining program.

To be able to machine the whole blade to final form, much more information than the cylindrical section is required to enrich the model. Leading edges are usually provided in the shape of gauges; trailing edges with the "anti-singing" alterations. Fillets, which are the rounded sections required to strengthen the base of the blades in order to transmit the full thrust without bending, are not well defined. Details of the trunnion or blade palm, the circular portion that fits in the hub allowing the blades to be turned to change pitch, must be very well defined.

Final Form and Finish

Now the real calculating begins. The goal is to machine the propeller blade, as Dominis Engineering refers to it, to "final form and finish." Final form of a propeller is defined by the propeller's table of offsets, while finish is the desired final surface roughness of the propeller which is dependent on scallop height, the scallops being the material left between passes of the cutter (Figure 8). The selected maximum scallop height was set at 0.3 mm, which means that the only operation left to be done by hand at the end would be polishing. The scallop height is determined by the size and type of the cutter, and by the spacing between cuts or passes. The larger the cutter, the more spacing that is required; however, the smaller cutters are more accurate. For a spherical cutter of radius r , distance between cuts (step over) being s , scallop height ϵ , can be approximated as $\epsilon = s^2 / 8r$.

As mentioned earlier, surface roughness is dependent on scallop height, where R_a (arithmetic average roughness) can be approximated as $R_a = 0.032s^2 / r = 0.256\epsilon$. These approximations are valid when $\epsilon \ll r$.

Propeller Blade Machining

One of the most important machining factors that must be considered is the cutting speed. The cutting speed is the result of many required decisions since it is influenced by many factors such as size and type of cutter, rotational

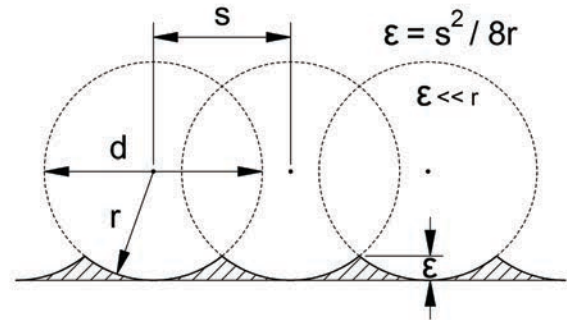


Figure 8: Relationship between Scallop Height (ϵ), Distance between Cutting Passes (s), and Radius of Cutter (r)

speed of the cutter, desired scallop height, base material, shape of the propeller section (less curvature can be cut faster than high curvature), heat-removal capacity, and let's not forget the computer controller speed. All these decisions result in hundreds of machining programs, each required to refine the features of the blade.

As with everything else, precision is the key. Special fixtures are created to fit under the blades to hold them in place, and to allow them to be turned 180 degrees to machine the opposite face. They are themselves accurately machined, and include dowel pins and locking devices. A minute error in the rotation of the blade during machining would result in the two faces of the propeller blade not matching.

One important factor required to be considered in the sequence of machining is the bending or movement of the blade under the pressure of the machining tool. If one face is fully machined from top to bottom before being rotated, then when the opposite face is machined, there would be less material behind it which would make the blade weaker (propeller blades are quite thin). The risk is that it will bend more in that direction and accuracy will be lost. To alleviate this problem the programs split the blade in smaller sections, and the blade is rotated after each section is machined; the machining also starts from the tip and proceeds down to the thicker sections so more material is at the base during machining, strengthening the blade.

Before the work is started on an actual blade, the programs need to be tested. A special program, CGTech's Vericut software, can simulate the whole operation on the computer. It will identify any conflict, any breach of the desired surface of the finished product, and identify parts

that were not well defined. It can also be used to optimize the speed in order to reduce machining time. A full-scale propeller blade is then manufactured in *wood* so that the fixtures, handling procedures, and the CNC milling operation itself can be tested before any actual metal blade material is machined.

While the engineering team is designing and refining the programs, the actual Nickel-Aluminum-Bronze blades are being cast at North America's only commercial foundry able to manufacture large propellers – the Rolls-Royce facility in Pascagoula, Mississippi. The propellers for our frigates were cast there, as were the large propellers for the *Arleigh Burke* destroyers, and those for the massive monoblock propellers for the USS *George H.W. Bush* aircraft carrier. Rolls-Royce was contracted to cast the blades one inch thicker than the final product. The key in machining from a casting is to initially position it on the CNC machine perfectly in the middle. A bit off and some sections of the blade will have no material left to machine at the other end. To help in the positioning, the castings included some reference points for which the foundry provided exact 3D coordinates.

Once the castings have been delivered, the first part to be machined is the palm of the blade – the round part that fits in the hub (Figure 9). This allows the propeller blade to accurately sit vertically on the fixture in the CNC machine when machining the face and back. Then, once everything has been tested, verified, checked, re-verified, and double-checked, the propeller blade is reinstalled on the CNC machine with a different precision fixture, and the machining programs are started (Figure 10). The machining progresses

24 hours a day under the supervision of qualified technicians until all 20 propeller blades are completed 40 weeks later.

Measurement and Analysis of Machined Controllable Pitch Propeller Blades

The last step in the contractual obligation is to prove the dimensional accuracy of the final product. Some features are easy to measure, but the actual shape of the pressure and suction faces are quite challenging. DNPS 3 has developed a unique measurement system that provides an accurate comparison with the points shown on the design offset table drawing. The method uses a coordinate measuring machine with six degrees of freedom at the probe to scan the cylindrical sections in 3D. The collected data is then superimposed on a 3D computer model made

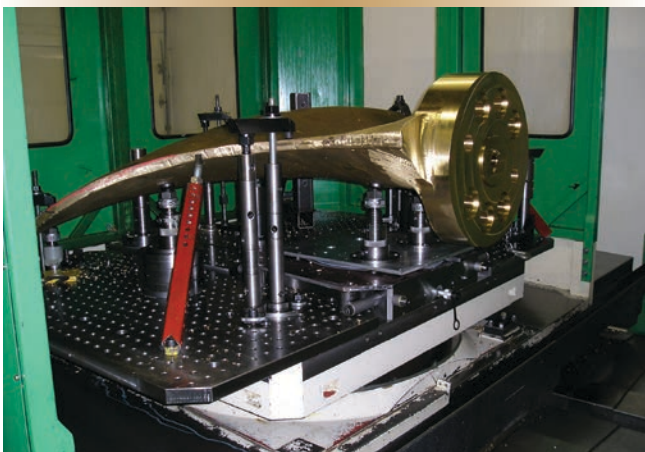


Figure 9: Propeller Blade Palm Rough Machined



Figure 10: Propeller Blade Machining

from the design drawing. Since the drawing points were given in 2D, the same mathematical conversion method of wrapping, pitching, skewing, and raking that were used to define the machining model are used. In order to determine the difference between the model and the actual measurement accurately, 3D helix reference lines are added to the model.

Using subroutines created in the AutoCAD software, the model and the actual scans are rotated and positioned perpendicular to the viewer's point of view so that accurate relative distances can be extracted. This measurement method was proven to be accurate and much faster than the traditional method that requires pre-shaped gauges, feeler gauges, a pitchometer, and many hours of labour with approximate accuracy.

Analysis was made of the measurements performed on the new propeller blades with respect to the following five key parameters: blade thickness, chord length, local pitch, mean pitch at each radius, and blade pitch. An example of the measured accuracy is shown at Figure 11. In this example the blade thickness deviation from design thickness is 1.0 mm in 97.5% of the blade point measurements. The 1.0 mm extra is half the highest ISO tolerance and is also set intentionally by Dominis to give an allowance for

wear throughout the propeller's lifespan. All 4360 points measured were found to be accurate to 0.3 mm, which is well within ISO 484/1 Class S tolerances.

Conclusion

The new spare propellers manufactured by Dominis Engineering Ltd were proven to be extremely accurate, and have already been installed on *Halifax*-class Canadian Patrol Frigates. The improved performance should become evident over time, but have the captains and crews of those frigates noticed where their new propellers were manufactured? Possibly not. The "Made in Ottawa" tags were quite small.



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Slobodan (Bodo) Gospodnetić is president of Dominis Engineering Ltd, a leading company in high-precision, five-axis machining of three-dimensional complex surfaces such as CPF propellers, and waterjet impellers for the U.S. Navy's LCS program.

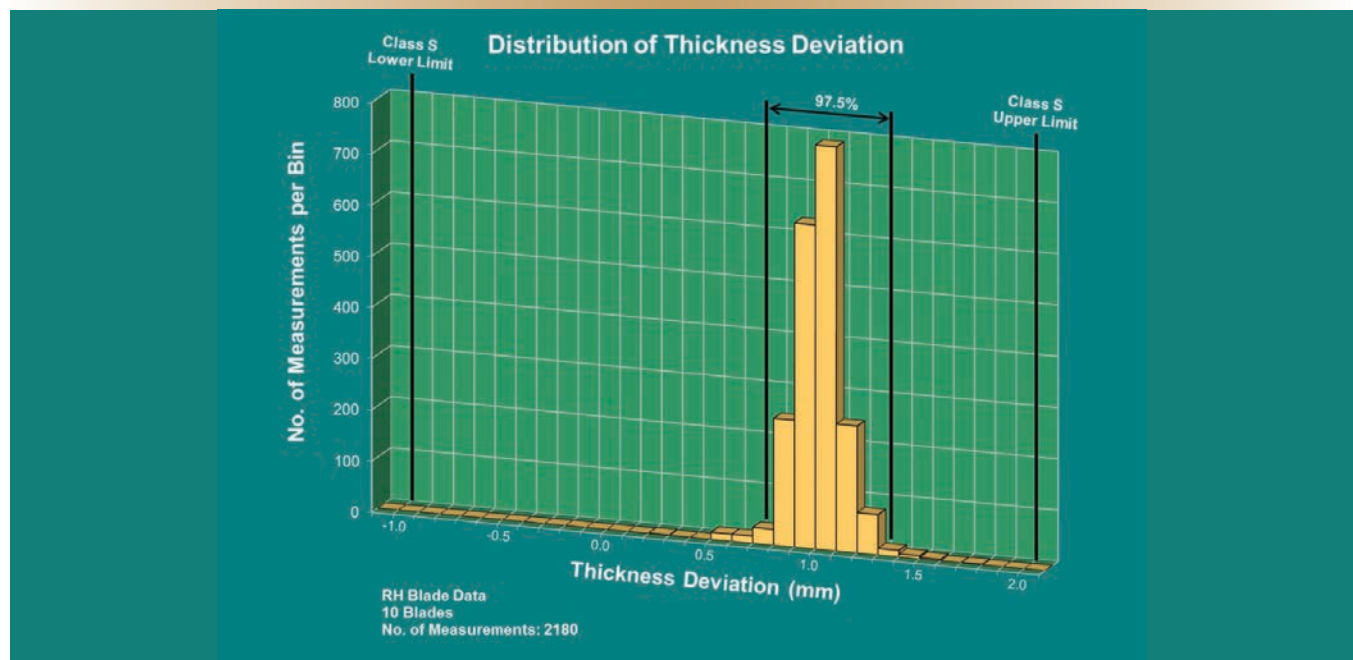


Figure 11: Distributions of Thickness Deviations for RH and LH Propeller Blades