INTEGRATED PROPELLER MANUFACTURING SYSTEM

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Abstract

This paper describes Integrated Propeller Manufacturing System which was developed by Dominis Engineering Ltd. for the purpose of Computer Numerically Controlled (CNC) milling of propellers to final form. The foundation of the system is propeller geometry data base which contains detailed definition of propeller geometry and all propeller surfaces. Propeller surfaces are defined with high resolution so that the data can be used throughout the entire design/manufacturing cycle of the propeller. Integrated Propeller Manufacturing System allows CNC milling of all propeller surfaces to final form and thus it eliminates need for hand grinding of propellers. The system has been used for CNC milling of propeller models, CNC milling of propeller blade patterns, CNC milling of marine propellers and hydraulic turbine blades, and CNC measurement of propellers and turbines.

1. Introduction

Manufacturing of propellers is a complex and time consuming process. The first step in this process is the evaluation of propeller design by means of model tests conducted in a ship research laboratory. Traditionally, propeller models are made either by highly experienced and skilled craftsmen on staff in model shops of ship research laboratories, or by firms specializing in model making. The second step in the process is building of propeller patterns, manufacturing of templates and production of propeller casting. Propeller patterns, templates and castings are made by skilled craftsmen in foundries specializing in propeller castings. The third step is propeller machining and polishing in order to satisfy ISO classifications requested by the client. Finally, before a propeller is accepted by the client, it has to be checked for its conformance to the requested ISO classification by client's acceptance team.

Hence, propeller manufacturing process requires involvement of four different teams of highly skilled professionals. Teams involved in propeller production process are: model makers, pattern makers, machine tool programmers and machinists, and propeller quality assurance inspectors. In order to accomplish their role in the manufacturing process, each of these four teams of professionals must re-interpret the original data supplied by the client's propeller designer.

The need to re-interpret propeller definition data is due to the fact that propeller designers usually do not supply sufficient amount of data to completely define all propeller surfaces. Typically, propeller designers specify 10 to 20 propeller blade sections, and fillet radii at each edge and a few radii on the back and the face of the blade.

When we first became involved with manufacturing of propellers and hydraulic turbines, our overall objective was to implement, use and, if necessary, develop manufacturing techniques which would enable us to manufacture propellers without any hand grinding. In order to satisfy this objective, a propeller geometry data base structure and milling procedures were developed, tested and put into production.

Next requirement, coming from the shop floor, was to position the propeller casting in the machine in order to optimize metal removal. This requirement led us to measurement of propeller casting and to development of algorithms for optimal positioning of propeller casting for machining.

Having successfully solved those two problems, using the same propeller geometry data base and procedures for milling, we naturally started to investigate the whole process of propeller manufacturing in order to identify stages where the acquired expertise would help and where more research and development should be done.

Before going any further let us first define three concepts which were always kept in sight during development, testing and commissioning of Integrated Propeller Manufacturing System. Three concepts to be defined are:

- no hand grinding
- all propeller surfaces
- machining to final form

Definitions of these concepts offered here will not be traditional definitions according to the formal rule "definitio est per genus proximum et differentiam specificam" but rather a combination of descriptive narrative and identification of measurable criteria.

No hand grinding means that all propeller surfaces have to be machined to final form under computer control and that the only operation which could be done by hand is polishing to obtain the required surface finish. In other words, removal of material by manual grinding in order to obtain correct shape and form of any propeller surface is not allowed.

For the purposes of having a measurable criterion for comparison and evaluation of various techniques of CNC machining of propellers, let us also define what we mean by **all propeller surfaces** and what we mean by **machining to final form**.

Marine propeller, as a solid body is described by a number of surfaces which are typically defined as separate entities. For example: pressure side and suction side profiles are usually defined independent of the leading and trailing edges. The onus is on the propeller manufacturer to connect the edges with the profiles and to smooth out the transitions between these independently defined curves. In total, monoblock propeller is defined by up to nine different surfaces: face profiles (pressure side), back profiles (suction side), leading edge, trailing edge, pressure side fillet, suction side fillet, trailing edge chamfer, tip profiles and propeller hub. Propeller blade for a controllable pitch propeller needs geometries for up to five more surfaces: leading edge overhang, trailing edge overhang, trunnion, fillets for intersection between overhang surfaces and blade surfaces, fillets for intersection between overhang surfaces and trunnion flange. Therefore, in order to completely machine a monoblock propeller or a propeller blade, up to 14 surface definitions have to be integrated and blended into a continuous and smooth surface suitable for generation of tool path for a numerically controlled cutter.

Machining to final form is defined in terms of scallop height and residual amount of material to be removed by hand after all numerically controlled milling has been completed. Criterion is different for propeller models and for full size marine propellers. For propeller models, machining to final form is defined in terms of maximum scallop height of 0.010 mm. For full size marine propellers we have selected maximum scallop height of 0.03 mm. The residual amount of material which has to be removed during polishing process will depend on the distance between the cuts and geometry, orientation and diameter of the cutter. For example: using a 50 mm diameter ball nose cutter, distance between cuts being 2.5 mm and material being stainless steel, the weight of residual material to be removed by hand after machining will be 80 grams per square meter. If 25 mm diameter ball nose cutter is used, for the same scallop height and same amount of residual material, distance between cuts should be 1.7 mm. However, the smaller cutter defines the surface better and offers better accuracy of the finished propeller blade than the larger cutter.

Integrated Propeller Manufacturing System, described in this paper, eliminates inefficiencies of traditional propeller manufacturing. This is achieved by the use of leading edge technologies for Computer Aided Design, CNC programming and machine tool control. Integrated into a manufacturing process, these technologies eliminate costly re-interpretation of propeller definition data by creating a unique Propeller Geometry Data Base which is used throughout the entire propeller manufacturing process. Propeller geometry data base, created prior to manufacture of propeller model contains all the data necessary for CNC machining of propellers to their final form. Once created and approved by the propeller designer, the data base is used for CNC machining of propeller models, CNC machining of propeller patterns, CNC machining of full size propeller and finally for inspection and measurement of finished propeller.

By using the same propeller geometry data base during the entire propeller manufacturing process, by using custom Computer Aided Manufacturing system and by computing the speed of cutting as a function of local curvature of propeller surface and a function of machine dynamics, the Integrated Propeller Manufacturing System ensures production of superior quality propellers with shorter lead times and at competitive cost.

2. Propeller Geometry Data Base and Procedures

Traditional graphical representation of propeller blade geometry is simple, efficient and adequate for manual, labour intensive manufacturing of propellers. This graphical representation is unfortunately inadequate for numerically controlled machining to the final form. CNC machining of propellers to final form requires a data structure and associated procedures which:

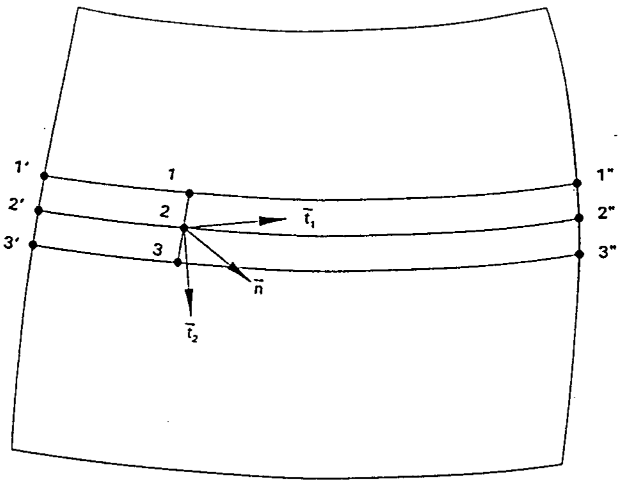
a) preserve all designer's data and intentions,
b) can determine the normal and curvatures at any point on the propeller blade surface,
c) can determine for any point in space whether it is on the propeller blade surface or not, and
d) can determine the normal and the normal distance to the propeller blade surface from any point in space.

The traditional graphical representation and procedures are in principle sound but they lack resolution to accurately perform those tasks. We adopted the digital counterpart of graphical method to increase their potential and speed.

To illustrate the advantage of the digital approach, consider the task of erecting a normal to the surface at a given point (see Figure 1):

- let an intersection line pass through the given point and find the tangent at that point (point no. 2),
- let one intersection line pass on one side and the other on the other side of the middle line,
- find points on each side line which divides its length in the same ratio as point no. 2 divides the middle line,

- let an intersection line pass through the three points and then find the tangent at the middle point,
- direction of the normal at the given point (point no. 2) can now be determined by computing the vector product of the two tangents.



$$\text{Ratio} = \frac{\overset{\frown}{1'1}}{\overset{\frown}{1'1''}} = \frac{\overset{\frown}{2'2}}{\overset{\frown}{2'2''}} = \frac{\overset{\frown}{3'3}}{\overset{\frown}{3'3''}} = \text{Constant}$$

$$\bar{n} = \frac{\bar{t}_2 \times \bar{t}_1}{|\bar{t}_2 \times \bar{t}_1|}$$

FIGURE 1 NORMAL TO THE SURFACE

Even if we disregard the long time required to perform these procedures graphically, the poor resolution would lead to large uncertainties in normals and a ball nose cutter center following these "dancing" normals would cut a very poor surface path.

The data supplied by propeller designers are usually not dense enough to completely define the whole propeller. The designer typically specifies 10 to 20 sections while variable radius fillets are defined by several radii, typically one at each edge and several on the face and back of the blade. There are also regions on the propeller which are defined very sparsely and in some cases not at all. Among these regions are: overhang surfaces on CP propeller blades, fillets which blend overhang surfaces with pressure and suction sides and fillets which blend overhang surfaces with flange of the trunnion.

In order to completely define a propeller for Computer Numerically Controlled (CNC) machining and for CNC measurement, an NC programmer has to verify definition of existing surfaces and create a number of new surfaces which have traditionally been defined by the grinders on the shop floor. Here is the list of propeller surfaces which have to be either checked and/or created on the basis of information supplied by the designer:

- Check face and back profiles for smoothness and continuity along the chord and along the span
- Check the blending of leading and trailing edge profiles with the defined propeller sections
- Create trailing edge anti-singing chamfer surface
- Create fillet surfaces for face and back side of propeller blade
- Blend face side fillet surface with propeller face surface and propeller hub

- Blend back side fillet surface with propeller back surface and propeller hub
- Check blending of blade's last designer supplied profile with desired propeller tip contour and tip profile
- Create leading and trailing edge overhang surface (only for CP propeller blades)
- Create fillets between overhang surfaces and back and face of the blade surface (only for CP propeller blades)
- Create fillets between overhang surfaces and flange of blade trunnion (only for CP propeller blades)
- Create surfaces for air channel slot (only for CP propeller blades with air emission channel)

As it can be concluded from the length of the above list, creating a complete propeller geometry data base suitable for CNC machining to final form, could be a long and tedious task. Once propeller geometry data base is created and after the propeller designer has approved it, propeller geometry data base remains unchanged and is used in all procedures involving manufacturing of that propeller.

3. Manufacturing Equipment

There is not much to be said in respect to the size and configuration of the CNC machines in general. Each application might favour a different machine. However, certain common capabilities might emerge when we consider machining to final form. The closer the cuts to each other the better the definition of the surface.

To answer the imminent question of cutting time, let us consider again a 50 mm diameter ball nose cutter working in stainless steel at 3000 revolutions/min, cutting 2.5 mm deep at a speed of 600 mm/min. With 2 cutting edges, each edge removes 0.1 mm/revolution. Peripheral speed at the effective cutting diameter of about 22 mm is about 200 m/min.

Consider now using a 25 mm diameter ball nose cutter. For the same scallop height of 0.03 mm the spacing between cuts should decrease from 2.5 mm to 1.7 mm. To keep the same peripheral speed, the depth of cut should decrease to 1.25 mm and spindle speed should increase to 6000 revolution/min. To keep the same load on cutting edges the cutting speed should be increased to 1200 mm/min. Thus, the length of cut is increased by a factor of 1.5 but the speed is increased by a factor of 2, and therefore the cutting time is decreased by a factor of 0.75.

High feed rate machine requires more than a high speed spindle in the range of 8000 rev/min and up. The machine has to move in small steps at a fast pace asking the controller to supply the drives with commands in time. Block processing time of about 10 msec/block might be appropriate. Direct Numerical Control (DNC) option and adequate buffering in the controller allowing a transfer rate from the program source of at least 5000 characters/sec is a necessity. Note that a machine equipped for high feed rate machining might not have low spindle speed and high torque needed for some heavy duty jobs around the shop.

Dynamics of the propeller milling machine plays a crucial role in high feed rate cutting. When the milling machine starts from rest, it reaches the commanded speed after a while and then moves at a steady rate. From that instant on, the true position of the machine is behind the theoretical position by a distance called following error. Assuming an exponential decay of the starting acceleration, the following error is equal to $V \times T$, here V is the speed and T is the time constant of the machine (see Figure 2).

A reasonable value for the time constant of a machine is about 33 msec. It is a good idea to check the vendor's value of T by a simple experiment. Disable the controller's automatic acceleration-deceleration feature and command the machine to execute two straight line movements orthogonal to each other at speed V (see Figure 3). The true machine path will start to veer off the straight line at a distance $V \times T$ away from the corner. However, it is easier to measure the distance from the corner to the intersection of a 45° line with the true path, which is $0.52 \times V \times T$.

Cutter center path is composed of a series of straight line segments. The length of each segment depends on the local curvature of the line, radius of the ball nose cutter and accepted deviation from the theoretical profile. The length of straight line segment can be computed as follows:

$$s = 2\,|\rho - r|\,\sqrt{E(2-E)} \qquad \text{where} \qquad E = \frac{\epsilon}{|\rho - r|}$$

and r = cutter radius

ρ = local curvature ($\rho < 0$ and $\rho > 0$)

ϵ = deviation tolerance

Standard value for ϵ is 2.5 microns. The maximum allowed straight line segment s and the time constant T of the machine dictate the maximum speed V at the point under consideration. If maximum acceptable following error is $s/2$, than the corresponding maximum speed will be

$$V = s/(2 \times T)$$

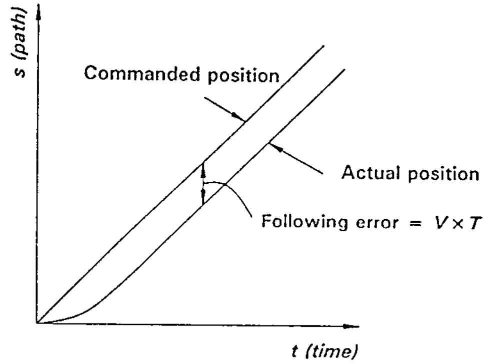


FIGURE 2 FOLLOWING ERROR

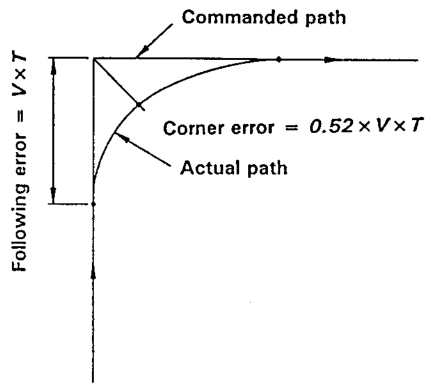


FIGURE 3 CORNER ERROR

Milling a curved line can be visualized as driving a car, looking ahead down the road, anticipating a curve and adjusting the speed in order to stay on the road.

The propeller geometry data base defines the propeller and associated procedures provide all the information to compute the most efficient code to drive the machine. Some controller manufacturers claim that their built in software looks ahead and adjusts the speed commands to fit the line curvature and machine dynamics. However, we prefer to compute the speed off-line and thus retain full control of the process.

Selection of cutting tools is another aspect of NC milling which deserves careful consideration in high feed rate machining.

The ball nose cutter is the simplest and most versatile tool for milling sculptured surfaces. The ball nose cutter shaft inclination is, up to a point, independent of the normal at the surface cutting point. Only the cutter center is required to be on the normal to the surface.

The dovetail cutter with sharp inserts must always have the shaft perpendicular to the plane of the curve. When using dovetail cutter only the normals to the curve in its cutting plane must be known. The height of the triangular scallop profiles depends on the spacing between passes and on cutting edge angle.

The toroidal cutter is somewhere in between the ball nose and dovetail. Orientation of the cutter shaft is more restricted than for ball nose cutter. Round inserts, small in comparison with the diameter of the cutter, favour smaller scallop heights and smaller step size. Normals and tangents to the surface must be computed very accurately in order to avoid gouging due to the sometimes very large "virtual spherical cutter" presented by the toroidal cutter.

3. Manufacturing of Propeller Models

Manufacturing of propeller models presents model makers with several major challenges. Contrary to the myth, that "since these are just small models, there are no problems with manufacturing them", propeller model making is quite complicated and time consuming, especially if we have to respect the same criteria selected for full size propeller manufacturing, i.e a) all propeller surfaces have to be CNC machined to final form and b) hand finishing is not acceptable.

Propeller models can be machined either on 3-axis or on 5-axis milling machines. Each approach has its advantages and its disadvantages.

Programming for 3-axis milling of propeller models is considerably easier than programming for 5-axis milling. However, there are several serious disadvantages to 3-axis machining of propeller models. They are:

a) Propeller blades have to be supported during machining. This is particularly important if propeller model blades are thin.

b) Some interference problems during machining of monoblock propeller models cannot be resolved even if the tool can be inclined at oblique angles using an universal head.

c) For monoblock propeller models with overlapping blades, certain areas of the blade cannot be reached.

d) Since propeller blades are machined first on one side and then on the other side, it is necessary to flip the propeller. Flipping propeller model on the machining fixture by using only propeller bore and hub face as reference is not accurate enough. Small errors in position and orientation of the hub can result in very large errors at the tip and poor alignment between blade face and back surfaces.

From the above list of problems associated with 3-axis machining it can be easily concluded that milling of propeller models and propeller model blades to final form cannot be achieved on a 3-axis milling machine. Therefore, in order to satisfy the criterion for machining to final form, all propeller models manufactured at Dominis are machined on a 5-axis simultaneous contouring milling machine.

There are two possible configurations for 5-axis machining: tilting rotary table and rotary table on rotary table. We chose rotary on rotary 5-axis configuration because it provides greater flexibility for machining of propeller models and monoblock marine propellers in general (see Figure 4).

Initial set-up and alignment of rotary tables is of great importance for 5-axis machining. Axes of rotation for the horizontal rotary table (B-axis) and for the vertical rotary table (A-axis) must lay in the same plane and have to be exactly at 90° to each other.

Propeller model is machined in the machining fixture on the vertical rotary table (A-axis). The machining fixture positions the propeller model hub in such a way that the origin of propeller coordinate system is exactly in the center of rotation of the horizontal rotary table (B-axis) and propeller's axis of rotation is in line with the axis of rotation of the vertical rotary table. The machining fixture should have sufficient stock so that the propeller model mounting face can be machined to size in situ on A-axis. Mounting surface of the machining fixture is also drilled and reamed in order to position 2 locating dowels, one in the center of the hub and the other as far as possible from the center of the hub. Mounting face of the machining fixture together with two dowels locate the coordinate system of the propeller model. In order for this precise set-up to succeed, the propeller model has to be prepared as follows. Propeller model hub has to be bored and hub face has to be machined at precisely 90° to the axis of the bore. At this stage the hub has a flange on one side which is used only for holding the hub during drilling, boring and facing operations (see Figure 5). After this operation is completed the flange is cut off and the hub is machined to size. Of course, at this stage we are mounting propeller model blank which should have extra stock on all blades and on hub contour. Once bolted in place, propeller model blank is not removed from the fixture until machining of the model is completely finished.

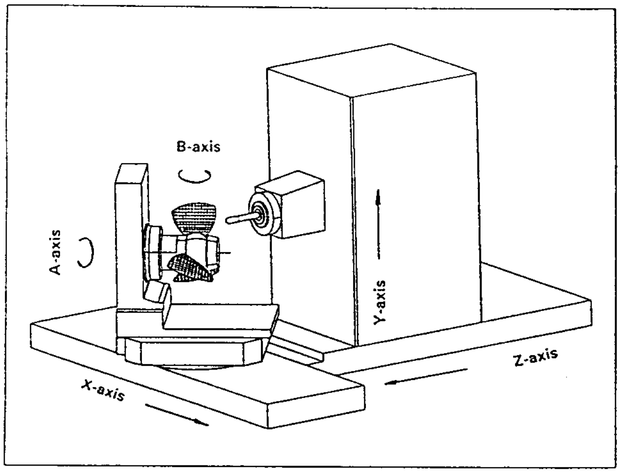


FIGURE 4 5-AXIS SET-UP FOR MILLING OF PROPELLER MODELS

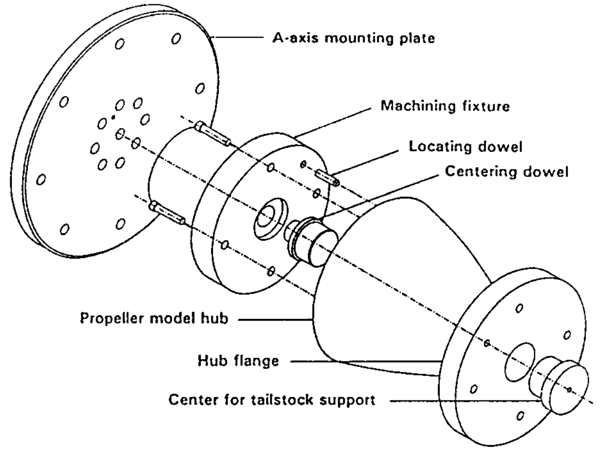


FIGURE 5 MACHINING FIXTURE FOR PROPELLER MODEL

The same set-up and fixturing technique is used for machining of monoblock propeller models and for machining of CP propeller models. Propeller blades for CP propeller models are machined assembled in the hub, in other words CP propeller models are machined in the same way as monoblock propeller models.

For models in brass or bronze, monoblock propeller model blanks are either cast or assembled from roughly machined hub with slots into which trimmed plates containing finished blades are silver soldered. CP propeller blade blanks are assembled by silver soldering roughly machined trunnions and palms with trimmed plates.

For models in stainless steel, welded assemblies for monoblock propeller blanks and CP blade blanks are not acceptable because of stresses induced by welding. Thus stainless steel propeller model blanks have to be either cast or machined from solid billets.

Machining set-up for propeller models described above, allows full 5-axis milling to final form in 1 set-up. In order to properly orient the tool and prevent collisions between tool shank and propeller model blades, we had to develop a software package for interference checking and collision avoidance. Once an obstacle is detected on the tool path, collision avoidance code selects an appropriate correction for tool orientation so that obstacle can be avoided. Every tool movement for the complete tool path for one propeller blade has to be checked by this package. After the tool path has been verified and all possible collisions eliminated actual machining of propeller model can commence. Machining of propeller model, is typically done without interruptions from beginning to end.

In order to achieve greatest possible accuracy in manufacturing of propeller models following precautions and practices have to be implemented:

- Tool diameters should be measured in the spindle and under load when machining the same material used for the propeller model. After cutter diameter is measured NC tool has to be re-computed for that diameter. This is necessary because the accuracy of inserts is ±25 microns.
- Milling machine has to be calibrated and aligned on regular basis.

4. CNC Machining of Marine Propellers

In our discussion on CNC machining of marine propellers we will restrict ourselves to machining of propeller blades for CP propellers. Monoblock propellers up to approximately 1.5 m in diameter can be machined on a horizontal 5-axis milling machines with exactly the same approach and in the same type of machining set-up as monoblock propeller models discussed earlier. Larger diameter monoblock propellers due to their weight have to be machined on a vertical milling machine.

All propeller blade castings have to be measured prior to machining. Measurement of casting has two objectives: a) to establish a coordinate system tied to the casting and to measure a sufficiently dense set of surface points in that coordinate system so that the geometry of the casting can be completely described, and b) to fit the coordinate system of the finished propeller blade within the coordinate system of the casting in such a way that the material to be machined off is distributed most favourably.

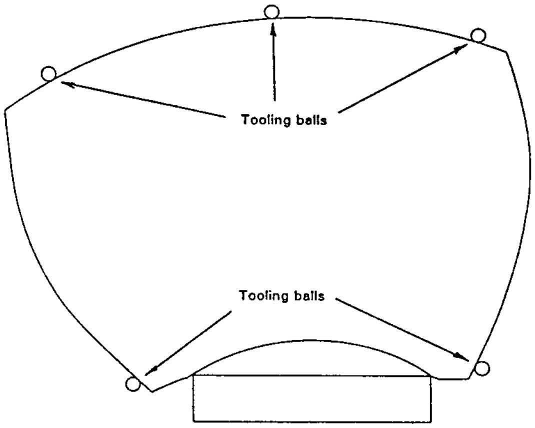


FIGURE 6 PROPELLER BLADE CASTING WITH TOOLING BALLS

Castings for CP propeller blades are measured on the milling machine using Renishaw touch probe. For this operation the milling machine is used as a very large coordinate measuring machine. Procedure for measurement of castings is as follows:

- Drill five holes on the edges of the casting and insert 5 (1" diameter) tooling balls with stems into these holes. Tooling balls must be visible from both sides of the blade casting (see Figure 6).
- Mount the casting on the holding fixture centered on the pallet of the milling machine.
- Measure coordinates of the 5 tooling balls in the machine coordinate system.
- Using Renishaw touch probe measure sufficiently dense set of points on the propeller casting surface facing the spindle.
- Rotate the pallet by 180 degrees, measure the other side of the propeller casting surface and measure again locations of 5 tooling balls.
- Compute the position of the finished blade system in the just established casting system for the best fit, in the least-square sense.
- Compute the position of the tooling balls in the machining fixture system.

After propeller blade casting has been measured and location and orientation of the finished blade inside the casting has been established, we can commence with machining. All CP propeller blades (and Kaplan turbine blades) are machined in 2 different set-ups and fixtures. All work on the trunnion is done in the horizontal set-up using Trunnion Machining Fixture (see Figures 7 and 8), while profiles, edges, tip, fillets and palm are machined in the vertical set-up using Profile Machining Fixture (see Figures 11 and 12).

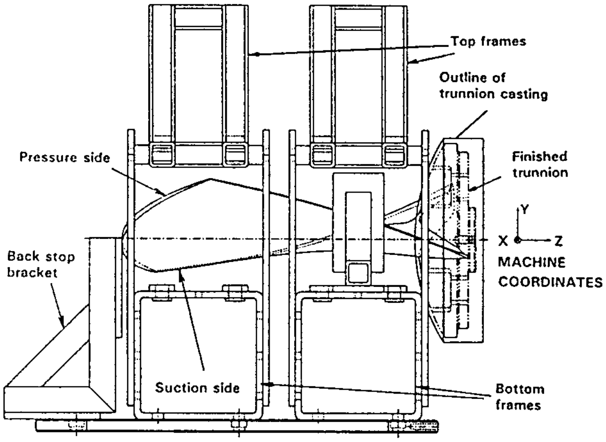


FIGURE 7 TRUNNION MACHINING FIXTURE (side view)

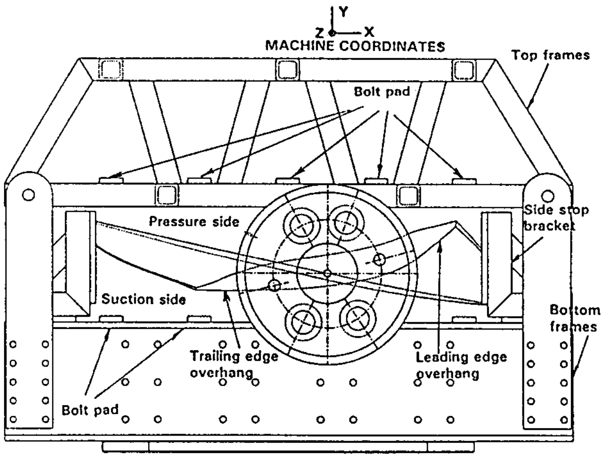


FIGURE 8 TRUNNION MACHINING FIXTURE (front view)

The propeller blade casting should be positioned in the trunnion machining fixture in such a way that the tooling balls on the casting which define the coordinate system of the propeller blade are in their proper locations. Three levelling bolts (not shown on Figures 7 and 8) in the bottom frame are used for levelling of the casting. Once positioned in the fixture, the casting is locked in place using bolts with gripper tips (not shown) from top and bottom frames, and 3 stop brackets, one on each side and one at the tip of the casting.

Machining of the trunnion requires a large number of CNC programs, CNC operations and tools. Main CNC operations are: rough machining of trunnion diameters and faces, drilling and boring of bolt holes, back counter boring of counterbores, drilling and boring of 2 dowel holes used for locating trunnion in the profile machining fixture, finish machining of concentric diameters and trunnion faces, and rough machining and finish machining of overhang surfaces.

Machining of overhang surfaces, blending fillets between overhang surfaces and blade, and blending fillets between overhang surfaces and trunnion are CNC machining operations which are usually omitted. The reasons why this critical area is usually done by hand are twofold: geometry description supplied by the propeller designer is sketchy and often incomplete, thus surfaces for actual CNC machining have to be created, and there are problems with tooling and interference when machining blending fillets on the trunnion side. However, Integrated Propeller Manufacturing System contains procedures for design and generation of CNC programs for machining of overhang surfaces and blending fillets to final form.

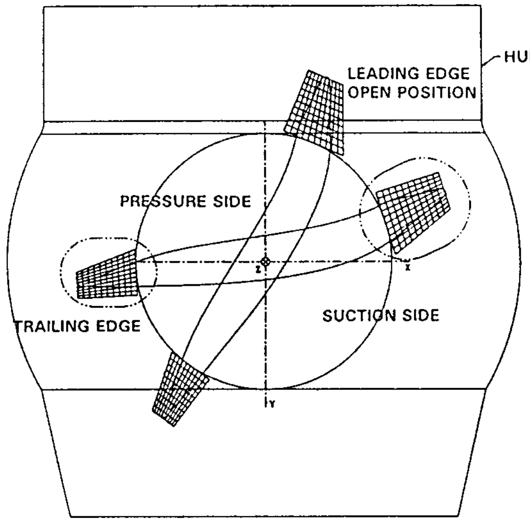


FIGURE 9 PROPELLER HUB

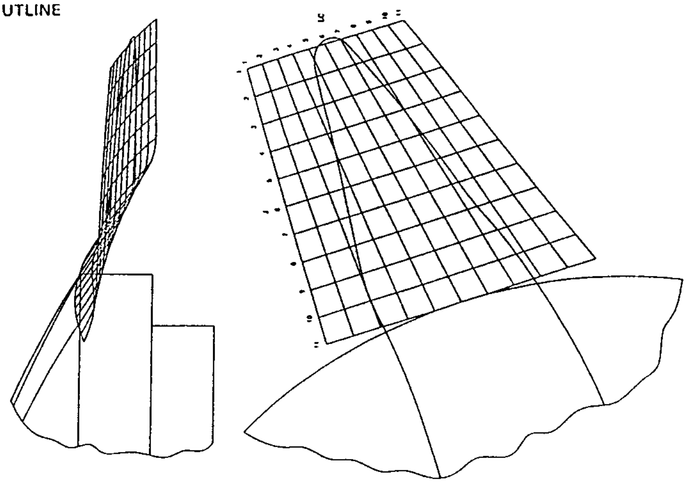


FIGURE 10 LEADING EDGE OVERHANG SURFACE

Overhang surfaces have to meet one criterion; when propeller blade is rotated from open to closed position, overhangs should be as close as possible to the hub (see Figure 9). To create overhang surfaces we first have to find intersections between the overhang outline (extension of the blade profiles into the hub) and hub surface at two extreme positions of the blade. The first candidates for overhang surfaces are hub intersection surfaces raised away from the hub by a nominal distance of 1 mm. The actual overhang surfaces are selected trough an iterative process during which the clearance between overhang surfaces and the hub is computed and orientation and position of overhang surfaces is adjusted to ensure that the blade can move without interference from open to closed position (see Figure 10). The next step is creating ("designing") blending fillets between overhang surfaces and propeller face, back and trunnion. Blending fillets on the overhang do not represent a great challenge for a skilled craftsman on the shop floor. However, for a typical CAD/CAM system, designing blending fillets can at best be frustrating and time consuming and at worst impossible. Number of special design tools were developed and implemented in order to overcome these problems. Before running, all CNC programs for machining of overhangs have to be checked for interference and subsequently adjusted in order to eliminate possibilities of collision between cutting tools and trunnion.

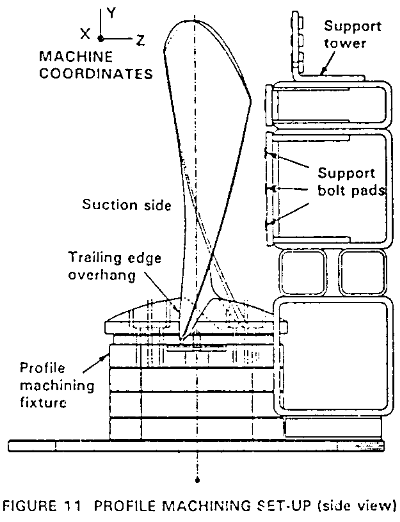


FIGURE 11 PROFILE MACHINING SET-UP (side view)

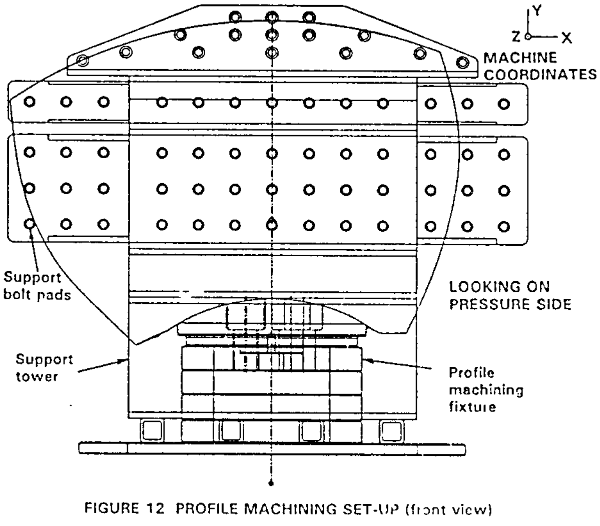


FIGURE 12 PROFILE MACHINING SET-UP (front view)

After completion of all work in the trunnion machining fixture, propeller blade is set-up in vertical position into profile machining fixture (see Figures 11 and 12). Propeller blade is positioned accurately in the machining fixture by means of dowel pins on top of the fixture and matching dowel holes in the trunnion bottom.

There are typically two roughing passes on each side of the blade followed by one finishing pass. Both roughing and finishing passes are always alternating between pressure and suction sides in order to eliminate the possibility of stress relieving of the blade during machining. During profile machining portion of the process, propeller blade is supported from the other side by bolts (not shown) locked in place on support towers. There are two support towers, one for each side of the blade. All support bolts have flat tilt heads which lean against the blade surface and thus eliminate blade vibrations during machining. Majority of the support bolts are placed along the edges and tip. It is important to note that these support bolts are only touching the blade surface and not pushing the blade towards the cutter. Supporting of CP blades during machining is not crucial for propeller blades which are relatively thick, however it is quite critical for thin propeller blades with trailing edge thickness between 2 and 5 mm.

Individual CNC programs for machining of propeller blade profiles generated easily exceed 100,000 lines of code. The efficiency of generated CNC code and machine cutting speed is maximized with respect to: type, size and orientation of the cutter, material of propeller blade, curvature of the cutter path and dynamics of the machine. As discussed earlier, in order to satisfy criterion of machining to final form, distance between cuts during finishing passes is between 1.5 and 2.5 mm, therefore programs are long, some running up to 8 hours without need for operator intervention. Generation of CNC programs on the system is automatic and it is easily reproducible through execution of command procedure files. Manual updating and/or fixing of CNC programs is strictly forbidden since manually changing of CNC code destroys reproducibility of the programs. It takes only a few minutes to regenerate a CNC program for a propeller blade.

After CNC machining is finished, propeller blade is removed from the machining fixture and the blade is set-up for polishing. For blades machined to final form polishing operation is rather short. Propeller blades which are finish machined with 50 mm ball nose cutter at distance between cuts of 2.5 mm require removal of approximately 80 grams of scallop material per square meter.

Measurement of polished propeller blade is the last operation of the propeller manufacturing process. In order to be measured, polished propeller blade must be mounted in the profile machining fixture on the milling machine. Renishaw touch probe is used for measurement of propeller blade profiles. Measurement data for each side is automatically saved in a file. Measurement analysis program reads this file, computes deviations from design data and produces measurement report. Figure 13 shows a plot of distribution of computed thickness deviation. For this blade, which is typical, out of 124 points measured on each side, over 90% of computed thicknesses are within ±0.25 mm. Client's specifications called for ±1.5 mm.

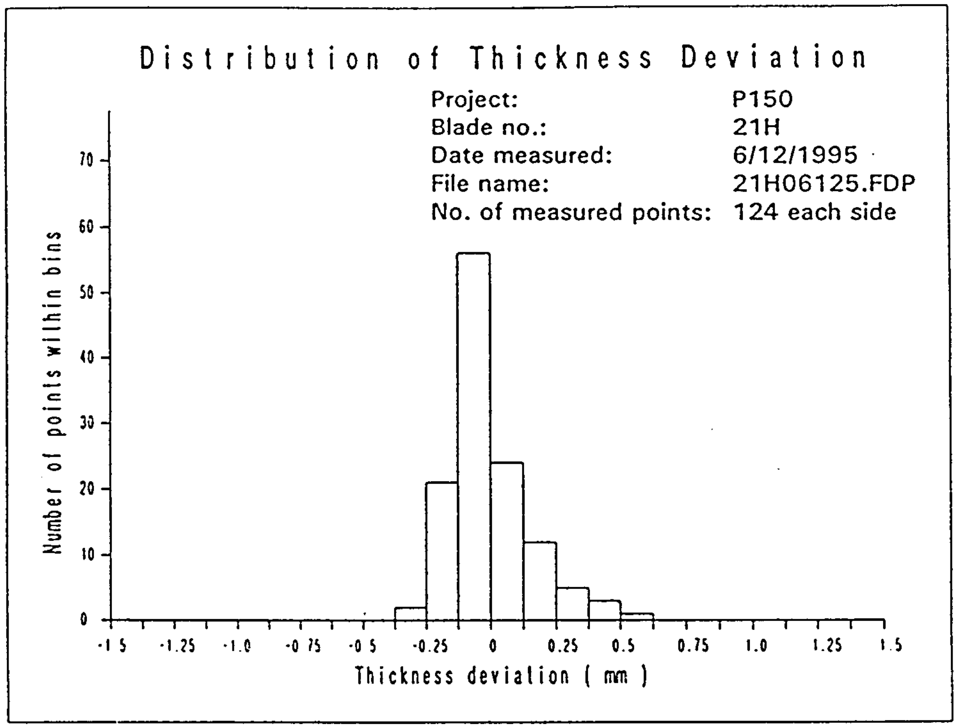


FIGURE 13 DISTRIBUTION OF THICKNESS DEVIATION

8. Summary, Conclusions and Future Developments

Integrated Propeller Manufacturing System in its current form has been used in production for three years. During this time period the system was used in production of 36 Kaplan blades, 34 Francis blades, Kaplan blade patterns, Francis blade patterns, several dozen monoblock and CP propeller models, aircraft propeller models and aircraft propeller molds.

Measurements done on all propeller blades, turbine blades and model propellers machined up to now by the Integrated Propeller Manufacturing System demonstrate consistency and repeatability of the manufacturing process which is best illustrated by the global accuracies of ±0.25 mm for marine propellers and hydraulic turbines and global accuracy of ±0.02 mm for propeller models.

Further developments and extension of system's performance are now under way in the following areas:

a) implementation of a system which would accurately model shrinkage and predict twisting and warping of propeller blade casting during cooling,
b) implementation of system for rapid measurement of propeller blades using remote sensing and machine vision techniques,
c) implementation of real time monitoring of tool wear, automatic replacement of used or damaged tool, real time measurement of new tool and adjustment of the NC program for the actual diameter of the replaced tool, and
d) implementation of production procedures which will facilitate quasi unattended operation of propeller machining.

Biographies

Dr. Draško Gospodnetić is an internationally recognized scientist with wide range of technical experience. Prior to his founding of Dominis Engineering Ltd., he worked for 23 years with the Marine Dynamics Laboratory of the National Research Council of Canada. He retired for National Research Council in 1985 as a Senior Research Officer. During his career he was actively involved in organization, design and building of two major towing tank institutes (Zagreb, Croatia; St. John's, Newfoundland). His technical expertise covers the areas of electronic and mechanical instrumentation, applied mathematics, model design, ship trials, computer technology and CAD/CAM.

S. Gospodnetić graduated in 1969 from Carleton University with a B. Eng. in electrical engineering. Prior to joining Dominis Engineering he worked on computer applications in the fields of computer communications, radar modelling and image processing. He is currently responsible for development of CAD/CAM applications for propeller and turbine blade machining and development of software for computer vision systems.