# INNOVATIVE CAM TECHNIQUES FOR PROPELLER MANUFACTURE

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## *ABSTRACT*

***An innovative approach is presented here for implementation of automation in the propeller manufacture right from the stage of acquiring design outputs of propeller design softwares, incorporating the state of the art technologies/equipment available in the general engineering field such as CAD/CAM softwares, four or five axes CNC machines, Computerised Measurement Machines(CMM) and Dynamic Balancing Machines etc.. The process has enhanced the quality of the propellers and propeller models in respect of their hydrodynamic and hydroacoustic performances, eliminated requirement of highly skilled and professional manpower and cutdown the lead and production times.***

## 1. Introduction

Propeller is an important element of the marine propulsion system for a seagoing vessel. Geometrical accuracy of the propeller is a vital requirement for its optimum propulsive and cavitation performance. With emergence of sophisticated CAM software packages, multi-axes CNC milling machines and computer aided measuring techniques, it has now become possible to undertake machining of the propulsors to very fine tolerance levels with high surface finish. Thanks to these developments and their innovative application, propeller manufacturing process at NSTL has made large strides in automation of the production technique (Fig. 1). This has eliminated the undue dependence on human skills, improved the accuracy of components and enhanced the productivity leading to reduced delivery time.

A reputed commercially available CAM software used in general engineering applications was customised for automatic generation of propeller geometries for a number of standard series and also for those designed by circulation theory. The customised modules of the CAM software system developed in C++ language and the system macros were written for various standard propeller series, such as B-Series, Ka-series as well as single screw and contra-rotating propellers being designed based on circulation theory. Three dimensional models of the propellers were generated using the macro routines of the CAM package, after which tool paths and part programmes for machining the propeller from a solid block were developed. Propeller models and their prototypes were manufactured using 4/5 axis CNC milling machines (Fig. 1) either as integrated propeller or as separate blade elements. The blades of the propeller were inspected on a computerised co-ordinate measuring machine (CMM) (Fig. 2 & Fig. 3) with advanced programmable features capable of using nominal point data along with surface normals of the CAM model. The data were analysed by an analysis software against specified tolerances and deviations are reported. The technique used for three dimensional surface generation, method employed for manufacture using CNC milling as well as inspection procedure of propeller blades on the CMM are discussed.

## 2. Complexities in Propeller Manufacture

Propeller has very complex three dimensional geometry formed with aerofoil sections following helicoidal surfaces and they are required to be machined to very high precision in order to meet the stringent propulsive, cavitation and acoustic performance requirements of the modern marine vehicles particularly those used for naval applications. It is very difficult to fabricate them by conventional machines as the blades have high degree of curvatures particularly at the leading edge, tip and root regions which require advanced curve and surface fitting techniques. Further discontinuities on the surface also cause considerable difficulties in case of anti-singing devices provided at the trailing edge. Though propellers are also made on special purpose precision drilling machines (Fig. 4), the process involves laborious and time consuming co-ordinate drilling which is inaccurate and repeatability is poor among the blades and dimensional control is hard to maintain. It will be much more complex for fabrications of overlapping blades with high blade area ratios. Inspection of these propellers for quality control is also highly complicated and difficult.

## 3. Accuracy Requirements of Propellers

Hydrodynamic and acoustic performance characteristics of propellers (Fig. 5 & Fig. 6) are highly sensitive to the blade accuracy. Propulsive performance, i.e., thrust, torque and efficiency are normally influenced by the section profile, mean line and pitch. Cavitation performance is effected by the profile, pitch, thickness, leading edge form, waviness and surface finish. Acoustic performance depends on the above features as well as material properties of the propellers and residual mass imbalance. Further blades are required to be identical and precise mass balance is essential. All these requirements demand a high precision manufacturing facility as well as adoption of numerically controlled milling techniques particularly for naval applications which can not be met by conventional machines and processes.

## 4. Traditional Methods and Limitations

Propellers manufactured from castings by point drilling and hand finishing (Fig. 4) or by hydrocopy milling techniques (Fig. 7 ) have serious limitation of accuracy and the blade surface waviness. It is difficult to maintain precise leading and trailing edge profiles which are sensitive to cavitation. Hard materials which can sustain erosion can not be used for propeller manufacture due to machining difficulty. Propellers manufactured by hydro-copy milling technique (Fig.7) needs a master propeller or master blade and inaccuracy is also high as functional clearances required for hydro-copy system is more. Inspection of blades using Propeller Polar Coordinate Measuring Machine (PCMM) (Fig. 8) is not accurate enough compared to that by a CMM due to inherent inaccuracy of the machine, human error involved and the process of measurement is also laborious and time consuming.

## 5. Computer Aided Machining (CAM) for Propellers

The above complexities of the propellers, accuracy requirements and the limitation of the conventional equipment, drives the manufacturing techniques to employ innovative and high technology oriented approach. In the recent time CAM has made rapid strides and are being used extensively in defence, space and engineering applications. Versatile CAM software systems such as Unigraphics, Pro-Engineer, SmartCAM, CATIA, etc., which are being used by the industry widely can handle a variety of complex geometries with sophisticated surface fitting techniques, have four/five axes programming capability and very good surface modeling features. Machine tool industry world wide are using a variety of CNC machines ranging from two axes lathe to five (Fig.1) or multiaxes machining centers and also very big gantry type CNC machines (Fig. 9) which can handle different jobs ranging from very small high precision weapon grade propeller components to 4-6 m diameter ship propellers. The accuracies of these machines can range from 3 to 10 microns. These CNC machines are also incorporated with sophisticated controllers and integrated as flexible manufacturing systems (FMS) suitable for network based data transfer and machine operations without memory limitations for handling 3-

D data and large part programmes. Such facilities are essential for machining propellers with high precision, surface finish/quality and ensuring high productivity. Also sophisticated metrology equipment, such as, computerised coordinate measuring machines (CMM) (Fig. 2) and surface finish measurement equipment which have come up recently can facilitate programmed inspection of propellers at the exact locations as required and interpretation of the deviation of components in terms of propeller tolerances. Good dynamic balancing machines (Fig. 10) are now available with the industry which are essential for ensuring precise balancing of naval propellers for low vibration characteristics. The new developments in the engineering industry have encouraged adoption of the state of the art technology for manufacture of propellers to the required precision in order to meet the various naval requirements ranging from very small torpedo propellers to very big ship propellers. This has made possible to formulate an innovative approach using novel technology for automation of propeller manufacture of standard series as well as new design special purpose propellers which is being successfully implemented at NSTL.

## 6. Innovative Approach for Propeller Manufacture at NSTL

The basic approach followed has been automation of the modeling and programming of propellers for the standard series and new design propellers and undertaking machining by CAM on 3/4/5 axis CNC machines with least involvement of highly skilled manpower or propeller specialists. Automatic inspection of propellers on CMM is undertaken to analyse/interpret the propeller geometrical deviations against set tolerance. On manufacture the propellers are balanced and the surface treated for corrosion resistance. A userfriendly and proven CAM software was customised to generate the surface models of the following standard series propellers/designs and produce part programmes

i) B-Series
ii) Modified B-Series
iii) Ka-Series
iv) Propeller designed by Circulation Theory
v) Contrarotating propellers

vi) Propellers developed using design softwares developed by other model testing basins

## 6.1 Userfriendly Software for Propeller CAM

The SmartCAM system was customised for developing 3-D propeller blade section geometry using a standalone. C++ User Friendly Module (UFM) from the non dimensional data of the above mentioned propeller series and the outputs from in-house propeller design softwares, such as Propdes , Contrarotating Propellers etc.. Scope of the userfriendly module is given at Fig. 11. The UFM generates the two dimensional sections and other propeller dimensions from the published data as well as the design outputs and prepares the macro files for SmartCAM, viz., SEC.MCL and PITCH. MCL along with a propeller data format. The latter facilitates detailed verification of the propeller data for incorporating any correction. SEC.MCL, on running generates graphical blade sections stacked at the respective radial stack positions. PITCH.MCL rotates the section by respective pitch angles and wraps on to the cylindrical surfaces at the specified radii ( Fig. 12).

Further the CAM specialist has to model the propeller and generate the part programmes for machining. The macro files also can be corrected and used for modeling directly without changing the input if required.

## 6.2 Modeling and Part Programming

Prior to the surface modeling, the two dimensional sections are verified for their fairness/correctness. These sections are further incorporated with the leading edge radii, anti-singing edges and any other features on the AutoCAD or SmartCAM graphic editor. Blade surfaces are generated by the Loft Surface Feature of SmartCAM (Fig. 13). Tool path can be edited for mistakes, possible surface gauging, idle passes trimmed/removed and finally optimised for minimum machine time (Fig. 14). Show Cut Models (Fig. 15) are used to simulate the machining to assess any mistakes in machining even after correction and optimizing the part programmes. Appropriate milling techniques are used for better surface finish, reduced cutting loads and to avoid tool chatter. The system also facilitates convenient modeling and part programming of overlapped blades with high blade area ratios for machining on 3 and 4 axes machines without necessitating a 5 axes machine. Tool path of a propeller model is shown at

Fig.14. Finally optimised tool path is post processed to generate the part programmes suitable for the machines and the cutting tools.

### 6.3 CNC Machining

At NSTL propellers are fabricated on a four-axis CNC machine or on a five-axis machining center (Fig.1). Model and full scale prototype propellers of underwater vehicles of size 400-500 mm in diameter are manufactured using Manganese Bronze or Aluminium alloy forgings. Pre-machined propeller blanks with the hub internal details completed in all respects are mounted and set on rotary table along with the appropriate mandrels or on special fixtures to a very high precision of face/run out of 20 micrometers. Propellers are machined using Tungsten Carbide ball nose end mills coated with wear resistant material which have very small wear necessary to achieve high blade accuracy and surface finish. The blades are initially rough machined with fairly large diameter ball nose tools ( 16-25mm) following coarse tool path. The finished surface is produced by cutting a nominal stock of 0.5-1mm left on blades at very high feed rates of 0-2000 mm/min with very close pass intervals of about 0.5mm in order to control the cresp height for attaining the desired accuracies while machining. Finally the product is hand polished using fine grade emery. Fig. 18 & Fig. 19 show the blade machining and Fig. 21 shows the picture of finally finished propellers.

### 6.4 Propeller Inspection on Computer Aided Co-ordinate Measuring Machine(CMM)

Propeller accuracies required for the underwater vehicle are stringent in order to meet the performance requirements and therefore high precision CMM is required for their inspection. As the blades are 3D surfaces having curvature in the three directions, it is impossible to measure deviations at specific predetermined points on the specified sections in order to assess the profile and pitch deviations by the direct inspection. To overcome this difficulty, nominal point data on the blade sections at 5 degree angular intervals along with normals are generated using Pro-Engineer or Unigraphics softwares. CMM is programmed for automatic inspection of the propellers using the above data and inspection is carried out for each individual blade. A propeller being inspected on a CMM is shown at Fig. 2

### 6.5 Analysis of Inspection Data

Output of the inspection results from CMM is further analysed with a special purpose programme. The program reads the CMM output and organises the data for processing, compensates for probe diameter if required and interprets the same against the set tolerances given in a data file and provides the report in a specified format. The tolerances are similar to the propeller tolerances at ISO: 484;1966. Profiles are also verified/compared with basic nominal sections of the blades (Fig. 20). The propellers are accepted/rejected on the basis of the report.

## 7. Dynamic Balancing of Propellers and Surface Treatment

The propeller models used for Towing Tank or Cavitation Tunnel experiment or prototype propellers for the naval underwater vehicles are required to be balanced to meet their dynamic, acoustic and vibration performances. These propellers are balanced dynamically to a very high grade G1 to ISO: 1940 (Fig. 10). For this purpose the propellers are mounted on high precision mandrels already balanced to grade G 0.4 and then dynamically balanced on a Shenk Avery, RL-2B balancing machine. Material additions or removal are made only on the hubs. Balanced propellers are hard anodised to 10-25 micrometer coat thickness for protection against corrosion.

## 8. Hydrodynamic and Cavitation Performance

The propellers produced using the above techniques/process have been found to be consistent in their hydrodynamic, cavitation and acoustic characteristics in Towing Tank and Cavitation Tunnel experiments. The variation in propulsive performance in open water tests for a series of propellers manufactured using the above technique and tested in the towing tank is found to be within 1-2%. Cavitation characteristics like cavitation inception and cavitation diagrams are also found to lie very close for two propellers of identical design and size machined with this technique. Cavitation performance of propeller is shown at Fig. 5 and Fig. 6 respectively.

## 9. Discussion

Customisation of the Smart CAM software has enabled automatic generation of complete geometrical details of the standard propeller series, viz. B-Series and Ka-Series and also any new propeller designed based on Circulation Theory. The userfriendly software develops 2-D blade section data and 3-D models of the propeller automatically using the macro routines of the CAM software generated by the UFM. The software facilitates incorporation of corrections at any stage of data generation, modeling and part programming. Simulation of tool path, tool path editing & Show Cut features allows us to check the models and part programs of the component. The entire process of geometry generation, modeling and part programming can be completed in one or two man days.

It has been possible to manufacture highly skewed and overlapped propellers with reasonably high blade areas to a very high precision (using Four or five axis machines) for the propeller of sizes commonly used at NSTL. Measurement of propellers on the Computer Aided Measuring Machine has enabled automatic inspection and reporting the deviations in terms of the standard propeller tolerances directly. This method of inspection is highly accurate, rapid and reliable. The dynamic balancing levels adopted for the propellers and the method have improved the dynamic performance of the components and minimised the vibration levels.

The results of the hydrodynamic and hydroacoustic experiments at the High Speed Towing Tank and the Cavitation Tunnel at NSTL have shown considerable improvement in terms of accuracy and consistency which is essential for experimental evaluation and full scale performance prediction. The technique has automated the process of propeller manufacture at NSTL with minimum requirement of highly skilled manpower.

## 10. Conclusion

The innovative approach described above and adopted for the propeller manufacture at NSTL has automated the propeller manufacture, eliminating the need for highly skilled manpower which is difficult to obtain. It has also enhanced the quality of the product in terms of meeting the hydrodynamic and hydroacoustic performance of propellers and minimised the production/lead times. The process has upgraded the manufacturing process by incorporating advanced technologies available in the engineering field today.

## References:

1. Exploring SmartCAM, Production Milling, Advanced Milling and Free Form Milling, SDRC, Milford, USA
2. Propeller Tolerances, ISO 484, 1966
3. Dynamic Balancing, ISO 1940

Fig:1 Machining of Propeller on 5-axis CNC Machine

Fig:2 Inspection of Propeller on CMM

Fig:3 Propeller Blade Inspection

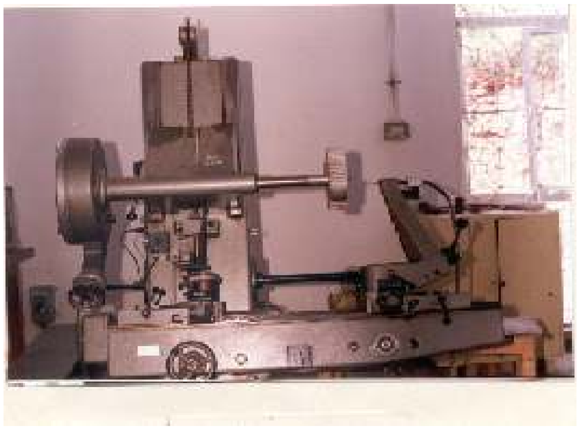


Fig: 4 Propeller Manufacture by Point Drilling

Fig:5 Propeller Testing for Cavitation/ Acoustic

Fig:6 Propeller Testing for Propulsive Performance under Cavitation

Fig: 7 Hydrocopy Milling of Propeller

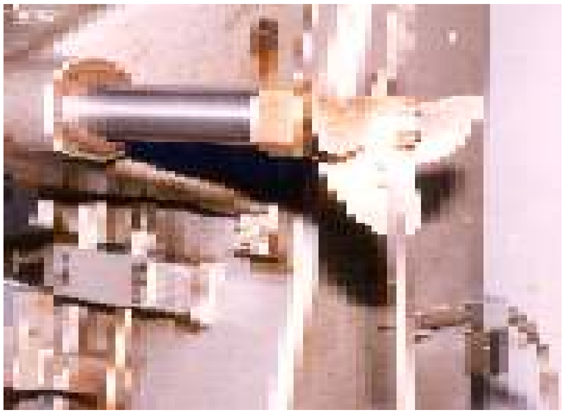


Fig: 8 Propeller Measurement on PCMM

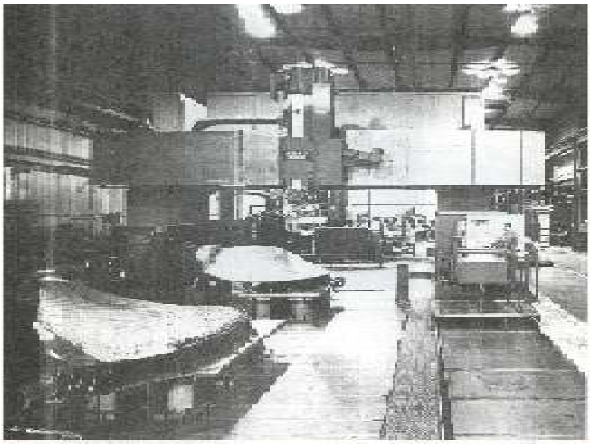
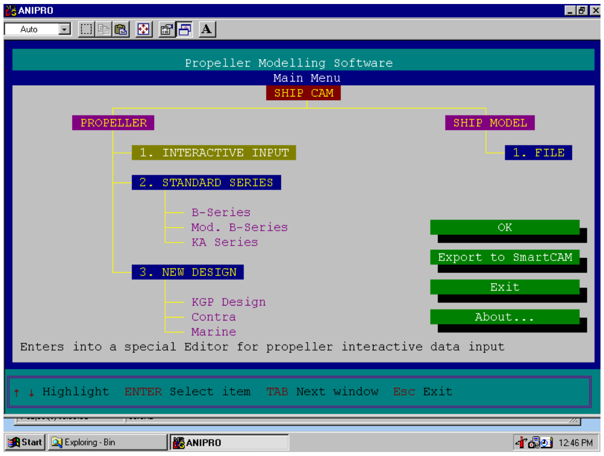


Fig: 9 Gantry Type CNC Machine for Propellers

Fig: 10 Dynamic Balancing



Enters into a special Editor for propeller interactive data input

Fig: 11 Scope of User Friendly

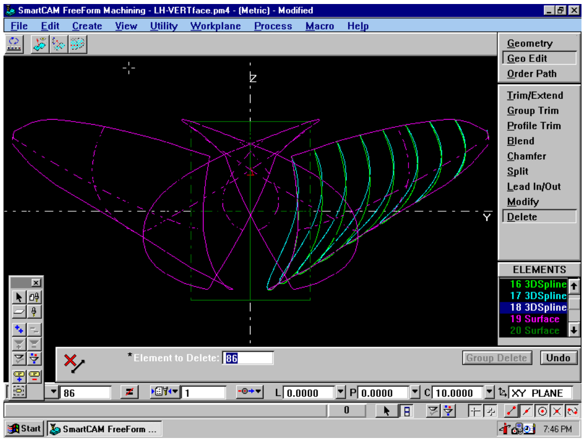


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Fig: 12 Stacked and Wrapped Blade Sections

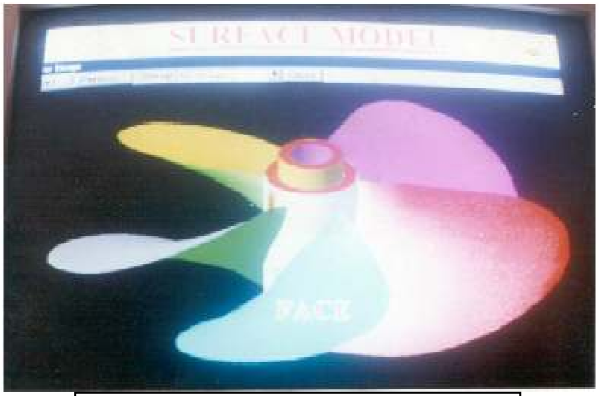

Fig: 13 Shaded Propeller

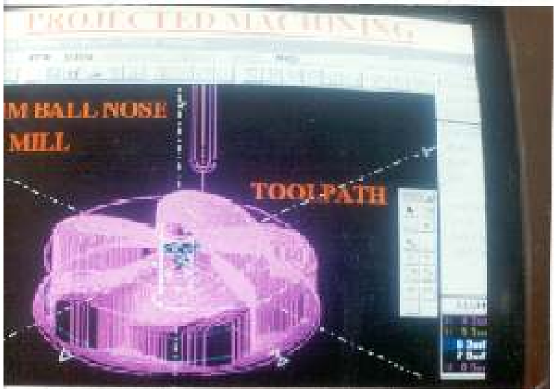

Fig: 14 Tool Path

Fig: 15 Show Cut Model

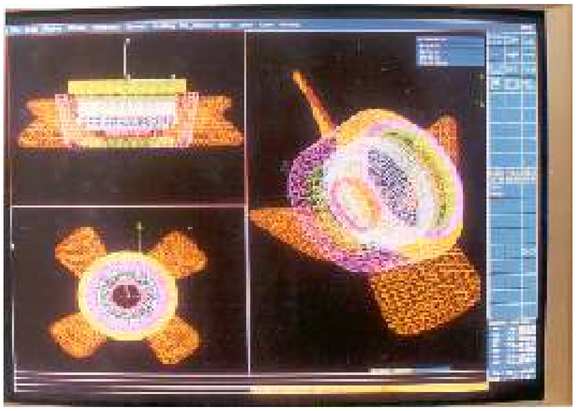

Fig:16 Surface Mesh

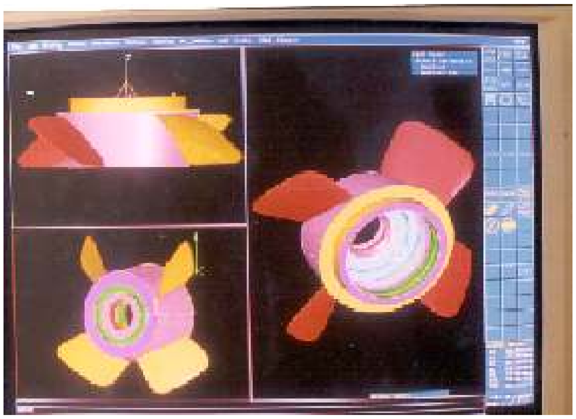

Fig: 17 Surface Model

Fig: 18 Propeller

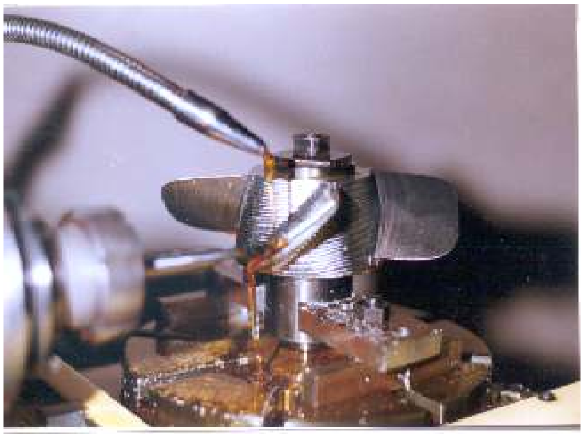

Fig: 19 Blade Machining

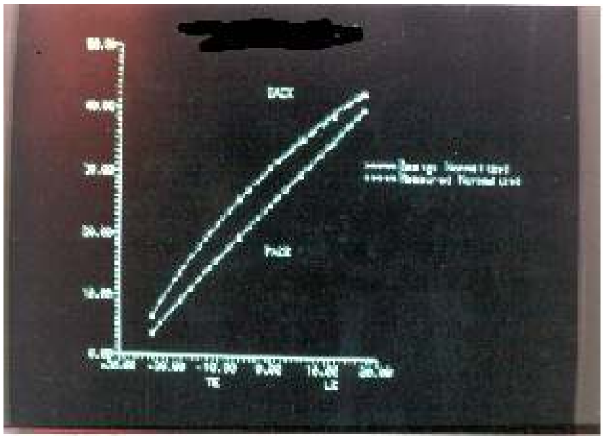

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Fig: 20 Profile Verification

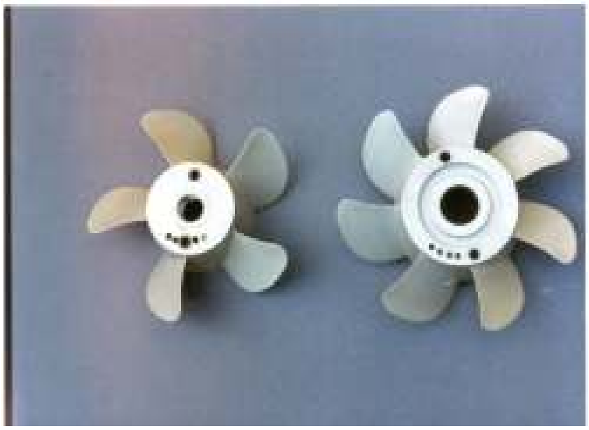

Fig: 21 Finished Propellers