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ARBITRARY SURFACE FLANK MILLING OF FAN, COMPRESSOR, AND IMPELLER BLADES

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ABSTRACT

It is generally conceived that a blade surface is flank millable if it can be closely approximated by a ruled surface; otherwise the slow machining process of point milling has to be employed. However, we have now demonstrated that the ruled surface criterion for flank milling is neither necessary nor sufficient. Furthermore , many complex arbitrary surfaces typical of our blades in fans, axial compressors, and centrifugal impellers in aviation gas turbines are actually closely flank millable and can be rendered exactly flank millable with one or more passes per surface often without sacrificing, indeed sometimes with gain, in performance.

INTRODUCTION

Point milling and flank milling are the two common metal cutting methods for compressor blades in aviation gas turbines. The former is a well known technique whereby a blade surface is cut by the ball-nose of a cutter following a dense set of isoparametric curves on the mathematical surface interpolating the blade design curves. While the implementatioa of a point milling software package may be complex, from a conceptual point of view, it is a simple, well defined problem. Its major advantage to the airfoil designer is that almost any smooth surface can be point milled, offering total freedom to the design process. From the manufacturing point of view, however, the main disadvantage of point milling is that it is a very time-consuming process, each passage of the cutter removes only a small amount of material. Another disadvantage is that by its very nature, point milling produces scalloped surface finish, the height of the scalloped ridges is directly related to the ball-nose radius and the number of cuts over the surface.

Compared with point milling, flank milling is a much less well known technique. In conventional flank milling, the entire blade surface is obtained after one single passage of the cutter through the blank material, engaging every point of the cutting edges on the conical as well as the ball-nose surface of the cutter. This is illustrated in Figure 1. Thus conceptually, flank milling is not as easy to understand as point milling. It is generally conceived that a surface is flank millable if it can be closely approximated by a ruled surface. To complicate the problem further, the milled surface may deviate from the ruled surface, sometimes quite significantly, owing to the twist of the surface along a straight line element. To our knowledge, previously such deviations have either been ignored, or minimized by compromising the design or slightly modifying the cutter orientation. Then finally there are the hardware difficulties such as blade and cutter deflection arising from the severe force from large volume metal removal.

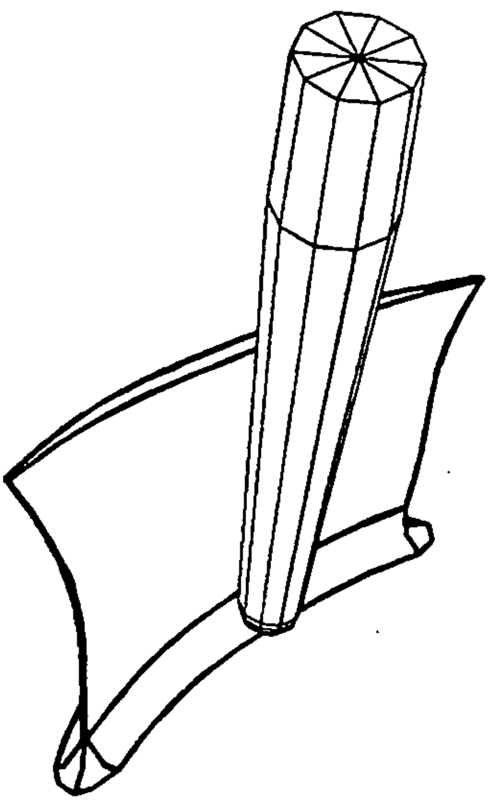

Figure 1: Schematic illustration of flank milling.

In spite of all these difficulties, considerable effort has been

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invested to understand and apply flank milling whenever possible. This is mainly because flank milling, when applicable, offers significant cost reduction over point milling. In particular, flank milling has been extensively employed in the manufacture of centrifugal impellers for aviation turbomachinery (Ref. Brown 1979, Pratt 1981, Willis 1975, Wu 1982). Another advantage is that it gives a good clean surface finish which is another productivity improvement factor because it reduces the time required for surface polishing.

At Pratt & Whitney Canada Inc., for more than a decade we have been striving to expand the domain of applicability of flank milling to cover axial compressors in the form of integrally bladed rotors (IBRs). Axial compressor rotor blades are generally considered to be not flank millable, owing to the severe twist of the blade surfaces as well as other complexities. However, by imposing 3 design curves to lie on a highly twisted but nevertheless ruled surface, and then reducing the deviation between the ruled surface and the machined surface by introducing the technique of multiple pass flank milling, (Ref. Wu 1983) we were able to flank mill two moderately complex rotors. This exercise clearly demonstrates that the ruled surface criterion is not sufficient to guarantee that a surface is flank millable in the conventional single pass manner.

Encouraged by our initial success with multiple pass, we attempted to flank mill more complex surfaces defined by four or more curves by dividing them into two or more overlapping ruled surfaces stacking one on top of the other. However, we were unable to blend in smoothly two adjacent passes. One cannot realistically resolve this challenge without first having a far more flexible and powerful software to facilitate the design of a flank millable blade and generating tool paths efficiently before resolving the hardware problems. This, in fact, was the motivation behind our drive to develop what we now call Arbitrary Surface Flank Milling (ASFM) system which is conceptually a quantum jump from the conventional ruled surface flank milling approach.

In the ASFM system, a surface can be defined with a lot more than 3 curves which the designer specifies without the constraint that they should be lying even approximately on a ruled surface; it is therefore an arbitrary surface. Given such a surface, the ASFM system rapidly generates a set of flank milling tool path to closely match the cutter surface to the design curves in a weighted manner. The matching is done by choosing one among the infinitely many curves on the conical surface of the cutter to match one point each on every design curve. Since one of these infinite number of curves on the cutter surface is a straight line, we have included the ruled surface constraint as a particular member of a much larger family of flank millable surfaces. The matching process is necessarily complex, requiring highly flexible, powerful and user-friendly software to facilitate the efficient convergence between design intent and flank millability and will be discussed further in the next section.

If the flank milled surface thus produced does not yield satisfactory performance, we would opt for two or more flank milling passes, stacking the passes one on top of the other, we have also solved the problem of blending the adjacent passes to yield a smooth surface.

We have applied the ASFM system to flank mill a large number of axial IBRs, fan IBRs as well as centrifugal impellers of high complexity inducer design which would not be flank millable in the conventional approach.

In what follows, let us first discuss the basic concept of arbitrary surface flank milling in some depth.

CONCEPTS & CHALLENGES

Figure 2 shows a blade surface designed with six curves together with a conical cutter. The actual number of design curves can vary widely between a minimum of 3 and a maximum of any number, we have had cases of 15 to 20 curves. Referring to Figure 2, one may imagine an arbitrary surface Sb interpolating the six design curves C_1 to C_6, then Cp is a curve on the cutter surface Sc which is closest to the blade surface Sb for the particular cutter position and orientation depicted in the figure; and Cb is a curve on Sb which is closest to Sc. If Cb is "sufficiently" close to Cp for the entire blade surface from the leading to the trailing edge then we have a flank millable surface which approximates the design intent surface.

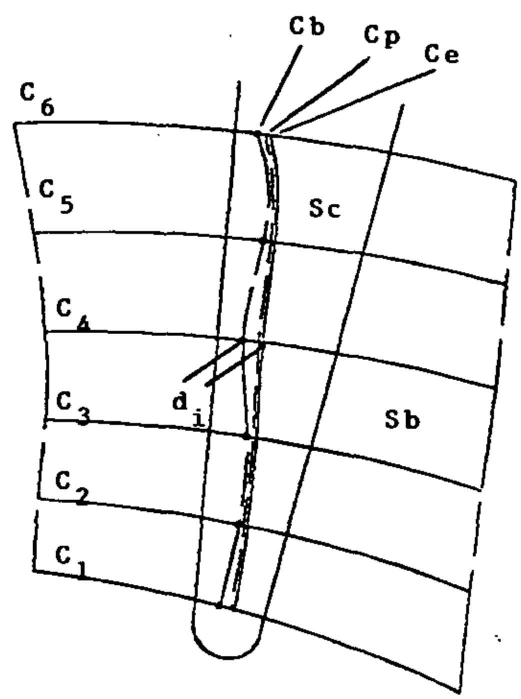


Figure 2: Schematic illustrating the relationships between the proximity curve and the enveloping curve on the cutter surface with the blade.

However, it is a subtle but important point to realize that the family of the proximity curves Cp does not generate the exact flank milled surface. The exact flank milled surface is the enveloping surface swept out by the cutter surface. It is composed of individual enveloping curve, shown as Ce in Figure 2, associated with each cutter position. The computation of each enveloping curve, however, depends not only on the particular cutter position but also on its immediate preceding and immediate following cutter positions. Such "nearest-neighbour coupling" can have very strong effects on the machined surface, especially when the cutter orientations are varying dramatically, usually near the leading and trailing edge.

Since the exact flank milled surface cannot be obtained before we have a complete trajectory, but a complete trajectory is known only after individual cutter position is determined approximately via proximity curve calculation, one has to arrive at the cutter trajectory iteratively. We start out using proximity curve calculation to determine the approximate cutter positions individually, then change over to compute the enveloping curves in subsequent refinement which involves variation of individual cutter position or groups of cutter positions simultaneously.

When there are three or more design curves, there is no guarantee that the flank milled surface could match all the curves exactly. Thus in Figure 2, Ce deviates from Cb by d_i with respect to each curve C_i. Typically in the design of the blade, some curves have tighter tolerance than some other curves, thus $\sigma_i=d_i/t_i$ is a measure of the significance of the deviation between the flank milled surface and the design curve C_i, where t_i is the tolerance assigned to curve C_i. So far we have been focusing on one particular cutter position. To generalize our discussion, we may use $\sigma_{ij}=d_{ij}/t_{ij}$ where i denotes the C_i curve and j denotes the jth cutter position or equivalently, the path length along curve C_i. If σ_{ij} is less than 1.0 for all (i,j), then the flank milled surface is acceptably close to the design intent. Theoretically at least then, our problem is to find a set of cutter positions such that $\sigma_{ij}\leq 1$, if we can very reliably define t_{ij}.

However, we cannot very reliably define t_{ij}. While there are many rules as to how to design a blade for targeted performance, such rules do not always yield a unique blade geometry. Indeed, given some performance requirements, there may be many possible blade designs which yield satisfactory results. Differences between two blades along some design curves may be compensated by differences along some other curves such that they give similar performance. One eventually has to rely on aerodynamics and structural analysis, and ultimately on experimental tests on hardware sometimes, to really decide whether seemingly different designs give equivalent performances.

With such understanding, we may view the challenge of finding a flank milled blade that gives equivalent performance as a "freely" designed blade in a bolder and broader perspective.

For each design intent blade surface, we initialize a complete set of values for t_{ij}, based on our experience and/or best guess. A scheme would then try to optimize the cutter positions and orientations by minimizing σ_{ij}, this is done for some 30 to 50 non-crossing cutter positions covering the entire blade surface. The resultant σ_{ij} will help in adjusting the t_{ij}s more realistically, the new t_{ij}s may now be defined with respect to the new nominal blade geometry obtained from the previous iteration or they may stay with the original design intent. How fast the iteration t_{ij} <--> σ_{ij} would converge to some meaningful values for highly complex blades is the major challenge to our design methodology and software capabilities.

How are the t_{ij}s set? They are set to alter and control the general as well as the details of all the blade section profiles so that the curvatures, the inlet metal angles, the exit metal angles, the leading edge radii, the trailing edge radii, the chord lengths, the chord angles, the blade thicknesses and the location of maximum thickness along each blade section, etc., all combine to give the targeted performance as achieved in the original design intent blade. In this context, the original design intent blade acts as a seed to start off the design of the flank millable blade. Highly efficient and reliable aerodynamics and structural analysis programs facilitate our setting of the t_{ij}s, alongside with the guidance provided by the ASFM system which sets the realistic manufacturing constraint on the t_{ij}s imposed by flank milling.

Ideally, the convergence of the t_{ij} <--> σ_{ij} iteration process should be carried out in a completely automated way and indeed, we have made great strides towards this goal. However, the problems are so immense and complex that much more effort will be needed. The next section outlines our systematic approach toward meeting the challenges.

THE ASFM SYSTEM

Our software system comprises of close to 30 batch programs, each one performs some special function that belongs to one or more of the following three logical phases of the system:

Phase I - Test For Flank Millability

The mission of this phase is: given a blade design in the form of a number of curves on its suction surface and pressure surface, rapidly allows the user to generate the probable flank milled blade profile with the associated tool paths. The important points here are the speed and the reliability of the results so that in a small fraction of the time added to the regular design cycle, we know whether or not we should go ahead with flank milling, and if we do, the designer should have the means to generate new design blades in the vicinity of the original design so that the new iterations will stay closely flank millable.

Starting with three or more design curves on each surface, cutter size specifications, and a set of user supplied initial t_{ij} values which could be just the best guesses only at this point, the main program DESIGN in Phase I will first define a set of cutter positions extending from the leading edge to the trailing edge of the surface, each cutter surface touching two of the design curves tangentially (e.g. C_1 and C_6 in Figure 2) with the axis perpendicular to the curve that is closest to the hub (e.g. C_1, in Figure 2). Next, the program begins an optimization of each cutter position by minimizing $\Sigma_i\sigma_{ij}$. Since the process involves one cutter position at a time, the distances between the cutter surface and the design curves are based on proximity curve concept as discussed in the previous section.

Now optimization is a tricky mathematical exercise that may not always converge to the best possible solution for each cutter position. However, if the process is carried out for a sufficiently large number of cutter position, one may observe how flank millable the design surface is and adjust the t_{ij} value accordingly. For simple and moderately complex blades this is not too difficult to do, especially after one has acquired some experience. Thus one may repeat the optimization process a few times rapidly and within a few hours, decides whether or not the blade has a good chance to be flank millable.

Phase II - Detail Matching

The results of Phase I become the starting point in this phase. In Phase I we obtain some cutter trajectories that give a probable flank milled surface, here we want to fine tune each enveloping curve associated with the cutter trajectories to yield a flank milled blade that gives equivalent performances aerodynamically and structurally to the design intent. In this phase there are over a dozen programs. We will only outline some key programs below:

(i) BKGEN: back-generate accurately the flank milled surface from a cutter trajectory using enveloping curve calculation. This is possible here because in this phase, we always have a complete cutter trajectory.

(ii) RENDN: rendering of the cutter vectors in directions normal to a chosen design curve.

(iii) RENDP: rendering of the cutter vectors in a sliding (parallel) manner along a chosen design curve.

(iv) SMTH: smooth out the cutter vectors along any section.

(v) CHKADJ: check whether or oot there are interferences between the cutter and the adjacent blade.

(vi) TLCHG: tool change program. This program allows one to change tool and generate new tool paths based on the old one. Slight rematching will be necessary.

(vii) LETE: coostruct leading and trailing edge circular or elliptical arcs from the back-generated flank milled blade sections.

(viii) GEOM: analyses the geometries of the flank milled blade profiles such as inlet and exit metal angles, leading and trailing edge radii, throat areas, thicknesses, etc.

The greatest challenge in Phase II is automation. In theory one should be able to complete the job in one batch run but in practice this is far from being easy, in spite of the fact that we have made great progress in this direction. Typically, we will first run SMTH and then RENDN to obtain good matching for one or more of the most critical design curves. Then RENDP is run to minimize the deviations from the other curves. Most likely then one needs to run RENDN agaia to depart from the most critical curve in certain areas to achieve better matching for the other curves; then we rerun RENDP again. This cycle is repeated a number of times for both the suction and the pressure surfaces. Good starting sets of tool positions from Phase I is very important so that one always searches in a small neighbourhood for the best solution. SMTH, CHKADJ, TLCHG, etc. are run every now and then. BKGEN is run back to back with every program that changes any cutter orientations. The programs are very user-friendly and fast, although run in batch mode, they give the feeling of interactive execution. LETE is run to create a complete blade geometry to be analysed by GEOM and then detail aerodynamics and structural analysis to check the performance. Depending on the complexity of the blade, it typically takes a few days, performing several to a dozen iterations between flank milling definition and performance analysis to reach a flank milled blade of equivalent performance to design intent.

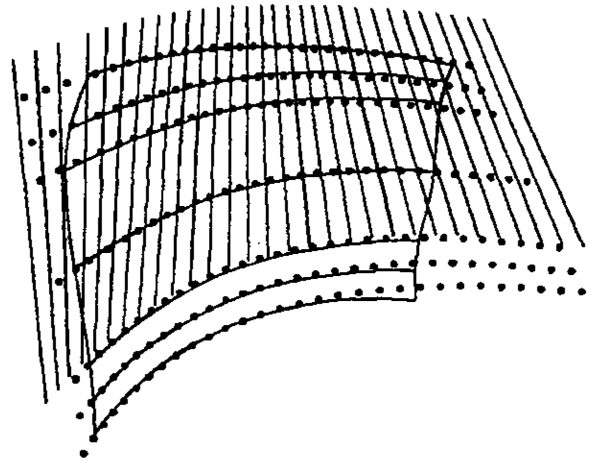


Figure 3: Results of detail matching for the suction surface of an axial compressor.

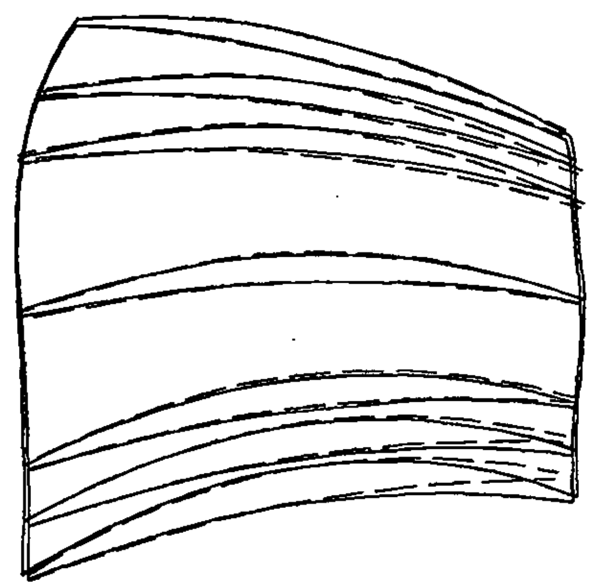


Figure 4: Comparison between blade sections of flank milled blade (dashed) and design intent curves(solid).

Figure 3 shows the results of detail matching tool path for the suction surface of an axial compressor. The solid curves are the design intent curves, the dots are points on the back-generated flank milled surface, while the straight lines are the associated CL vectors.

In Figure 4, we compare the blade sections for both surfaces of the design intent(solid) and flank milled(dashed) blade. While one may see significant differences in individual section, overall the performances of the two are quite close.

Phase III: Manufacturing Concerns

The tool path generation in Phase I & II are solely concerned with the finishing cut. When we come to actual metal removal, we need to generate roughing cut, semi-finishing cuts, and very important, we have to have a way to cope with blade and cutter deflections. Phase III addresses these problems with a number of programs:

(i) OPEN: this program generates cutter location vectors for a flat-end or ball-end cutter right between two adjacent blades with a user specified lead angle of the cutter for efficient opening cut between two blades.

(ii) SEMROU generates semi-finishing and roughing pass from the finishing pass by offsetting the finishing pass away from the blade.

(iii) TLCHG: tool change, same program as in Phase II, to allow rapid change to different size roughing or semi-finishing cuts, but not finishing cuts at this stage.

(iv) CHECK: checks tool-blade interference after OPEN, TLCHG, or SEMROU has been run.

(v) DEFL: adjusts the cutter vectors to compensate for blade thickening due to blade deflection and cutter deflection.

(vi) INTERP: interpolates a dense set of CL vectors from a spare set to facilitate smooth metal cutting.

The circular or elliptical leading and trailing edges of the blade are usually not flank milled. They are point milled to blend in smoothly with the flank milled surfaces.

We conclude this section with photographs of some of the rotors we have actually fabricated.

Figure 5 shows three axial IBRs welded together to form a drum rotor. The diameters of the rotors are approximately 12". The 1st rotor (the one on top in the photo) has relatively simple blade geometry, while the 2nd and the 3rd have increasingly complex blade shapes.

In Figure 6 we show an experimental impeller. The main blade is 10" long while the splitter blade is 6" long. The main blade leading edge is 3" tall. Note the very complex blade geometries.

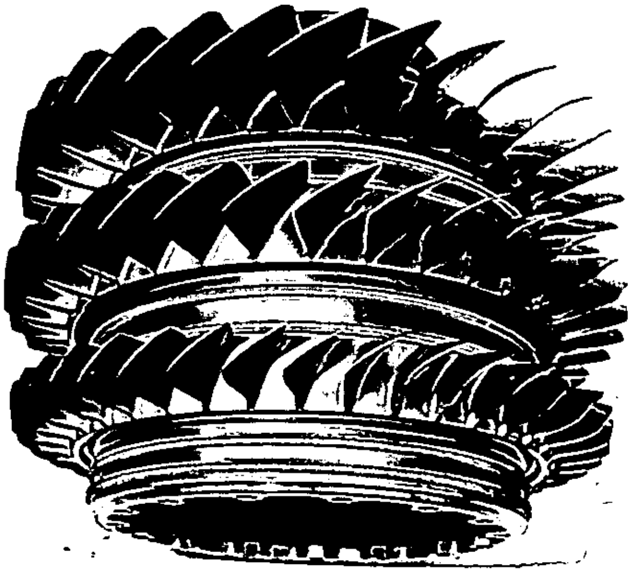


Figure 5: Three flank milled IBRs welded together.

Figure 6: An impeller with highly complex blades.

Multiple Pass Flank Milling

If a blade is too complex to be flank milled in the manner outlined above we may want to flank mill each surface with two or more passes, one stacked on top of the other. Owing to the complexities, both software-wise and hardware-wise, multiple pass is only employed with large rotors, typically our fan IBRs. So far we have not gone beyond two passes, but the techniques are the same for more passes.

Figure 7 shows the computer simulation of two pass flank milling of a fan blade. The top pass resembles the regular single pass.

with a standard tapered ball-end cutter. The tangency point between the tapered cutting edge and the ball end follows a curve on the blade surface which is the boundary curve between the two passes. The length of the cutting edge is not important as long as it is long enough to cover the entire top part of the blade. The length of the tapered cutting edge of the bottom pass, however, is important: that entire length is engaged in metal removal so that the transition point between the tapered cutting edge and the straight shank lies just on the boundary curve between the two passes. Such arrangement gives optimal chance for the cutter to clear the top part of the blade and the adjacent blade. Along the boundary curve, the two flank milled surfaces are tangential radially to ensure smooth and continuous blade profiles. A small radial profile is given to the bottom pass cutter in the transition from tapered cutting edge to straight shank to avoid sharp step along the boundary curve due to hardware discontinuity.

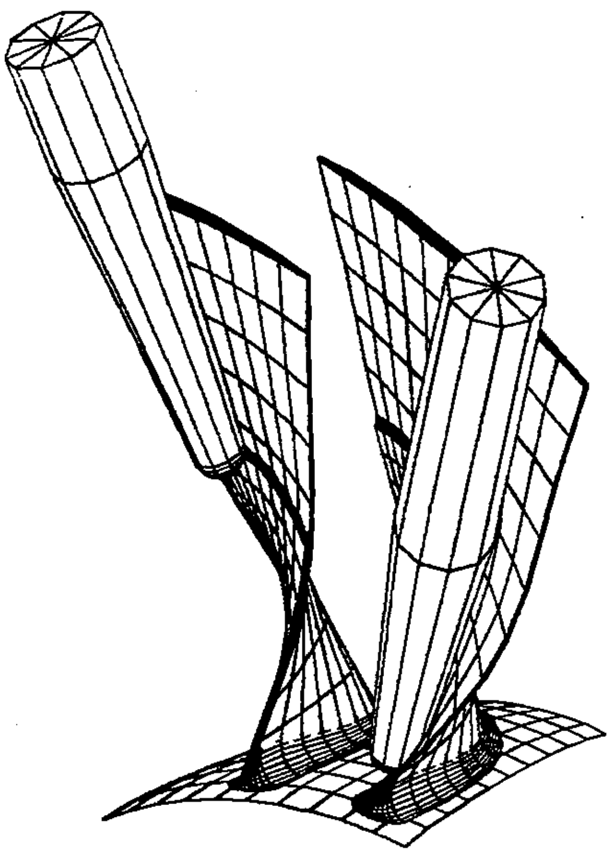
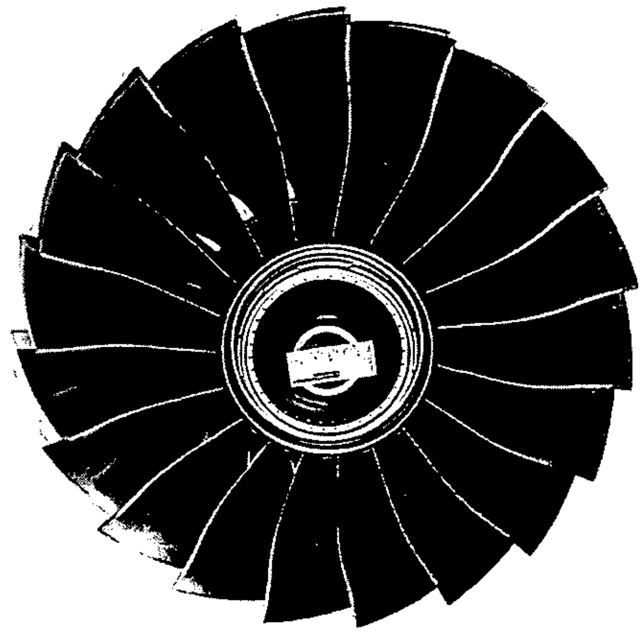


Figure 7: Computer simulation of 2-pass flank milling of highly twisted fan blades.

A number of fan IBRs have been fabricated this way, the blade dimensions vary between 7" high x 5" wide to 9" high x 6" wide. Figure 8 shows the two photographs of such a fan IBR. The top photographs shows the leading edge view while the bottom one shows the trailing edge view.



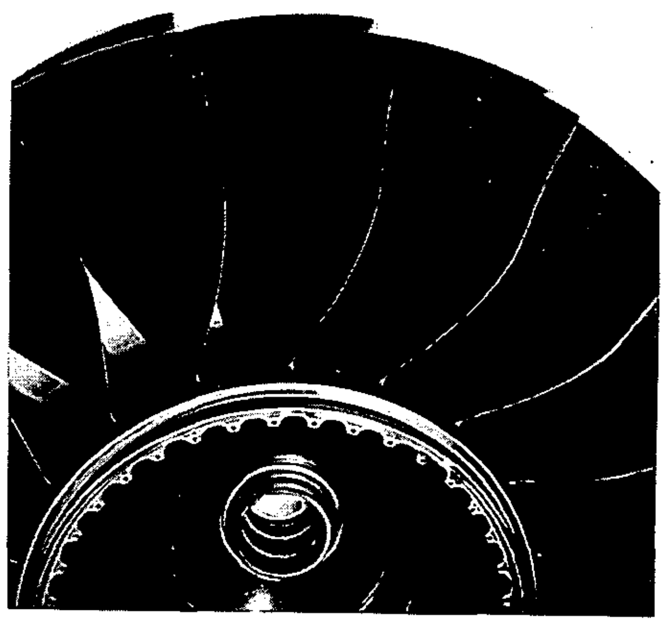


Figure 8: A 2-pass flank milled fan IBR as viewed from the leading edge (top), and from the trailing edge (bottom).

CONCLUSION

We have presented the concepts, the structure, and the applications of our Arbitrary Surface Flank Milling system.
There are two central themes to bear in mind throughout the development and implementation of this system. First, if any

surface is flank millable, our system will very rapidly give such an indication, this is Phase I. Second, subsequent refinement to give a high quality flank millable blade with optimal performance has to be rapidly convergent, this is Phase II. Speed is absolutely important here because we cannot afford to add significant lead time to an already complex and lengthy blade design process involving critical compromise between aerodynamics, structure, and dynamics.

From a different perspective, one wonders whether there is a way of completely incorporating flank millability in the blade design process from the very beginning so that when the design is finished, one automatically has a blade that is guaranteed flank millable. In theory this is a good approach and our ASFM system is in fact quite capable of doing so. As soon as there are 3 design curves, one obtains the tool paths, interpolates more design curves in-between to more fully cover the blade, then renders the tool paths only to produce different designs. This will guarantee every blade as designed would be flank millable. However, in practice , such an approach has not yet been tried.

This is because there is advantage to first design a blade without any flank milling constraint, obtain the best results possible, and then modify it to be flank millable. In this way we know exactly what is being compromised or gained. We have up to now worked on 25 different fans, axial compressors, and centrifugal impellers that are not flank millable in the conventional ruled surface approach. Analysis of the back-generated ASFM blades shows results that analytically are sometimes slightly better, sometimes slightly worse in performance and structural integrity. However, on the several parts which have actually been fabricated and tested, the performances were always slightly better than expected. This is especially so for the structural properties and life of the rotor. One cannot help wondering, maybe there is something intrinsic in the flank milling process in that it imposes a very uniform variation of geometric parameters such as curvature and blade thickness in a radial direction, thus reducing stress concentrations and may also be beneficial to the aerodynamics. These may be interesting topics for further studies.

As of now, the greatest benefit we reap from ASFM is cost reduction. This is especially true for our large IBRs and impellers.

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Finally, I would like to thank P&WC for permission to publish this work.

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