Int J Adv Manuf Technol (2010) 49:675–687
DOI 10.1007/s00170-009-2409-9

ORIGINAL ARTICLE

Improvement of reverse-engineered turbine blades using construction geometry

Kamran Mohaghegh · Mohammad H. Sadeghi · Amir Abdullah · Reza Boutorabi

Received: 24 February 2006 / Accepted: 27 October 2009 / Published online: 15 November 2009

Abstract The paper reports the latest outcomes of using design-based reverse engineering on turbine blades. For a long time, the focus of the reverse engineering methods has been the trend toward higher accuracies and faster measurements. Authors introduce a different viewpoint which focuses on design intent of a part. How to reverse engineer a complex shape like a turbine blade is the subject of current research. The attempt toward taking advantage of the construction geometry behind a sample heavy duty turbine blade is thoroughly discussed in three phases. First phase consists of 2D analysis of the reference sections. Then, the stacking axis is introduced as an important non-tangible feature which has the main role to connect the sections in 3D in lean and tilt directions. The third phase uses the concept of blade twist to provide a constraint to define rotational position of the sections with respect to neighbor sections. All the three phases have been applied to different types of original and non-original products which are available in the gas turbine market. The presented comparisons show clearly that the new method of reverse engineering incorporating construction geometry and design intent of the part is quite useful and recognizes many features behind the external geometry which is impossible to follow by the previous conventional methods. The turbine blade 3D model resulted from this new method will have a smooth arc-based surface, straight stacking line passing through turbine axis with maximum section tilt of 0.2 mm and maximum section lean of 0.3 mm to original equipment manufacturer parts and linearly increasing stagger angle from hub to tip which are some of considerable improvements compared to conventional method.

Keywords Reverse engineering · Beautification · Turbine blades geometry · Solid modeling

K. Mohaghegh (✉)
FICASABZ,
Unit 1, No.25, Khalili-shahanaghi Alley, Sheikh-bahayee St,
Teheran 1993685945, Iran
e-mail: kmohaghegh@yahoo.com

M. H. Sadeghi
Department of Mechanical Engineering,
Tarbiat-Modares University,
Teheran, Iran

A. Abdullah
Faculty of Mechanical Engineering, Amir-Kabir University,
Teheran, Iran

R. Boutorabi
Product Engineering, MAPNA Turbine Blade Engineering
and Manufacturing Co. (PARTO),
Karaj, Iran

1 Introduction

Unlike conventional engineering, which begins with the description of what the part will do and produces a geometric model suitable for manufacturing it, reverse engineering begins with the manufactured part and produces a geometric model of it. A broader interpretation of the term “reverse engineering” might perhaps involve deducing the intent of the original designer to some degree [1].

If we say that engineering converts a concept into an artifact, then reverse engineering converts an artifact into a concept [2].

In this paper, we focus on the blade geometry which is a 3D freeform shape and plays the main role in the performance of the whole turbine. A small change in blade geometry can lead to a large change in turbine performance. The following two points gives us the problem statement:

- Always a typical reverse engineering process starts with measurement activities on a sample part. But in this case (turbine blade), selection of a valid part to start with is very difficult. There is almost no certain way to recognize manufacturing errors imposed in the part during its various production processes. Turbine blades are usually made by investment casting. Analyzing the process shows that to avoid deflections of blade in the final state, it is cast in a larger size and then dimensions are fine tuned by hand blending. So, manufacturing errors of each part differ to other ones.
- Turbine blades are so expensive that nobody throws them away after standard service life but will try all the possible refurbishment activities. Blade refurbishment is of utmost importance, and this is well growing every day. These all show that in fact, it is very difficult to guarantee whether the reverse engineering sample (the turbine blade), which is going to be used as the first step of making a nominal model for production, is actually new. It is clear that a refurbished part is a part with some "frozen-in" errors.

To overcome the mentioned shortfalls, authors of this paper decided to present a new approach in reverse engineering of such a complex and freeform part. Instead of sticking to the reverse engineering sample as the only source of information, we decided to think about what this part should really look like. This way of thinking brought us to the idea to incorporate design aspects of the turbine blades into the reverse engineering process. In this paper, a combined reverse engineering process has been presented, which at the same time gets information from two different sources, i.e., measuring the part (conventional way) and reviewing design aspects. Doing this way, instead of copying every detail of the part, we will try to capture the designer's intent to some extent. Then, our aim would be to filter manufacturing errors and exclude them from the geometry in order to tend toward the nominal geometry. It is important to note that we are performing reverse engineering and not design. The only way to end with the 100% exact nominal values of a part is to use directly the original drawing of the particular blade! In this paper, it is shown that using some general rules during reverse engineering facilitates the process toward better results, which is much more valid.

2 Terminology

In order to help the readers who are not familiar with turbine blade terminology, the following terms are explained:

Suction side (SS): The curve on the convex side of a blade where the gas flow pressure is decreased (Fig. 1).
Pressure side (PS): The curve on the concave side of a blade where the gas flow pressure is increased (Fig. 1).
Leading edge (LE): The edge where the gas flow hits the blade first (Fig. 1).
Trailing edge (TE): The edge where the gas flow leaves the blade (Fig. 1).
Stagger angle: Angle between cord line of airfoil section and the turbine axis in a radial view. The deviation of actual stagger angle against its nominal value is called "twist" (Fig. 1).
Lean angle: Angle between stacking axis and meridional plane in an axial view (Fig. 2).
Tilt angle: Angle between stacking axis and radial datum in a meridional plane view (Fig. 2).
Thickness distribution: Procedure of thickening the camber curve to make a solid airfoil section.
Stacking axis: Linear axis which passes through all airfoil section centeroids and intersects the turbine axis (Fig. 3).
Camber curve: Spine curve passing through the middle of each airfoil section. Each point on the camber curve has equal distance to suction and pressure side curves.

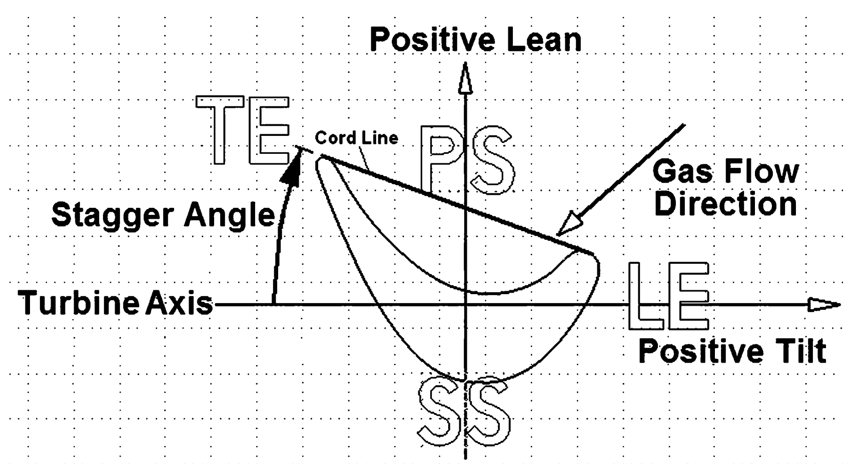


Fig. 1 Airfoil terms and direction of gas flow

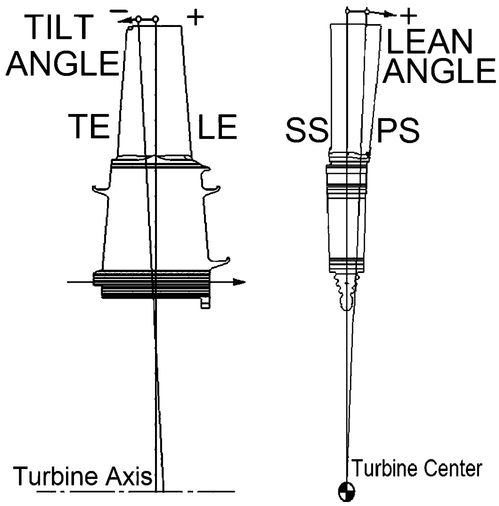


Fig. 2 Definition of tilt and lean of a turbine blade

3 Related work

Turbine blade has an outstanding status in industry. Its tremendous price has brought it to the top line of business competence, and its high shape complexities has made it quite attractive for researchers in the field of reverse engineering and geometric modeling. It is customary to approve the ability of new freeform manipulation techniques using a turbine blade as an example [3, 4]. One of the published works on reverse engineering of turbine blades is the research of Chen and Lin [5]. It is mainly about new techniques of digitizing and modeling of freeform surfaces and uses a turbine blade as a case study to prove its viability. The paper presents a method to perform digitizing and modeling activities, but there is no reference to design aspects or shape constraints and regularities of turbine blades. Tai and Huang [6] mentioned the importance of design intent during reverse engineering. They proposed that the best way to get a high-quality curve fitting of a B-spline on measured data is to use data points, which have been segmented manually by the engineer according to the design intent. Their work is mainly concentrated on how to manipulate the measured points to prepare them for a successful B-spline fitting and deals with algorithms for noise reduction and regenerating missing points in order to get a smoother B-spline. It contains some general useful hints but does not show actually how to deal with design aspects of a part.

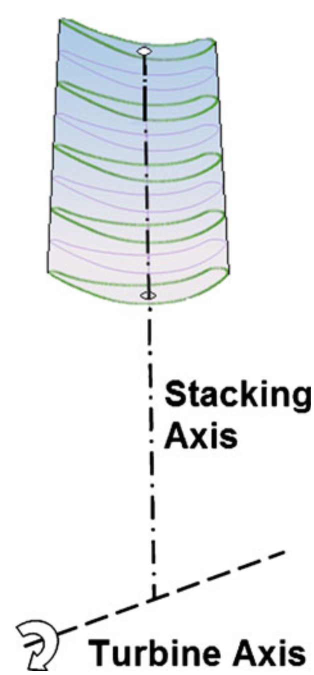
Dealing deeply with the part geometry, the engineer gradually finds consisting design features which step by step lead him/her toward the intended design of the part. In this regard, taking advantage of construction geometries might be a useful tool. Thompson and Owen described a prototype of a reverse engineering system that uses geometric primitives [7]. The main advantage of feature-based approach is the capability of producing highly accurate models, even when the 3D point data have substantial errors. This is due to the fact that some geometric primitives are known to the system, so after identifying a known feature, there is no need to go for higher accuracies. The primitives known to these types of software are limited to quadric features such as flat surfaces, cylinders, etc. So these systems are by no means capable to recognize freeform surfaces like blades. Another related subject to feature recognition is analysis of the geometric regularities in reverse engineering. The long-term goal is building a system which will analyze a preliminary reverse-engineered model for the approximate presence of geometric constraints, features, and regularities and will enforce some set of them on the model to produce an improved model [8]. The work is about relationships between features but not feature detection itself. The features that have been considered are simple ones like planes, spheres, cylinders, cones, etc. and not freeform surfaces.

On the other hand, recognition of freeform surfaces in reverse engineering usually does not deal with constraints and regularities. There are plenty of works about reconstruction and beautification of freeform surfaces using the most advanced techniques [9], but they just stick to one side of the problem which is measurement data and try to include noise filtration, curvature analysis, etc. on this basis.

Yongqing et al presented a rules-based reverse-engineering approach for the turbine blades, but they focused more on quadric surfaces of the root and shank and did not go deep through the reverse engineering of the blade based on design data [10].

The use of constraints in object modeling is an important topic in CAD and solid modeling literature. Werghi and

Fig. 3 Definition of the stacking axis of a blade



Fisher [11] proposed an approach for object reconstruction by incorporating geometric constraints. He minimizes an objective function that defines a relationship between the measured data points and the shape parameters. It is a minimization of least squares residuals subjected to geometric constraint equations. His approach is again limited to quadrics, and he notes some problems like complex representation of the objective function and need for accurate initial estimations.

To overcome some of these limitations, Benko and Varady [12] proposed another approach, which uses faithful representations. This type of representation makes it possible to separate two groups of measurement data and shape parameters and converts the problem to a much easier form which can be solved within a shorter time.

According to Fisher [13], the objects that human constructs are not arbitrary; the shapes of most normal objects follow standard conventions arising from tradition, utility, or engineering design, so this is a knowledge-based approach. He argues that exploiting this extra knowledge allows improved reverse engineering. His approach is again minimizing a statement which consists of two terms: the first term is a least square fitting term that ensures that model surfaces lie close to the image data; the second term encodes the penalties for constraint violations.

Using the latest techniques of constrained fitting, authors of this paper presented a method to find the correct airfoil sections of turbine blades based on design intent [14].

The current work is a complete 3D beautification of turbine blade. During this work, a total of 14 blades in three types all made for the same engine have been thoroughly examined:

- Type A: five original equipment manufacturer (OEM) parts
- Type B: six non-OEM parts (old revision)
- Type C: three non-OEM parts (new revision from the same manufacturer of type B)

For each part, a complete sequence of measurement and data manipulation have been implemented and discussed. The first phase mainly deals with 2D section modifications. Then, we use the benefits of defining the stacking axis and using this geometric non-tangible feature in reverse engineering to modify the displacement errors. The third step inserts the rotational concept of "twist" inside the project and makes use of rotational constraints to fully define the blade in 3D.

4 Phase 1: thickness distribution of the airfoil 2D sections

In this project, digitizing of the parts were done using ATOS II™ laser scanner with the following specifications:

- Measuring points—1,300,000 points in 7 s
- Point spacing—0.08 mm
- Measuring noise—0.002–0.008 mm
- Measurement Accuracy—0.010 mm (double checked by scanning a precise gage)

Manipulation of heavy point clouds five OEM parts has been done with the aid of RAPIDFORM2004™ software.

4.1 Definition of thickness distribution

Thickness distribution is the process of adding sufficient thickness to camber curve to create an airfoil section. There are different methods to distribute the thickness of an airfoil section. In our case, the thickness was distributed by a number of circular arcs around the camber curve. It is worth to note that this is a specific method for this type of blade.

Using these arcs as primary construction geometries enables us to solve a system of equations to best fit appropriate number of arcs to the measured points while they are tangent to their adjacent arcs at the same time [14]. Due to the large number of degrees of freedom in splines, this would be a cumbersome procedure if splines were used instead of arcs. Furthermore, there is no need for downstream smoothing or beatification algorithms though it is an inevitable task when splines are fitted to measured data.

4.2 Selection of the best fit strategy

To make a logical basis for comparison purposes, the five point clouds should be best fit. Carelessly bypassing this step will result in a total wrong geometry at the end of the reverse engineering process. Figure 4 shows the location of mechanical contact surfaces between the blade and turbine disk.

Best fit strategy is to select mechanical contact surfaces in order to use the surfaces with least deviation to compare

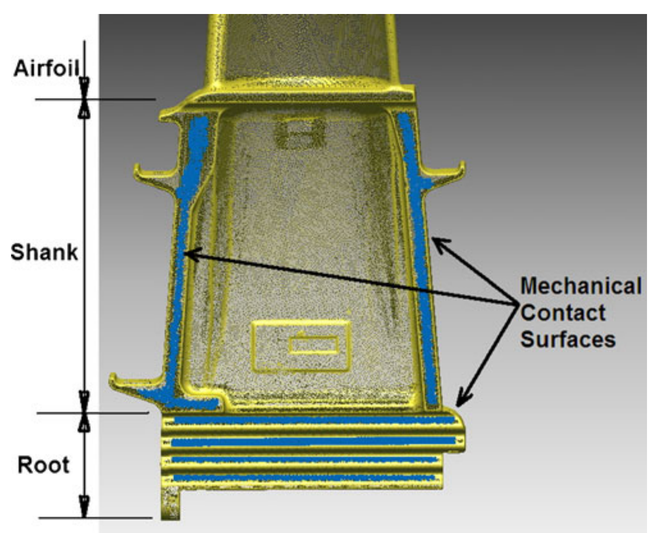


Fig. 4 Mechanical contact surfaces of the reverse engineering sample blade

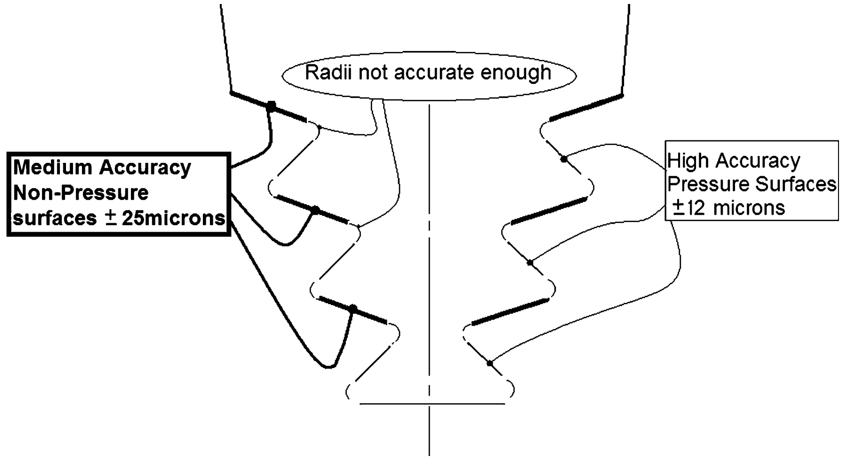


Fig. 5 Accuracy of different zones of the Firtree root

different parts. Figure 5 explains accuracy level of different zones of the blade Firtree root. The main role of this part of the blade is to withstand the centrifugal forces as well as to position the blade with the highest accuracy.

When the turbine rotor starts to rotate, the blade moves outwards in the radial direction, and the contact will occur with the pressure surfaces of the blade root as mentioned in the figure. This is the reason that the upper Firtree surfaces are called pressure or load-bearing surfaces. Designers use the maximum attainable machining accuracy on these surfaces. For the blade size of our consideration, setting a profile tolerance tighter than ±0.012 mm is not practical for the creep-feed grinding process, which is the right process to make this location of the part.

Partial best fitting of five OEM blades has been implemented taking into account root pressure and shank surfaces. Results show a measured total (min to max) deviation of 20 µm within all samples.

4.3 Preparing the airfoil sections

Designers use either three or five sections to define a blade within a technical drawing. The next step is to section all the blades while they are located in the best fit position (Fig. 6) and cut them with five sections.

The important note is to avoid selection of sections in the vicinity of blade tip and hub because usually, in these two locations, there might be some shape modifications. The closed curves in RAPIDFORM2004™ are third-degree splines which is outcome of intersection of the cutting planes with the triangulated surface.

Now, we have to interpret the five profiles (from five blades) in each section. From these results, it is worthwhile to select the part with best location among others (in the middle of deviation) to use further as the "middle part."

In phase 1, we are interested to find the thickness distribution of the airfoil, so we may transfer the data from RAPIDFORM2004™ to UNIGRAPHICS-NX3™ to best fit the cross section results of the five parts on the same section of the "middle blade" using a special routine written in GRIP language. This best fit program uses rotation of the section points as well as displacement until the minimum allowable deviation is met.

The next GRIP routine in UNIGRAPHICS automatically recognizes the minimum and maximum thickness of all five samples and creates a mean curve just in the middle of the profile band. This theoretical closed airfoil curve is calculated for each section height according to the five OEM parts.

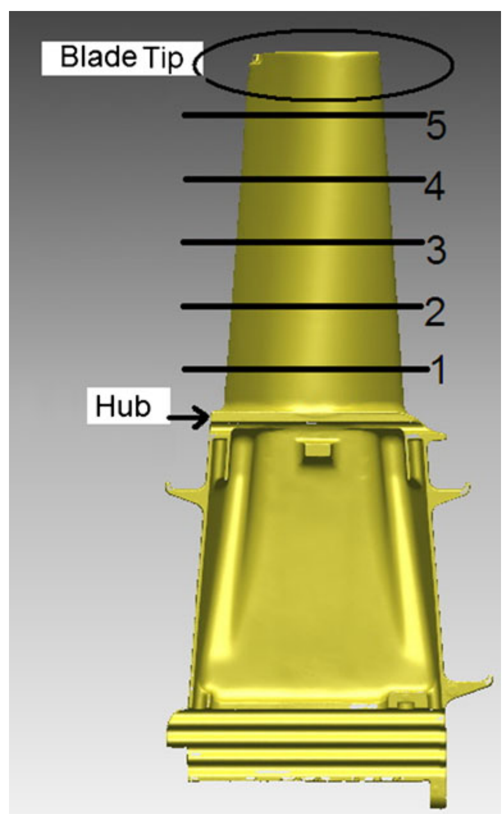


Fig. 6 Reference airfoil sections

After dividing the closed section spline to four separate curves for LE, TE, SS, and PS, a UNIGRAPHICS command tessellates points on each curve, so that the distance between point segments on leading and trailing edge are 1% of cord length (Fig. 1) and for the points on suction and pressure side 3%. This will make a 2D point cloud for each section height of the blade.

4.4 Segmentation and constrained fitting algorithm

Importing the section points (.txt file) to MAPLE9™ is the next step. A tailor-made software named segmentation and constrained fitting algorithm (SCFA) has been written in MAPLE to get the section points and provide segmented points of seven arcs all tangent to each other and forming a complete airfoil of the section in a way which the total deviation of the fitted arcs are minimized according to constrained fitting relations. The details of SCFA and application of this program on the same blade airfoil has been thoroughly studied in [14].

Result of SCFA is a file in .dat format which contains arcs radii and center coordinates and will be imported again to UNIGRAPHICS. There, a GRIP program trims all the circles and provides a complete airfoil section.

The deviation of the actual section points with respect to final seven-arc geometry is depicted in Fig. 7. This figure shows that the phase 1 model surface lies in the middle of a reasonable tolerance band of ±0.3 mm deviation from the measured point cloud.

5 Phase 2: stacking analysis

It shall be noted that a 2D thickness distribution analysis is a prerequisite of starting the 3D stacking process on a turbine blade.

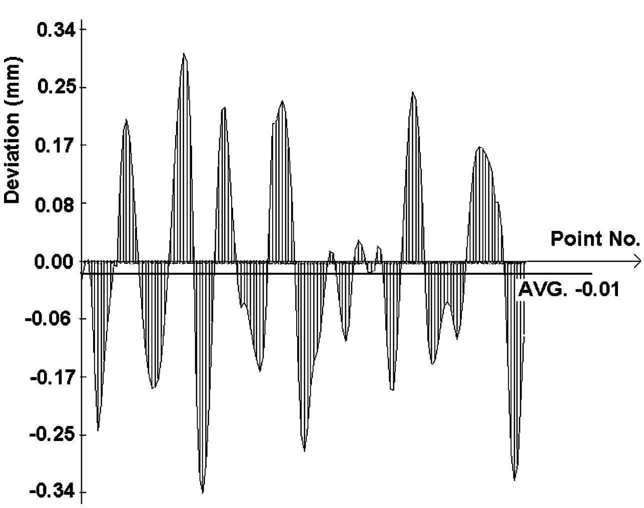


Fig. 7 Deviation of actual airfoil compared to seven-arc model out of SCFA

5.1 Definition of stacking axis

Stacking point of a blade usually coincides with centroid of the section. Stacking axis is a straight line passing through the stacking point of each section which intersects turbine axis [15]. After specifying 2D sections, designers use the stacking axis to stack the sections upon each other in the gas path to provide a complete 3D blade. Figure 3 shows a series of airfoil sections and their stacking axis.

Figure 2 shows the two important views of a turbine blade stressing the location of stacking axis. The left view shows the meridional plane, LE, and TE of the blade. In this view, we define positive tilt as inclination of the blade stacking axis toward the leading edge. The right view shows the plane perpendicular to turbine axis, SS, and PS of the blade. In this view, the inclination of the blade stacking axis toward PS is called positive lean.

5.2 Tilt analysis

For each sample blade after phase 1 (thickness distribution analysis), the section closed curve is available. The centroid of these closed curves can be easily obtained using UNIGRAPHICS commands. Tilt value of a section is the displacement of its centroid in LE–TE direction. Tilt results of the centroids for each section of each blade from different types of blades (A, B, and C) are demonstrated in Fig. 8.

The vertical axis in this graph is the height of section (increasing from blade hub toward the tip). Samples of the three groups—although having some deviations—all show their own manner. As the results come from real parts, it is obvious that the stacking axis of each sample is prone to errors and deviates from an ideal straight line. The type As which are the OEMs generally have less tilt, non-OEM type Bs more tilt, and type Cs even more. To get a better idea, an average value tilt for each type is calculated and presented in Fig. 9.

Figures 8 and 9 demonstrate:

The tilt values of OEM parts (type A) are less than half of the non-OEMs (types B and C) at tip section (−0.8 mm type A compared to −1.8 mm types B and C). This measurement shows that the manufacturer of non-OEM type B has not recognized the correct construction geometry behind the part. Type C has even made more mistake and is far from the designer's intent. Mentioning the fact that type C is the new revision provided by the same blade manufacturer after type B makes it clear that only sticking to the conventional reverse engineering may mislead the manufacturer and result in a poor quality product. This is inevitable because of the frozen-in manufacturing errors in OEM parts. The doubled error (1.8 mm tilt) occurred in non-OEM parts are due to

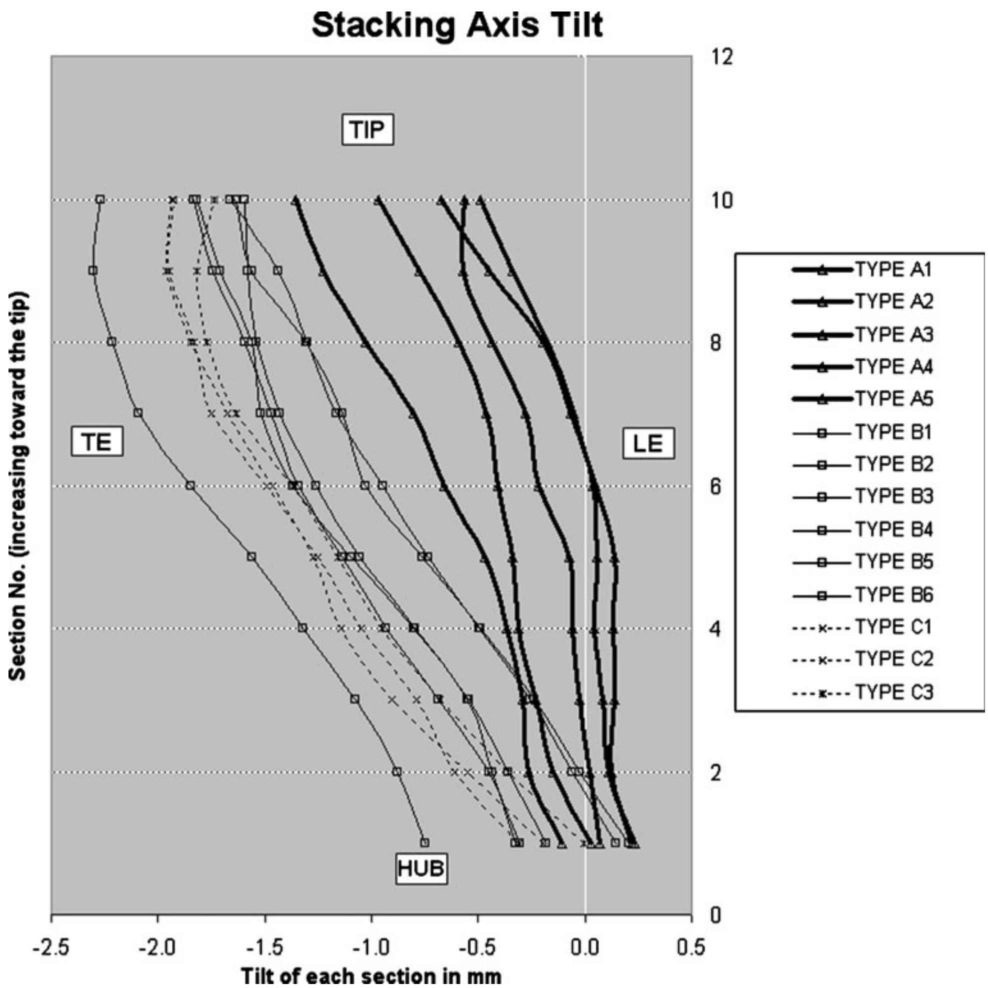


Fig. 8 Stacking axis tilt values for all samples

superposing the manufacturing errors on a wrong and deviated base line.

Figure 8 shows that type C (new revision products) have a tighter deviation band among samples compared to type B (old revision). Although the manufacturer has put more effort and has made new type C products with a tighter tolerance band, it has ignored the construction geometry behind the blade (stacking axis), and the end product quality is even worse and far from OEMs.

Stacking axis of all samples (Figs. 8 and 9) shows completely different and unpredictable curvature patterns. Severe difference in curvature patterns even in OEMs means that the shapes are not reliable for copying. In such a situation, the only reliable way is to stick to design data and not to measure the part [14]. So fitting a straight line to type A points and simultaneously intersecting the turbine axis [15] would be the best choice for the stacking axis. This straight line is shown in Fig. 9 and mentioned as "phase 2 model."

The last feature recognized in the graph is the fact that in all types of samples (A, B, and C), the stacking axis is not exactly radial (turbine radial direction) and has an inclination towards TE which is called positive tilt. This phenomenon is further discussed in Section 5.4.

Typical blade tolerances could be used as well during the reverse engineering for comparison purposes. It is worthwhile to mention that this project is an attempt toward recognition of nominal 3D model, so manufacturing tolerances are only used for comparison purposes and do not directly affect our decision making. Tilt tolerance of a blade with the size under our investigation could be selected as ±0.6 mm (tip section) around the nominal value [16]. This tolerance band is depicted in the Fig. 9 with dashed lines apart from the probable nominal stacking axis, such that each of them 0.6 mm far from the nominal at the tip section and zero at the hub (this tolerance is height dependent). Observing the status of the type A curve with respect to the tolerance band shows the amount of required modifications from the OEM sample toward the nominal value. It should be stated that the said tolerances are typical values for comparison only and do not exactly reflect the designer's data.

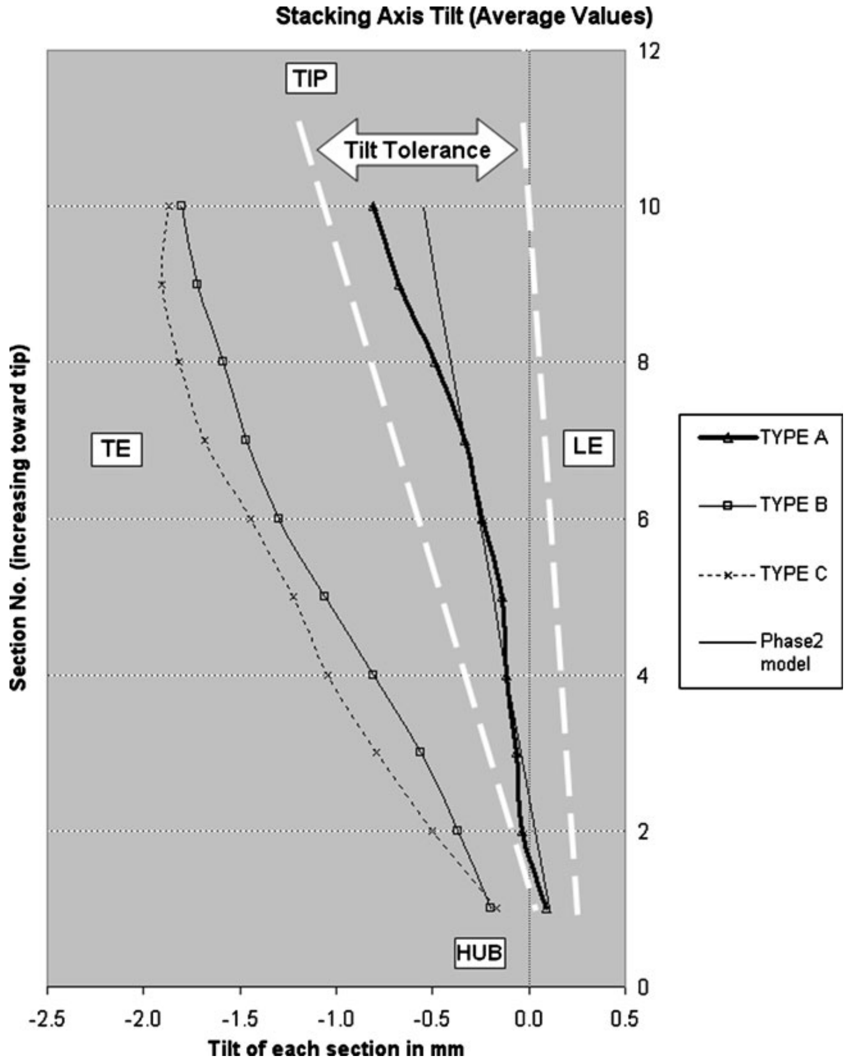


Fig. 9 Average values of stacking axis tilt

5.3 Lean analysis

Using the same routine used to prepare input data for tilt analysis, the centroids of each sample blade is projected in SS–PS direction as explained in Fig. 2 and is called lean value. Lean results of the centroids for each section of each blade from different types of blades (A, B, and C) are demonstrated in Fig. 10.

The vertical axis in this graph is the section height. Again, samples of the each three groups show their specific manner although showing some deviations. In this view as well, the real results do not lie on a straight line. The graph shows a surprising difference between OEM and non-OEM parts completely separated from each other. The OEM type As all have a negative lean, while non-OEM types B and C have positive lean. Also, it is obvious that in this case, type B results lie in between the two others. Average values for lean are calculated and presented in Fig. 11.

Figures 10 and 11 demonstrate:

The lean values of OEM parts (type A) are as big as the non-OEMs (types C and especially B) but in opposite directions. Deviations increase with section height. This measurement shows that in this direction as well, the manufacturer of non-OEM type B has chosen the wrong direction. The type C is a bit better but still far from being a reasonable part.

Waviness of the stacking axis patterns of all samples (Figs. 10 and 11) are quite different. Stacking line should be made by fitting a straight line to type A points intersecting the turbine axis (Fig. 11) [15].

The inclination of the stacking axis towards SS (negative lean) will be discussed as a phenomenon in the next section.

To make a comparison to the lean tolerances in part manufacture, two dashed lines (each 0.6 mm apart from the nominal "phase 2 model" line in tip section) are drawn in Fig. 11. The lean tolerance is height dependent and decreases from tip toward the hub. Observing the graph shows that the mentioned relationships are conforming and the OEM results are close to the theoretical straight line

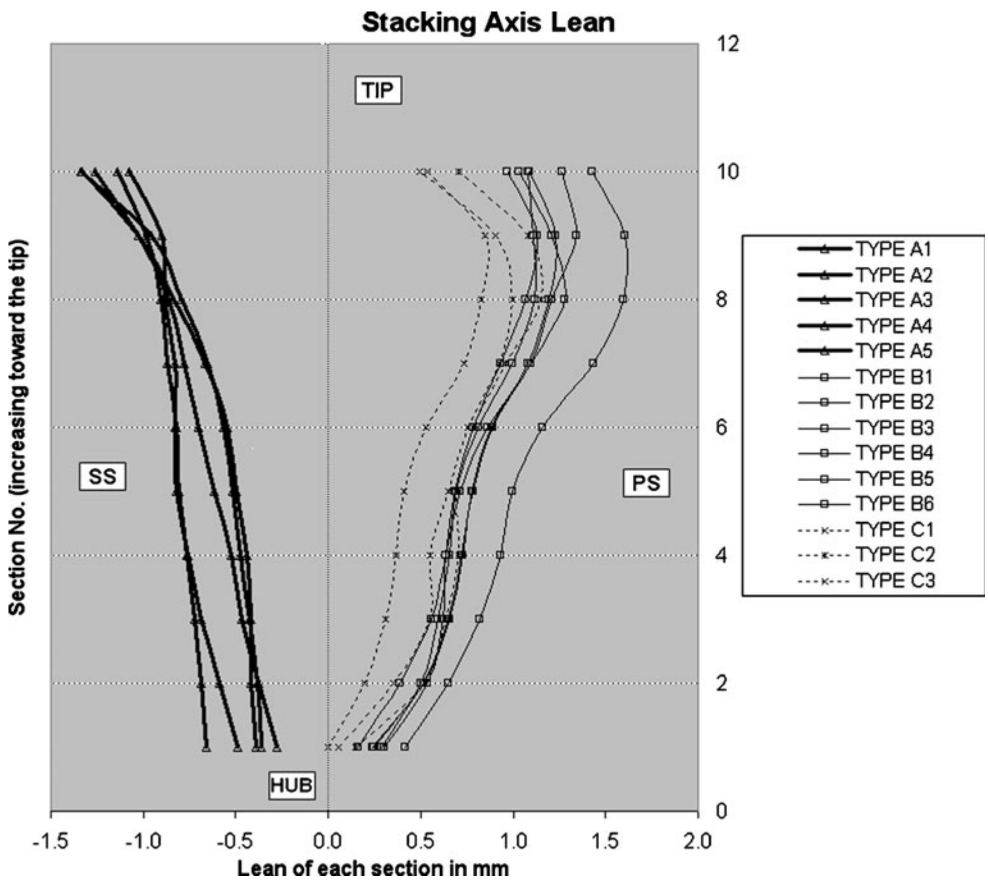


Fig. 10 Stacking axis lean values for all samples

which passes the turbine center line. This line has been calculated from a dedicated GRIP program. The program uses the centroids and turbine axis and finds a line passing the axis having the least square error from the points. After finding the stacking axis by this method airfoil sections are translated to superpose the centroid to the stacking line. This establishes the phase 2 model. It should be stated that the said tolerances are typical values and are used for comparison only and do not reflect the designer's data.

5.4 Gas force compensation

Direction of gas flow exiting from the previous nozzle guide vane and entering the pressure side of a turbine blade is from PS–LE side as shown in Fig. 1. This is as well the direction of gas force. To compensate this force, designers usually make an intentional inclination of stacking axis toward the opposite side which is toward SS–TE (Hearsey, private communication, rmh@hearsey.org). This way, the center of gravity of the blade inclines toward SS–TE; therefore, during the rotation of the rotor, the centrifugal force makes a resisting bending moment against the moment created by the gas force improving the blade life.

Our observations indicate that for the phase 2 model, position of the stacking axis in tilt and lean analysis presented in this paper are showing the same phenomena. On the other hand, the non-OEM parts did not follow this rule and ended up with an opposite lean direction. A positive lean inclines the center of gravity toward PS and makes a bending moment with the same direction of gas flow having a detrimental effect on blade life.

6 Phase 3: blade twist analysis

6.1 Definition of blade twist

In this part of the paper, we are actually performing the reverse engineering steps not blindly but based on design knowledge of the part. Having known that dealing with a freeform surface like a blade, there is a parameter, i.e., stagger angle, somewhere that is one of the most important categories of the part from designer's point of view, we are close enough to hit the target of the part geometry.

Blade twist is the rotation of airfoil section in its plane. To have an indicating baseline to determine the rotational position of an airfoil section, designers use the stagger angle (Fig. 1) which is the angle between a line tangent to LE and TE (cord line) and the turbine axis. In this work, we rather talk about stagger as an indicator of blade twist.

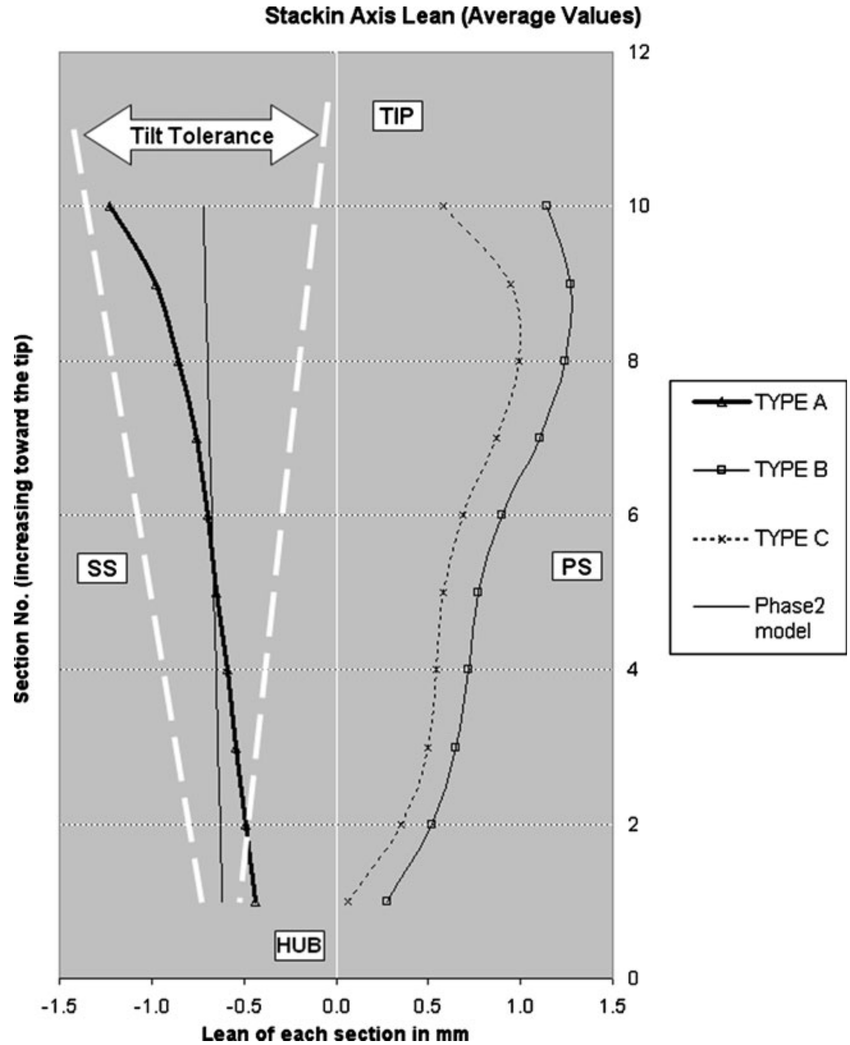


Fig. 11 Average values of stacking axis lean

Twist deviation of a blade is defined as the angle between actual stagger (measured from each section of a blade) and nominal stagger of the same section.

6.2 Stagger analysis

Up to now, the best data for the blade under our investigation comes from model after phase 2 manipulations. In fact, the data coming from this 3D model has the following positive characteristics:

- It originates from TYPE A data (OEMs) which is the best selection of the sample parts to start with.
- It has the best thickness distribution due to application of phase 1 manipulations (SCFA) [14].
- It contains a straight stacking axis due to phase 2 manipulations.

Due to abovementioned characteristics, the phase 3 manipulations should fine tune the model coming out from phase 2.

The first investigation in this regard is to measure the stagger angle of all types of samples namely A, B, and C. This has been done using a dedicated program written in GRIP™ language in UNIGRAPHICS™. The program inputs are the solid body of each blade sample and the turbine axis. Then, the program uses its default information to find the right section and the cord line and measures the stagger angle value for each section. The outputs are stagger angles and section number in a text format.

The results show a delightful linear variation of stagger with respect to section height. The samples from different types lie quite close to each other (Fig. 12).

The error value of the curves in Fig. 12 from an exact line is less than 1° in a scale of 6° to 37° change of stagger. Knowing that a typical twist tolerance for such a blade is around ±0.55° in the maximum height [16], one can easily relate the total deviations less than 1.1° to manufacturing errors. As mentioned above, we continue the reconstruction of the model with the one with least errors which is the data

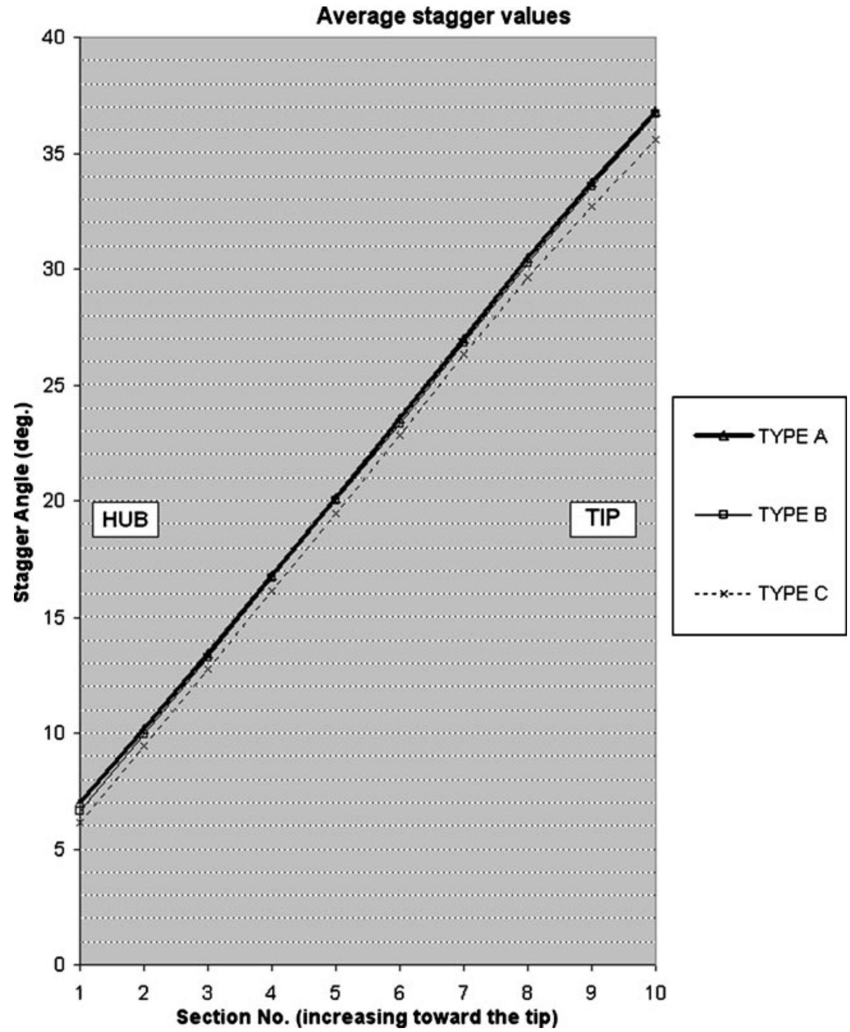


Fig. 12 Average values of stagger

regarding the end of phase 2 model. In this case, we have modified the stagger curve of the phase 2 model to a straight line which is the result of a linear regression of stagger angles in phase 2 model (horizontal axis in Fig. 13). To have a basis for display, all other data are plotted against this line. Figure 13 depicts the fine deviation of each type average value from this straight line. This line is nominated as the new guideline for our phase 3 model and phase 2 stagger angles are modified accordingly by rotating the sections to establish the phase 3 model.

Figure 13 demonstrates:

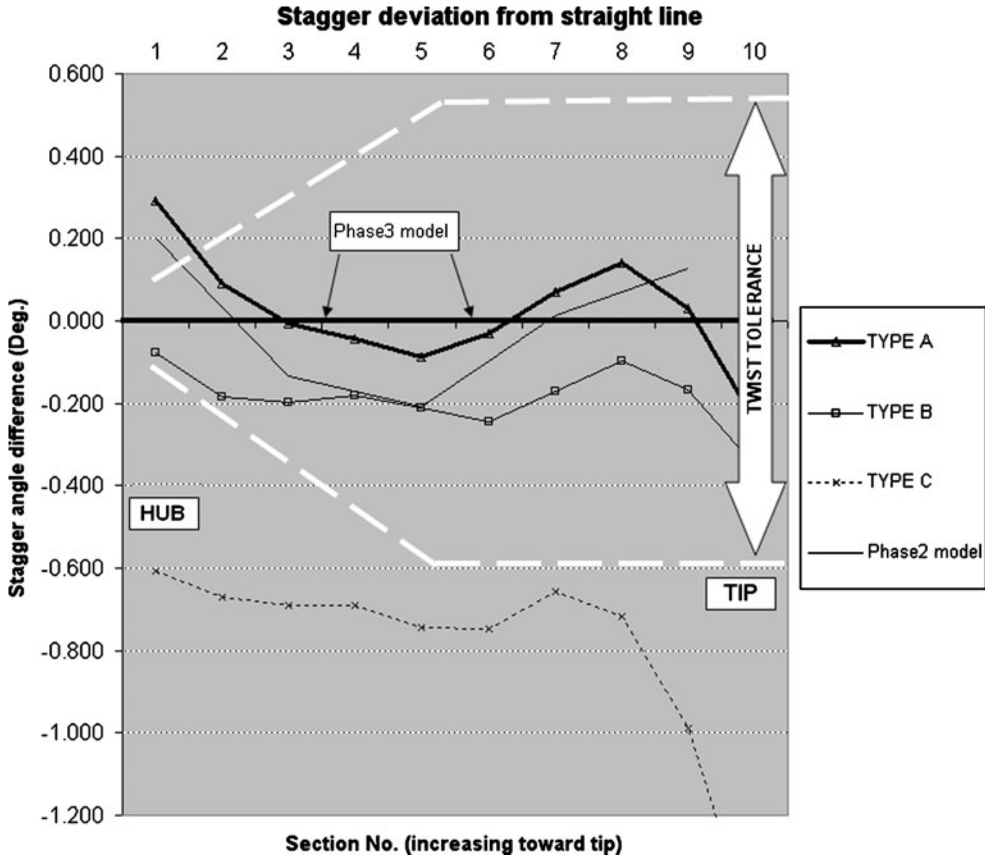
- Type A and phase 2 model are quite close to each other and inside the typical tolerance, but they are not exactly the same. This is due to minor modifications done during the phases 1 and 2 on the basic 3D model originating from Type A. This means that the basic stagger pattern of Type A changes to curve nominated as "phase 2 model" after complete thickness distribution filtration and stacking axis filtration. The fact that both curves are still within the tolerances and that they are located quite close to each other is one of the important characteristics of this method.
- The straight line pattern for stagger deviation scheme is only 0.2° apart from OEM data while the stagger itself changes from 6° to 37°.
- Type B blades look accurate enough inside the typical tolerance band.
- Type C blades which are the new revision of type Bs are just misaimed from the right way and far from being acceptable. This has been clarified only after such a detailed investigation on non-tangible geometric features.

7 Conclusion

In order to perform reverse engineering of turbine blades, some classified airfoil manipulations have been presented in three phases with the following conclusions:

Improvement in the reverse-engineered blades using construction geometry has been clearly discussed. Instead of

Fig. 13 Stagger deviation from straight line



measuring the external surfaces of the part, authors have aimed to find the location of stacking axis of the blade (a non-tangible feature belonging to construction geometry) as the most important feature and governing axis of the 3D body.

The results coming from measurement of real parts depicts that stacking axis encounters many errors and deviates from a straight line. Analyzing the different types of samples show that the non-OEM manufacturer has put a considerable effort to enhance the quality of type B and, therefore, has achieved a tight deviation among the samples of type C, but because of ignoring the construction geometry behind the blade (stacking axis concept), the end product quality is even worse than before.

The lean graph shows a wide difference between OEM and non-OEM parts. The OEM type As all have a negative lean, while non-OEMs are all positive in lean which has a detrimental effect on blade life.

Surprisingly, the results of investigations show a perfect linear variation of stagger with respect to section height. It should be mentioned that this outcome is not accidental. This is the benefit of performing the reverse engineering steps not blindly but based on design knowledge of the part. Having known that dealing with a freeform surface like a blade, there is a parameter (i.e., stagger angle) somewhere that is one of the most important categories of the part from designer's point of view, we are close enough to hit the target of the geometry.

The characteristics of the presented blade model are:

✓ It is made by input data of the profiles of type A (OEM) samples.

✓ The thickness distribution is completely applied (using SCFA). This results in an arc based smooth 2D profile which is compatible to OEM design of turbine blades of this type.

✓ The stacking axis filtration is completely applied. It results a blade with a straight stacking line passing through the turbine axis. Maximum section tilt of this blade against OEM average is about 0.2 mm compared to 1 mm deviation of other Non-OEM parts. It also results a maximum section lean of about 0.3 mm to OEM average compared to nearly 2 mm deviation of Non-OEM parts.

✓ Stagger angle modifications completely applied. It makes linearly increasing stagger angle from hub to tip with a maximum deviation of 0.2° to OEM parts compared to up to 1° deviation of Non-OEM ones.

✓ The modifications applied are all within the manufacturing tolerances and there is no large change in the presented model.

References

1. Varady T, Martin RR, Cox J (1997) Editorial special issue: reverse engineering of geometric models. Comput Aided Des 29(4):253–254
2. Langbein FC (2003) Beautification of reverse engineered geometric models. PhD Thesis. Dept. of Computer Science, Cardiff University
3. Wolovich W, Albakri H, Yalcin H (2002) The precise measurement of freeform surfaces. Trans of ASME: J Manuf Sci Eng 124:326–332
4. Huang J, Menq CH (2001) Automatic data segmentation for geometric feature extraction from unorganized 3-D coordinate points. IEEE Trans on Robotics and Automation, V17, No. 3:268–279
5. Chen LC, Lin GCI (2000) Reverse engineering in the design of turbine blades – a case study in applying the MAMDP. Robot Cim-Int Manuf 16:161–167
6. Tai CC, Huang MC (2000) The processing of data points basing on design intent in reverse engineering. Int J Mach Tool Manuf 40:1913–1927
7. Thompson WB, Owen JC (1999) Feature-based reverse engineering of mechanical parts. IEEE T Robotic Autom 15(1):120–125
8. Mills BI, Langbein FC, Marshall AD, Martin RR (2001) Estimate of frequencies of geometric regularities for use in reverse engineering of simple mechanical components. Internal Technical Report GVG 2001–1, Computational Geometry and Computer Vision Group, Dept. of Computer Science, Cardiff University, http://ralph.cs.cf.ac.uk/papers/Geometry/survey.pdf
9. Huang J, Menq CH (2002) Combinatorial manifold mesh reconstruction and optimization from unorganized points with arbitrary topology. Comput Aided Des 34:149–165
10. Li Y, Huang X, Gong C, Wang K (2004) An engineering rules based parameterization approach for turbine blade reverse engineering. Geom Model Process 2004:311
11. Werghi N, Fisher R (1999) Object reconstruction by incorporating geometric constraints in reverse engineering. Comput Aided Des 31:363–399
12. Benko P, Varady T (2002) Constrained fitting in reverse engineering. Comput Aided Geom Des 19:173–205
13. Fisher RB (2004) Applying knowledge to reverse engineering problems. Comput Aided Des 36:501–510
14. Mohaghegh K, Sadeghi MH, Abdullah A (2007) Reverse engineering of turbine blades based on design intent. Int J Adv Manuf Tech 32:1009–1020
15. Society of Automotive Engineers (1996) Airfoil shapes: dimensioning of turbine engine, aeronautical recommended practice ARP 265A. Society of Automotive Engineers, New York
16. FEP International Private Ltd (1980) Investment casting handbook. FEP, Punjab, pp 205–210