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Automated selection and assembly of sets of blades for jet engine compressors and turbines

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Abstract

Aircraft engines need to pass regular maintenance intervals, which go along with a complete disassembly, part inspection (with necessary repair or replacement) and finally reassembly. Especially the manual composition and assembly of blades are time-consuming processes. Increasing air traffic and growing pressure on costs in aviation MRO, demand more efficient approaches. This paper introduces an automated approach for increasing efficiency in selection and assembly of sets of blades for jet engines. Chapter 1 gives a short overview on different designs for compressor and turbine stages. Additionally, the process of adjusting and mounting a set of blades into a circumferential groove is described. Furthermore, a potential for an automated assembly process is determined. Chapter 2 gives an overview of the overall concept, including robotic blade handling, measuring of blades, balancing a set of blades and gap measurement. Chapter 3 focusses on the two measuring tasks. For measuring the width of the blades, optical and tactile approaches are compared. Image processing and laser triangulation are compared to current use of feeler gauges for the gap measurement. In chapter 4 a force-guided assembly strategy, using a force-torque-sensor is presented. Chapter 5 concludes with a brief overview of the planned future work.

Keywords: MRO; jet engine; blade assembly

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1. Introduction

To ensure safety in operation and to maintain economic efficiency, jet engines need to pass regular maintenance and overhaul intervals throughout their life cycle. In case of an off-wing maintenance event the engine is disassembled and parts are inspected. For damaged parts a repair is performed, if possible, or it is replaced by a new part.

Regarding aircraft operation costs and especially for jet engines, MRO is of particular significance. Total costs for maintenance, repair and overhaul cause approx. one third of engines operation costs [1, p. 25]. Manual, time-consuming processes thereby dominate aircraft MRO. Therefore automation shows potential for increasing efficiency and repeatability.

Dominating cost drivers are damaged compressor and turbine blades and vanes, which is why research concentrates on efficient inspection and repair methods for those parts, like damage detection and regeneration of high pressure turbine blades [2,3]. Potential for automated assembly solutions is thereby mostly neglected. Wolff et al. present an automated approach for disassembly of turbine blades with solidified connections to the disk [4].

This paper introduces an automated approach for compressor and turbine assembly, as well as presenting involved processes for adjusting a set of blades in the field of jet engine MRO. For that different rotor designs are analyzed and an assembly process for radial mounted blades is developed. Similar approaches in the described field are, to the best of the author's knowledge, not addressed in literature.

1.1. Rotor Designs

In modern jet engines, essentially three different designs for compressor and turbine rotors are known. These are disks or drums with circumferential groove, disks or drums for axial blade mounting and blisks (blade integrated disks). In the following, the different designs are analyzed concerning their potential for automated assembly.

In rotors with circumferential groove blades with hammer-type feet are used, which are mounted through a small opening and then arranged along the groove. While the blades are fixed in radial position by contact between groove and feet, the position on the circumference is determined by the width of all mounted blades. Due to manufacturing deviations and wear during operation, each set of blades needs to be adjusted to meet the requirements concerning gap width. Additionally the blades must be brought into an order, which minimizes the resulting imbalance due to various weights of used blades. Remaining imbalances will be compensated by additional balancing weights in follow-up processes.

Disks for axial blade mounting are equipped with slots in which the dovetail or fir tree roots of related blades are inserted axially. Since the circumferential position of the blades is determined by the slot, no further adjustments concerning gaps between blades are necessary, nor possible. Balancing of the rotor is performed the same way as described before.

Blisks are increasingly used in modern jet engines, such as the PW1000. They are manufactured by machining from one piece, or connecting disk and blades through friction welding. This design allows weight savings and avoids disassembly and assembly for overhaul, but increases complexity for blade exchange and repair [5, p. 149].

According to this overview of rotors it is obvious, that the design with circumferential grooves takes by far the most effort for adjusting and mounting a set of blades for one stage. Therefore and due to the fact, that this design is the one mostly used for low and high pressure compressors of the widespread engines CFM 56 and V2500, the approach for automated assembly will concentrate on this design.

1.2. Assembly Process

In the following the current assembly process for a high pressure compressor of a CFM 56 engine during maintenance operations is described. Potential for reducing the effort of the presented process is derived subsequently.

Compressor stage 1 - 3 are not taken into account, due to their design as disks for axial blade mounting. Each stage has a small opening of the groove, through which the feet of blades are inserted radially and - when reaching contact with the drum - moved along tangentially along the groove. As small tilting of the blades during tangential movement leads to sticking, tactile sensitivity is necessary for manual assembly.

For each compressor stage approx. 70 blades are to be mounted. Due to deviations of blades as mentioned before, the same number of blades does not always result in the same gap width, which is measured by a feeler gauge inserted between two blades. To meet the requirements concerning gap width, wide and narrow blades are used, which differ in width by approx. 0.25 mm. By mounting a certain number of wide and narrow blades the specified tolerance limits of approx. 0.35 mm can be met, whereby the absolute gap width increases for later stages due to higher operating temperature. Adjusting the ratio of wide and narrow is performed as an iterative change of blades.

Pre-balancing of the compressor is reached by arranging the blades in an order in which deviations in weight of single blades are compensated. Therefore the weight of each blades must be determined in a previous step.

The overall process can be organized into two different forms. One approach is to select blades, adjust the sets of blades on the drum to be assembled, determine a balanced order of blades and afterwards perform the final assembly on the drum. The alternative approach is to separate the process of selecting sets of blades and the assembly process. In this case adjusting of gap width and balancing can be prepared on a drum taken out of service. Reduced time for compressor assembly has to be weighed up against increased total duration.

In both cases several steps for adjusting gap width and balancing are necessary. Furthermore each blade has to be mounted and dismounted several times, resulting in a high amount of handling operations which are not part of the final blade assembly. This offers potential for reducing the amount of operations by following an automated assembly approach according to chapter 2.

2. Overall Concept

The proposed concept for assembly of rotors with circumferential groove for blade mounting, significantly reduces the amount of handling operations, by minimizing the effort for adjusting a set of blades. Fitting sets of blades are chosen and mounted in an optimized order to achieve a matching configuration at the first attempt, based on previous measurements. Therefore each blade returning from overhaul or each spare part has to be measured. For adjusting the circumferential gap between blades, the width of their platforms needs to be determined. This enables the selection of the right ratio between wide and narrow blades for each individual case. The right order of blades is determined by rotor balancing. Since balancing for compressor blades is performed considering only their mass, blades need to be weighed, too. An algorithm calculates an optimized order, by evaluating changes in imbalance through swapping blade positions. Blade assembly on the drum is performed using a standard industrial robot, using a gripper system for blade handling. To meet the tactile sensitivity requirements a force-guided assembly strategy is applied. After completing the assembly of a stage, compliance of resulting gap width with the specified values is investigated. In case specified tolerance values are exceeded, fitting blades are selected and blade exchange is performed. Measurement of compliance of resulting gap width will be repeated. The flowchart for the introduced concept can be taken from figure 1. Besides reducing effort for adjusting sets of blades, automated documentation of rotor assembly leads to further increases in efficiency.

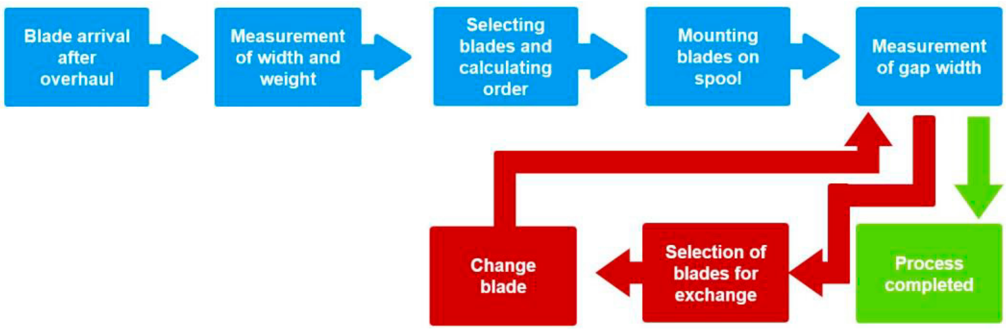

Fig. 1. Flowchart of proposed overall process

The main components of the described concept are presented in chapters 3 and 4. Two approaches for the measurement of the platform width are presented in chapter 3.1; in chapter 3.2 two approaches for gap width are given. A force-guided assembly strategy, meeting the requirements concerning tactile sensitivity, is presented in chapter 4.

3. Measurement tasks

Key components of the proposed concept are the two measuring tasks, since the selection of sets of blades is based on the blade width and their compliance with specified tolerance values is investigated by gap measurement. For both measuring tasks, two approaches have been developed and are validated in the following sections.

3.1. Description and analysis of blade width measurement approaches

In the following two measurement approaches for determining platform width of the blades are presented. One setup holds the blade in mounting conditions whereas the second measurement is performed contact-free. Required measurement accuracy is defined by dividing specified tolerance values by number of blades as stated above. Thus an accuracy of 5µm is demanded (see section 1.2).

The first approach is a tactile measurement, emulating the contact conditions between drum and blade and between neighbouring blades. For reproducing the mounting situation within the groove, blades are clamped at the edges of their hammer-type feet to establish a repeatable position and orientation. Contact between side surfaces of blades are simulated by two metal plates with high-precision surfaces, pressed against the blades contact surfaces. Both clamping processes are performed by pneumatic actuators. For compensating the offset during blade insertion and clamping, the second actuator is mounted on a linear guiding. Measurement is carried out by an inductive displacement transducer. Using this setup, multiple measurements of different blades were performed for validation. The resulting standard deviation obtained in these measurements was quantified with 3.12µm. In figure 2 the setup for measurement and an exemplary temporal variation of measured value after clamping is plotted.

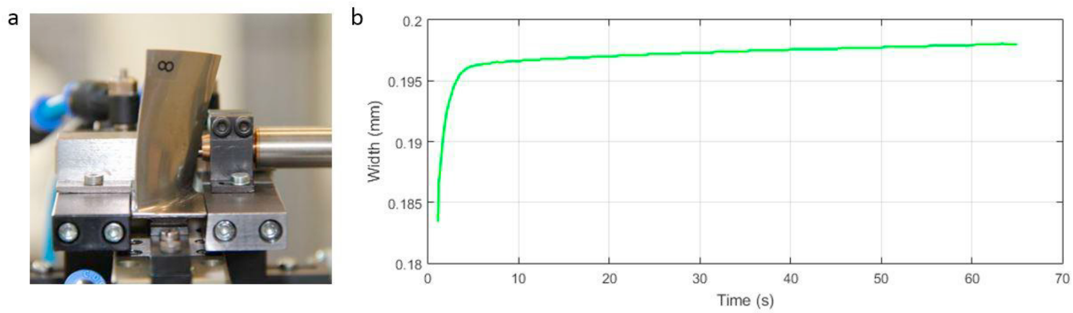

Fig. 2. (a) measurement setup; (b) time dependency of measured blade width

After a quick increase, the measured value takes approx. 60 seconds for converging towards a constant value. Time for converging thereby depends on the size of the blade offset during clamping, which needs to be compensated by the linear guiding.

The second approach is an optical measurement using an optical micrometer, a device measuring the width of an object by measuring the shaded area of a laser line. In contrast to the first approach, the two edges of the blade platforms are used as a reference, not the whole contact surface. Blades are gripped at their feet, the same way as in the first approach. For measurement, they are inserted into the laser line by the industrial robot. Figure 3 shows a plot of measured blade width along the height of the blade platform.

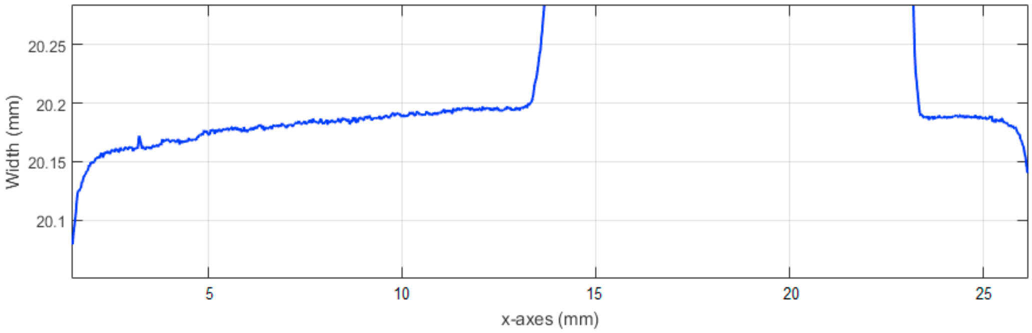

Fig. 3. Blade width along the height of the blade

The blade is not showing a constant width. The maximum width can be found in the middle, near the area where the end of the leaf intrudes the measurement of the platform (x = 13 – 23 mm). This suggests a contact between two blades in this point, so it was determined as measuring position for a static measurement. For multiple measurements of blades (including gripping process), the repeatability was quantified with a standard deviation of 2.16µm. Required time for measurement is approx. 5 seconds.

Due to better accuracy and faster measurement, the optical approach was chosen for blade selection. For adjusting various sets, 170 blades were measured. A set of blades meeting the specified tolerance values, measured by feeler gauge, was adjusted. Since a direct relation between the sum of widths of blades mounted and the resulting gap is assumed, the sum of widths is used as a reference for following sets. Multiple sets of blades have been adjusted by choosing blades, resulting in a sum of blade widths, close to the reference. Those sets were mounted and the resulting gap width was measured. To take the maximum of possible deviations into account in set four and five the largest feasible difference in ratio of wide and narrow blades was chosen.

Table 1. Sets of blades, based on optical measurement

Nr. of set	Σb (mm)	wide blades	narrow blades	Gap (mm)
1	1376.2550	25	43	0,40
2	1376.2734	26	42	0.40
3	1376.3186	25	43	0.35
4	1376.2426	22	46	0.50
5	1376.2858	29	39	0.30

In all cases the resulting gap width met the specified tolerance values (0.25 mm – 0.60 mm), as given in table 1.

3.2. Description and analysis of gap width measurement approaches

Described below are the two measurement approaches for determining gap width. The first approach utilizes image processing resulting in better edge detection whereas the second approach incorporates a laser line sensor, which is more robust against environmental changes, especially light. Since after automated assembly a final inspection will be carried out manually, the reference for these measurements will be the feeler gauge currently used. The required resolution is therefore minimum 0.05 mm, which can be realized by typical feeler gauges. The measuring range is defined as 0.2 – 3 mm.

The first approach under investigation is an image processing system, where the gap is defined as the orthogonal projection of blade edges, according to the inserted feeler gauge. The camera therefore is equipped with a telecentric lens. Additional monochromatic lighting and filters are used to obtain repeatable image quality without influence of ambient light. Recorded images are evaluated by an algorithm for edge detection after a preprocessing step generates a monochrome image and determines a region of interest. The middle axis of gap and edges are detected by differences in intensity distribution. For obtaining a mean value, the measured values are iterated along the middle axes of the gap. Using this setup, measurement series with multiple insertions of a feeler gauge between the same two blades were recorded for different gap widths. By determining a regression line, using least square method, a relation between measured pixels and adjusted gap width could be determined. The results of these measurements can be taken from table 2.

Table 2. Gap measurement using image processing

Nominal gap width (mm)	$\bar{d}$ (mm)	d_{min} (mm)	d_{max} (mm)	σ (mm)
0.25	0.235	0.195	0.248	0.012
0.50	0.509	0.494	0.559	0.012
1.00	0.996	0.963	1.048	0.016
2.00	2.001	1.961	2.028	0.021

The second approach under investigation is the use of a laser line sensor, which offers a 2D-profile of the measured gap (figure 4). When configuring the image capturing, a conflict for determining optimal exposure time occurred. To guarantee a sufficient saturation in the edge regions an exposure time needed to be chosen, which leads to reflections within the gap. Consequently, the gap could not be defined as the width of the area, where no point is detected, as incorrect points were recognized especially for small gaps and the gap needed to be defined using geometrical elements in the captured profile. Therefore, beginning and ending of the gap were defined as the intersection points of the straight lines (red lines in figure 4), parallel to the surface of blade platforms, with the rounding in the edge regions.

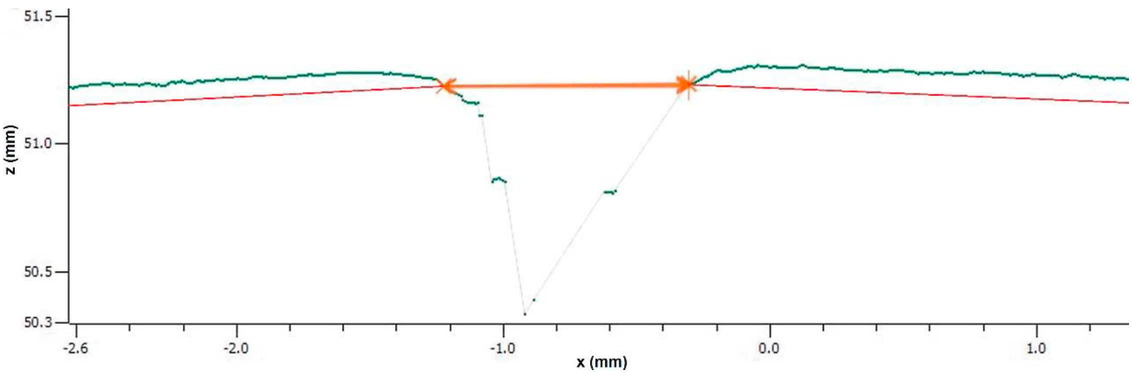

Fig. 4. Definition of gap geometry

Following approach two, measurement series with multiple insertions of a feeler gauge between same pairing of blades were performed. The results of these measurements can be taken from table 3.

Table 3. Gap measurement using laser triangulation

Nominal gap width (mm)	$\bar{d}$ (mm)	d_{min} (mm)	d_{max} (mm)	σ (mm)
0.25	0.251	0.235	0.259	0.010
0.55	0.547	0.532	0.569	0.015
0.85	0.851	0.834	0.860	0.009

For both measuring approaches a clear functional correlation between nominal gap width, adjusted by feeler gauge, and measured gap width can be stated. The determined standard deviations comply with demanded measurement accuracy. By comparison, between the two devices, slightly smaller standard deviations are obtained for laser triangulation. Since measurements of both approaches show big outliers compared to their standard deviation, the repeatability of feeler gauges as a reference must be questioned. A selection of one of the presented measurement approaches can thereby not be reached as addressed in chapter 5.

4. Force-guided assembly

The blade assembly on the drum is performed by a standard industrial robot. Blades are handled by a gripper system and inserted in the opening of the groove. Two challenges are to be solved for a reliable process: Due to the small oversize of the groove opening, a compensation for positioning deviations during gripping is needed for insertion of blade feet. Furthermore sticking of blades during tangential movement needs to be avoided. To reduce the risk of sticking as a consequence of tilting, the gripping point on the leaf is chosen as close to the platform as possible. In addition to the industrial robot, an external axis is used for drum rotation. This eliminates deviations in the robot path during tangential blade movement.

The main contribution for reliability in blade assembly results from the proposed force control. The design of groove opening and feet of blades allows compensation of positioning deviations by evaluation of occurring forces. To avoid tilting of blades, a defined contact force between drum and blade is applied in radial direction. Therefore an explicit force control using a force torque sensor was implemented according to Winkler [6, p. 33]. This allows superimposition of given robot paths with force guided compensation movements and movements based only on measured forces and torques.

The compensation of positioning deviations during blade insertion is realized by two controllers for x- and y-axes of the tool. A compensation movement in the direction of acting forces is performed, trying to eliminate these forces completely, resulting in avoidance of contact between drum and blade. For avoiding a permanent control offset, x- and y-axes are implemented as PI-controllers. For applying a defined contact force in radial direction a P-controller is implemented in z-direction. A movement is performed in positive z-direction, until defined contact force is acting in negative z-direction.

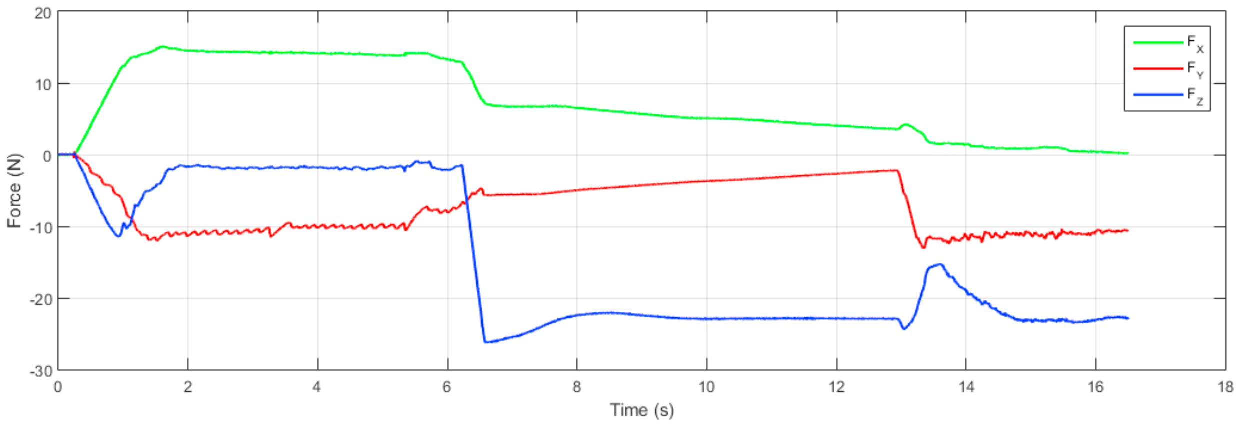

Fig. 5. Forces during blade insertion

The assembly process for inserting a blade into the groove can be divided into three steps. In the first step a blade, which is positioned in front of the groove opening, is inserted by a radial movement. The path controlled movement in z-direction is combined with force guided compensation movements in x- and y-direction to compensate positioning deviations between groove opening and blade. The target point of this movement is defined in such a way, that the foot of the blade has passed the opening, but no contact in z-direction is established. In step two, force guided movements in all three directions are used to ensure contact between blade and drum in z-direction and a centered position of the blade in the opening. In the last step the blade is moved tangentially along the groove. In this case a rotation of the external axes is combined with force control in z-direction. While the rotation of the drum leads to a movement of the blade along the groove, the applied contact force in z-direction avoids tilting of the blade and therefore sticking. Forces in x- and y-direction are only monitored to abort movement in case of exceeding force limits. The occurring forces during these steps can be taken from figure 5.

When the blade reaches contact with the opening of the groove forces in all three directions are observed. At second six step 2 begins and force control in z-axis is enabled. A contact force of 22.5 N is building up, with an overshoot at second eight. Forces in x- and y-axes remaining from step one are reduced until the values are falling below the threshold of 3 N. At the beginning of step three (second 13) steps in z- and y-direction are observed. The contact force in z-axes is rebuild, the force in y-axes is constant due to friction during movement.

5. Conclusion

This paper introduces an automated approach for selecting and assembling sets of blades for jet engine rotors during MRO. The potential for an automated assembly was shown for radially mounted rotors. A concept for increasing efficiency by reducing the effort for adjusting sets of blades based on previous measurements is proposed. Furthermore, different solutions for subsystems are presented. Multiple measurement series were conducted and results were evaluated. In case of the measurement of blade width, better results were obtained using an optical measurement approach. The realized measurement accuracy enabled selection of sets of blades which - in the investigated cases - did not require further adjustments.

For the measurement of resulting gap width, both approaches provide a sufficient measurement accuracy. A correlation between measured gap width and reference provided by feeler gauge was determined. Due to uncertainty in repeatability of opening the gap by feeler gauge, an alternative method for reliable gap opening is demanded for further investigation of measurement quality. This requires a model for a deeper understanding of the mounting and contact conditions, which will provide insight for the selection of an approach for gap width measurement.

The presented force control for blade insertion enables a robust assembly process. Positioning deviations occurring during gripping processes are compensated reliably. To further investigate and evaluate the proposed control strategy, measurements have to be conducted with defined positioning offsets and variation of additional parameters. Besides an optimization of controller tuning, the expansion on torque control for assuring the correct orientation of inserted blades is to be investigated. An improvement of force control may permit higher speed for robot motion and drum rotation. Especially a faster insertion and rotation of blades as well as reduced time for offset compensation will lead to a further increase in productivity.

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