Development of an in-situ measuring system for blisk manufacturing

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Abstract: In order to solve the in-situ measurement problem of workpiece with complex structures, a cantilever coordinate measuring machine (CCMM) is proposed to adapt to the finite space constraints of the 5-axis computer numerical control (CNC) processing site. Structure design of dense ball bearing shafting is analyzed and optimized. Factors affecting measurement accuracy of CCMM are analyzed, and measurement accuracy is validated by experiments. Results show that the structure of CCMM is able to satisfy requirements of technical specification, and the in-situ measurement of blisk manufacturing is realized. The CCMM developed is of important significance for machining quantity improvement of blisk and development of large aircraft production.

Key words: blisk; in-situ measurement; cantilever coordinate measuring machine (CCMM)

CLD number: TH721 **Document code**: A
Article ID: 1674-8042(2018)02-0115-06 **doi**: 10.3969/j.issn.1674-8042.2018.02.003

0 Introduction

As the heart of all kinds of aircrafts, aero-engine is an integrated high-tech product based on subjects such as engineering thermo-physics, chemistry, material science, structural mechanics, information science, mechanics and so on. Aero-engine is featured as high-value, long research and development cycle, technical sophistication and advanced materials, and it is also an important mark of industrial foundation, science and technology capability, economic and national defense power[1-3].

The thrust weight ratio is an important parameter of advanced aero-engine. Structure of blisk can be able to effectively improve not only thrust weight ratio but also aerodynamic and vibration efficiency of aero-engine. It has been widely adopted in aero-engine abroad[4-6]. According to a plan of United States Deparment of Defense, every engine turbine on the fighter must employ structure of blisk until 2020.

Blisks are generally manufactured by computer numerical control (CNC) milling machines in developed countries such as USA and UK, and they are usually made of titanium and high-temperature alloy, the value of which accounts for about 8.25% of the fighter's total price. However, many factors such as residual stress, cutting force and heat and machining path can lead to machining error of blisk, which will unquestionably result in millions of economic loss[7,8]. Therefore, the on machine in-situ measurement of blisk in manufacturing is of great national defense and industrial significance for improving machining quality and developing large aircraft project.

Liu Z W[9] proposed an in-situ measurement system of blade surface based on combination of machine vision and robot, in which robot rotated with blade and scanner to acquire point cloud data of blade surface under different perspectives. Wu L L[10] presented a contact on-line inspection method of blade surface, and brought forward a new method of disposal and layout of measure points, i.e., UV intercept method. However, there is no literature or achievement about in-situ measurement of blisk up to present.

A cantilever coordinate measuring machine (CCMM) is proposed to adapt to the finite space constraints of 5-axis CNC processing site[11-13]. By rotation of cantilever, not only narrow and long space restriction of processing site is broken through, but also requirement of in-situ measurement of blisk is realized.

Received date: 2017-10-25

Foundation items: National Natural Science Foundation of China (No. 51375338)

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1 Design of measuring system

1.1 Restriction of processing site and structure of blisk

The space of 5-axis CNC processing site is shown in Fig. 1.

The measuring system can be only placed in the narrow and long space("restricted space" in Fig. 1), the width and length of which are 460 mm and 2 570 mm, respectively.

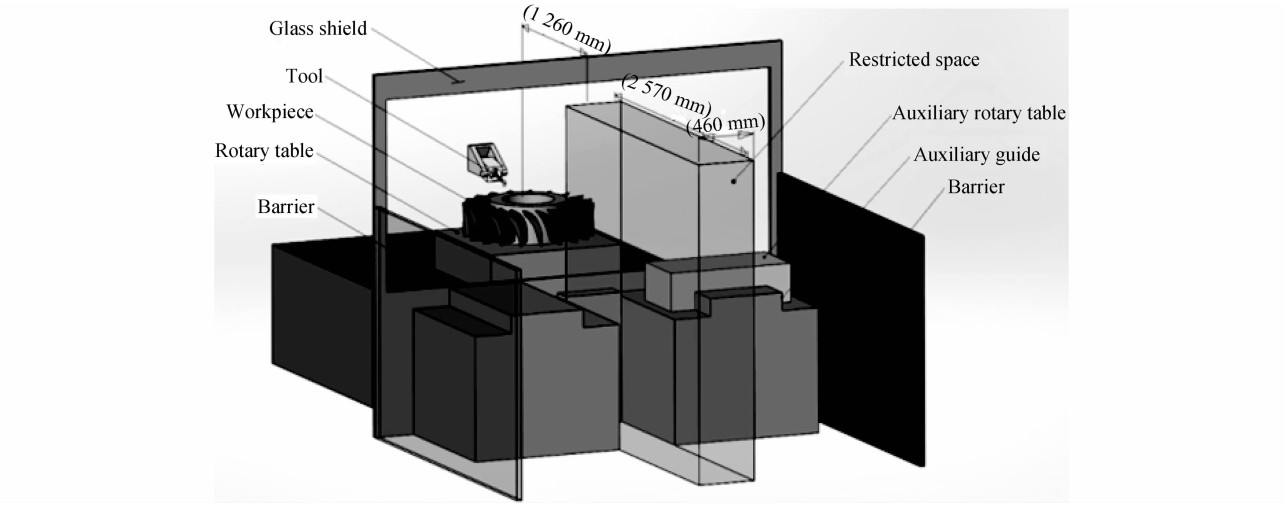


Fig. 1 Restricted Space of 5-axis CNC processing site

The structure of measured blisk is shown in Fig. 2.

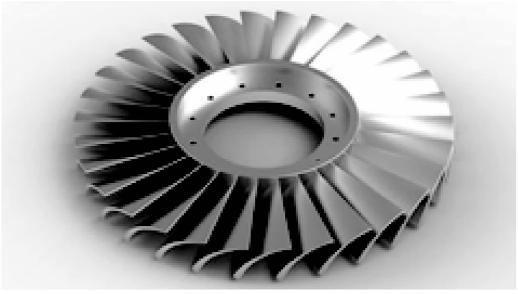


Fig. 2 Structure of blisk example

Blades with same specifications distribute uniformly on the whole blisk, the number of which varies with the size of blisk. The minimum distance between two adjacent blades is no more than 10 mm, and the maximum twist angle of single blade is as big as 60°. Blisk is clamped on the workbench. Measuring system must be outside of glass shield when processing, and it should start to work as soon as processing comes to an end.

1.2 Structure of CCMM

The overall design of CCMM takes into account factors comprehensively, such as measurement accuracy, reliability, economy, formative design and life of machine. The structure of CCMM is shown in Fig. 3, which consists of pedestal, X motion part, Z motion part, dense ball bearing shafting, cantilevered beam, REVO head, linear and circular grating and servo motors and so on.

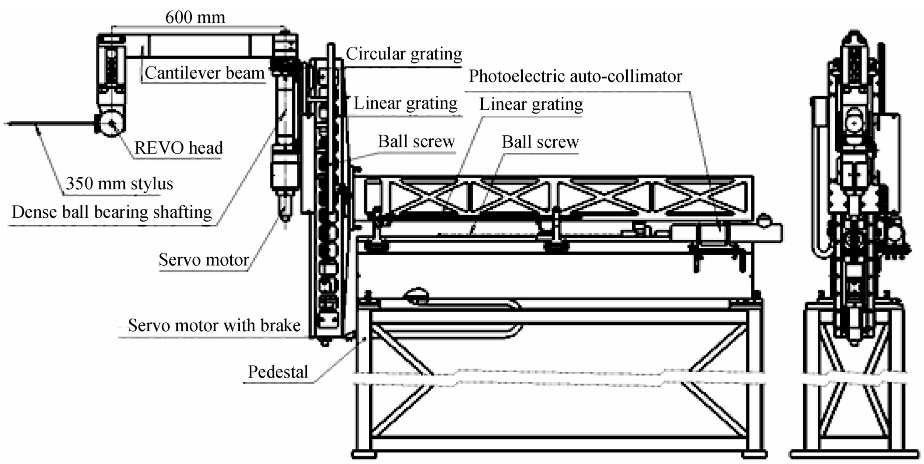


Fig. 3 Structure of CCMM

Linear design is adopted in the relative unrestricted directions, for example, horizontal and vertical directions; cantilevered design is adopted in restricted direction. *X* motion part drives *Z* motion part, cantilevered beam and REVO head to move horizontally; *Z* motion part drives cantilevered beam and REVO head to move vertically; cantilevered beam drives REVO head to rotate about axis of dense ball bearing shafting; stylus of REVO head rotates about it is *A*-axis and *B*-axis continuously.

1.3 Structure of dense ball bearing shafting

Structure of dense ball bearing shafting is shown in Fig. 4, which consists of shaft, shaft sleeve and ball bearings with interference fit. Ball bearings are placed on cage, and thrust balls are placed on end cage. Circular grating is fasten on its holder by screws, and two read-heads are installed diametrically around circular grating to remove installation eccentricity error of circular grating. Lengths of cantilevered beam and stylus are 600 mm and 350 mm, respectively. As a result, any minor error of dense ball bearing shafting will be amplified at stylus tip center in a great proportion. Under the same axial and radial run-outs, the longer the shafting is, the smaller effect of shafting error on displacement of tip center is. Length of dense ball bearing shafting is designed as long as 290 mm, and the rotation accuracy of shafting is no more than 0.001 mm.

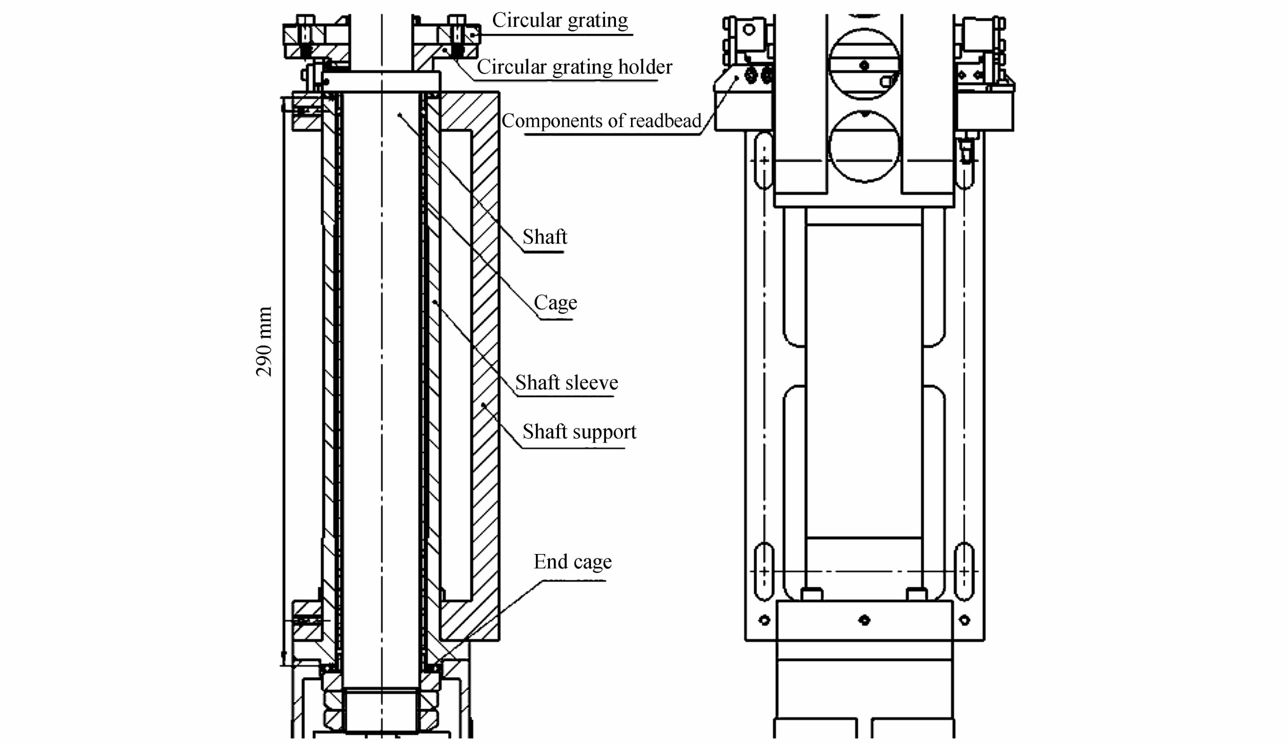
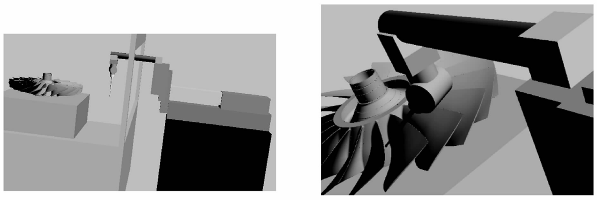


Fig. 4 Structure of dense ball bearing shafting

1.4 Working process of CCMM

The CCMM is outside of glass shield in processing. When it comes to an end and the measurement is needed, glass shield opens, cantilevered beam rotates, and *X* motion part move so that stylus can be close to measured area. And then, surface is measured by rotation of cantilevered beam and *A*-axis and *B*-axis of REVO head.

Fig. 5 shows working process of CCMM. It is a virtual coordinate measuring system developed according to this project to validate the feasibility of structure design of cantilevered beam and detectability of REVO head.



(a) Close to measured area (b) Detection of measured surface

Fig. 5 Working process of CCMM

By rotation of cantilevered beam, not only movement of tip center in *Y* direction is realized within the restricted narrow and long space of

460 mm×2 570 mm, but also travel of X motion parts is reduced to half, which avoids the possibility of components in X direction to exceed the restricted space. The main technical specifications of CCMM are: 1) Measurement uncertainly is no more than $(10+L/30)$ μm (L is length of measured object); 2) Resolution of CCMM is 0. 001 mm. The novel structure style is of universal significance to in-situ measurement of workpiece with complex features.

2 Accuracy analysis of CCMM

Measurement accuracy of CCMM is mainly affected by factors such as errors of mechanical system, errors caused by force and heat deformations. Taking the measurement size of 187 mm projected to horizontal plane as an example, factors affecting measurement accuracy are shown in Table 1.

Table 1 Analysis of factors affecting measurement accuracy

Error item		Maximum error value	Error value at tip center δ_i
Errors caused by X motion parts	Positioning error (μm)	1. 0	1. 0
	Straightness error in Y direction (μm)	1. 5	1. 5
	Straightness error in Z direction (μm)	1. 5	1. 5
	Yaw angle caused by straightness error in Y direction	0. 48″	4. 2 μm
	Pitch angle caused by straightness error in Z direction	0. 48″	4. 2 μm
	Roll error	2. 0″	3. 8 μm
	Roll error caused by rotation of cantilevered beam	1. 95″	2. 8 μm
Errors caused by Z motion parts	Positioning error (μm)	1. 0	1. 0
	Straightness error in X direction (μm)	1. 5	1. 5
	Straightness error in Y direction (μm)	1. 5	1. 5
	Pitch angle caused by straightness error in X direction	2. 76″	3. 5 μm
	Pitch angle caused by straightness error in Y direction	2. 76″	3. 5 μm
	Roll error	2. 0″	9. 8 μm
Errors caused by rotary axis motion parts	Axial run-out (μm)	1. 0	1. 0
	Radial run-out in X direction (μm)	1. 0	1. 0
	Radial run-out in Y direction (μm)	1. 0	1. 0
	Yaw angle caused by radial run-out in X direction	0. 7″	3. 3 μm
	Yaw angle caused by radial run-out in Y direction	0. 7″	3. 3 μm
	Pitch angle caused by axial run-out	0. 7″	3. 3 μm
	Errors caused by force deformation (μm)	6. 5	6. 5
	Error of REVO head (μm)	1. 0	1. 0
	Error caused by variation of temperature (μm)	6. 0	6. 0

Assuming factors in Table 1 is independent to each other, and the correlation coefficient of every two factors is zero. Errors in Table 1 bring measurement errors not only in normal direction but also in two orthogonally tangential directions of measured surface, and errors in the 3 directions are the same. Then module of the total error is $\sqrt{3}$. However, none but error in normal direction can affect measurement accuracy. As a result, the average influence factor is $\xi = \sqrt{3} \approx 0.6$. Then the estimated value of total measurement error of CCMM is 12. 7 μm. According to JJF1094-2002, the total measurement error of CCMM satisfies requirement of technical specifications.

3 Results

The developed CCMM for in-situ measurement of blisk is shown in Fig. 6. Measurement accuracy of CCMM is validated by experiments of measuring gauge blocks with different lengths placed in different directions according to GB/T 18779. 2(ISO10360-2) and JJF 1408.

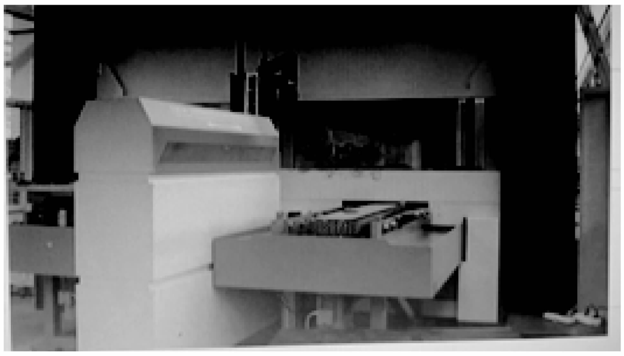


Fig. 6 CCMM developed for in-situ measurement

In order to test and verify the comprehensive performance of CCMM, points are measured by all the 5 axis motions of CCMM; as a result, even for gauge block of 8 mm, measurement error is as big as 7. 7 μm. Measurement results are shown in Fig. 7.

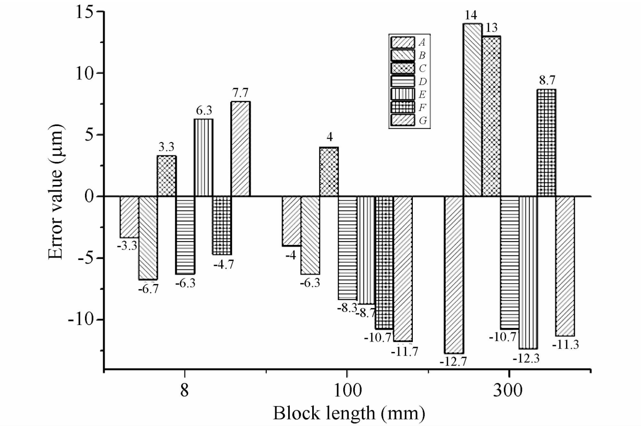


Fig. 7 Measurement results by 5-axis motion

Gauge blocks with different lengths are placed in 7 different directions. *A*, *B* and *C* in Fig. 7 represent that gauge blocks are placed in *X*, *Y* and *Z* directions, respectively; *D*, *E* and *F* represent that gauge blocks are placed along the diagonal directions on plane *XOY*, *XOZ* and *YOZ*, respectively; and *G* represents gauge blocks are placed to have an intersection angle of 45° with all 3 axes. Fig. 8 shows measurement results of gauge blocks by motion of only one axes or two axes of CCMM, and measurement error is no more than 0. 001 mm.

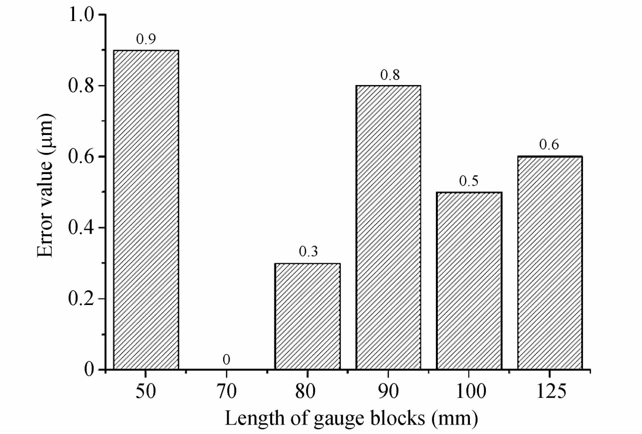


Fig. 8 Measurement results by only one or two-axis motion

4 Conclusion

A CCMM with REVO measuring system is developed to realize the in-situ measurement of blisk based on both the narrow and long space restriction of processing site and complex features of blisk. Design of dense ball bearing shafting is analyzed and optimized to minimum the effect of shafting errors on displacement of tip center. A virtual coordinate measuring system of cantilever is developed to validate the probability and feasibility of structure design such as cantilevered beam and detectability of REVO head. Factors affecting measurement accuracy of CCMM are analyzed and the maximum measurement error is estimated theoretically. The CCMM developed is able to satisfy requirements of technical specifications, which is validated by experiments and practice. The structure of CCMM not only realizes in-situ measurement of blisk, but also is of universal application significance to in-situ measurement of workpieces with complex features.

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整体叶盘加工原位测量系统的研制

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摘　要： 针对五轴数控机床加工现场狭长空间的限制以及整体叶盘原位测量的需求，研制了一种悬臂式坐标测量机。设计并优化了密珠轴系的结构，分析了影响测量机测量精度的各项因素，并通过实验对测量机的测量精度进行了验证。结果显示，所设计的测量机结构能够满足测量指标的要求，可在机床加工原位对整体叶盘加工质量进行检测。所研制的测量机对于提高整体叶盘加工质量及发展大飞机生产都具有重要意义。

关键词： 整体叶盘；原位测量；悬臂式坐标测量机

引用格式： ZHANG Hai-tao, LIU Shu-gui, LI Xing-hua, et al. Development of an in-situ measuring system for blisk manufacturing. Journal of Measurement Science and Instrumentation, 2018, 9(2): 115-120. [doi: 10.3969/j. issn. 1674-8042. 2018. 02. 003]