AUTOMATIC COMPENSATION OF ERRORS OF MULTI-TASK MACHINES IN THE PRODUCTION OF AERO ENGINE CASES

Automatyczna kompensacja błędów obrabiarek wielozadaniowych w produkcji kadłubów silnika lotniczego w warunkach produkcyjnych

Grzegorz SZYSZKA
Daniel KWIATANOWSKI
Jarosław SĘP ORCID 0000-0003-2544-2211
Katarzyna ANTOSZ ORCID 0000-0001-6048-5220

DOI: 10.15199/160.2021.1.5

Abstract: The article presents a procedure which has been developed for rapid machine tools geometry selected errors compensation without machining process interruption, during long-term machining in the industrial shop floor conditions with the use of touch probe. The method presented in the article aim to increase quality of large machining components (DIA > 1000 [mm]) and a significant difference of the part height for aerospace industry, with machined on the same production line, to achieve zero non-conformances and minimize the effort of manufacturing engineers of process control. The article presents results of tests and implementation methodology results for large, sheet metal engine cases production on 5-axis multitasking machines. Presented method is directly connected with specific engine components manufacturer needs however it gives an opportunity for other industry areas implementation.

Keywords: CNC, part probing, 5-axis machining, machine accuracy, aviation industry

Streszczenie: W artykule przedstawiono procedurę, która została opracowana w celu szybkiej kompensacji wybranych błędów geometrii obrabiarek bez przerywania procesu obróbki, podczas długotrwałej obróbki w warunkach hali przemysłowej z wykorzystaniem sondy dotykowej. Przedstawiona w artykule metoda ma na celu podniesienie jakości dużych elementów obróbczych (DIA> 1000 [mm]) oraz znaczną różnicę wysokości części dla przemysłu lotniczego, obrabianego na tej samej linii produkcyjnej, aby uzyskać zerowe niezgodności i zminimalizować wysiłek inżynierów wytwarzania kontroli procesu. W artykule przedstawiono wyniki badań i metodyki wdrożeniowej do produkcji dużych blaszanych obudów silników na maszynach wielozadaniowych 5-osiowych. Przedstawiona metoda jest bezpośrednio związana z konkretnymi potrzebami producentów podzespołów silnika, jednak daje możliwość wdrożenia w innych obszarach przemysłu.

Słowa kluczowe: CNC, sondowanie detali, obróbka 5-osiowa, dokładność maszyn, przemysł lotniczy

Introduction

The use of 5-axis machine tools in production processes is currently a common phenomenon in practically every branch of industry and especially in the aviation industry, due to the possibility of complex manufacturing of geometrically complex objects [1]. The production of advanced components for aircraft engines is usually characterized by a small number of pieces in production batch, variability of the products made and a long production time. A key aspect in aviation production is the quality of manufactured elements, and new designs of aircraft engines place ever higher demands on the accuracy and repeatability of machining processes.

The accuracy of the part is significantly influenced by the machine tool error, which can generally be defined as the difference between the actual and programmed position of the tool in relation to the machined assembly. This difference is causing among others by errors forced by the production process and changing production environment [2]. The most common errors which occursin the implementation of production processes are [3]: geometric errors, kinematic errors, thermal errors, errors in drives and measurement systems, errors caused by the machining process, errors in product measurement systems, errors due to natural wear and tear or history of use.

A particularly important parameter, influencing the stability of the machine tool operation, is the variability of the ambient temperature in the production environment combined with the temperature influence of the machine tool units. Large gradients of the daily temperature change cause the formation of thermal errors in the machine tool, significantly affecting the correctness of its geometry, which directly affects the quality of the workpiece and may be a decisive factor for the dimensional and shape compliance of its performance [2].

In the case of the aviation industry, 5-axis multi-task machining centers are particularly useful machines that enable the implementation of complete machining in one

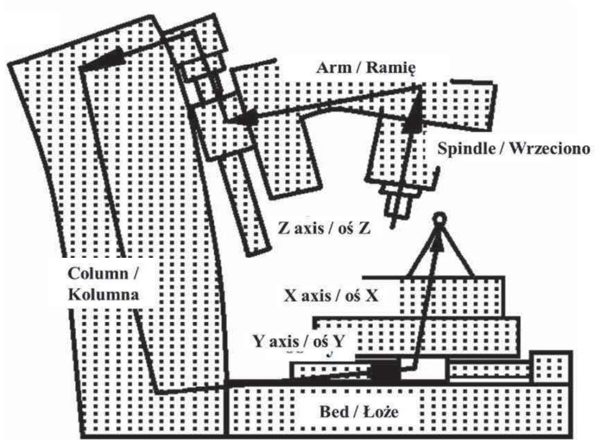


Fig. 1. The nature of changes in the geometry of the machine tool under the influence of thermal deformations [2, 4]

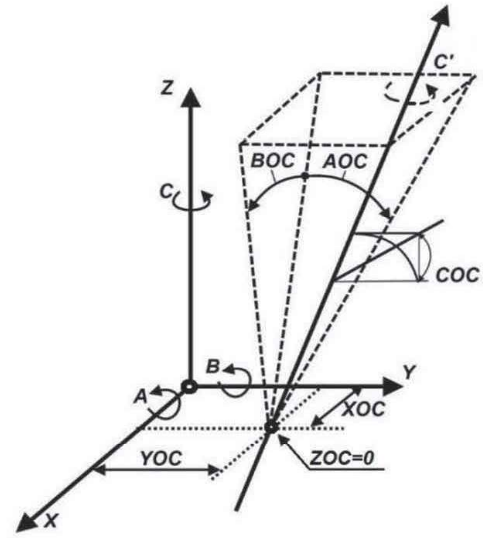


Fig. 2. Displacement of the kinematic center of the rotary axis, where [6]:
- X, Y, Z are numerically controlled linear axes, intersected in the initial position,
- A, B, C - are rotaryin the initial position,
- axesXOC, YOC, ZOC - shifts of the kinematic center of rotation of the axis,
- AOC, BOC, COC - angles of rotation of individually numerically controlled axes,
- C'- new position of the center of rotation of the C axis.

clamping, thanks to the possibility of a comprehensive combination of many types of machining, from turning, through drilling, milling, boring, threading to grinding, which allows for obtaining geometrically complex elements maintaining the required dimensional and geometric tolerances subjects [5]. Due to their design, large, 5-axis, vertical multi-task machine tools with a tilting head are particularly exposed to the impact of the above-described thermal errors that have a destructive effect on their geometry, and additionally, due to the design of the tilting head, they are exposed to deformations resulting from component forces from the process turning, which increase the geometric and kinematic errors of the machine tool. This is of particular importance in complete machining processes, where deformations of the geometry, after the turning part of the process, negatively affect the quality of the milling and drilling part of the process, especially the conditions of the position of the holes.

The above-described errors directly affect the position of the center of the kinematic rotation of the rotary axes, the errors of the rotary axes influence each other and, as a result, affect the quality of the machined parts. The displacement of the kinematic center of rotation of the -C- axis (intersections of the XYZ controlled axes) can cause errors in the produced parts both for 5-axis simultaneousmachining [1] and indexed. Fig. 2 shows the positioning errors of the rotary axis center of rotation -C-. The shift of the kinematic center of the C axis is described as XOC, YOC, ZOC and the individual torsion angles about numerically controlled axes denoted as AOC, BOC, COC where -X-, -Y-, -Z- are linear axes and the axes -A-, - B- and -C- are rotary axes. -C'- is the new point of actual rotation of the -C- axis [6].

This issue is of particular importance in the production of large cases for aircraft turbine engines (part ø> ø 1000 [mm]), which due to their design characteristics require a significant number of holes in the flanges or external and internal surfaces (Fig. 3a and 3b), using the index of the machine table, usually within tight tolerances of

a) b)

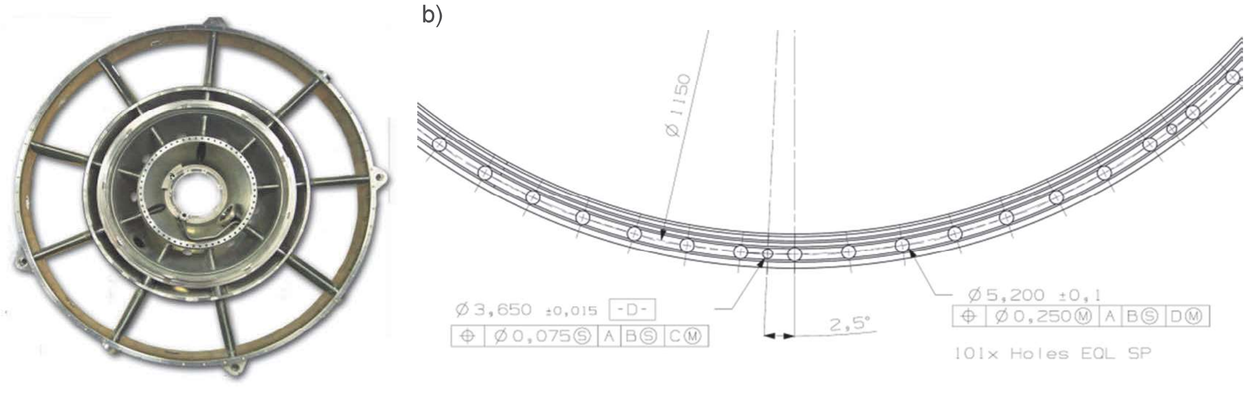


Fig. 3. Parts of the fuselage type of an aircraft turbine engine:
a) general view,
b) example requirements of the construction drawing, tolerance of the position of the holes in the fuselage flange.

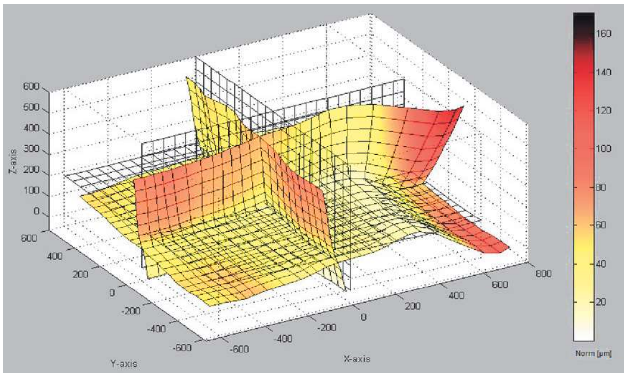


Fig. 4. Visualization of the value distribution of the vector field of spatial positioning error for tool reach Z = -400 [mm], measurement of the analyzed machine tool made with the use of the EtalonLaserTracer-MT tracking interferometer.

the condition of the position of the holes, in relation to the construction bases parts, which in particular requires minimizing the position error of the center of rotation of the -C- axis with respect to the machine spindle axis in the -XYZ- plane. The necessity to use the axis of rotation, instead of the movement with linear axes, usually results from the design limitations of the machine tool, where the travel behind the axis of rotation is from 5 [mm] to several hundred mm.

The use of the axis of rotation of the C axis also allows for higher accuracy of hole positions for large-size products, which results from the usually highest accuracy of the machine tool in its central part when setting and compensating the machine tool without using volumetric compensation. Machining of holes with the use of cycles allows you to reduce the movements of the machine tool only to the rotation of the table (C axis) and spindle movement (Z axis). Fig. 4 shows an example of the results of the measurement of the machine tool geometry in the entire machining space, where in the extreme positions of the linear axes, the machine tool geometry is burdened with the greatest error. The smallest error is in the center and at the level of the machine table.

Problem description

Currently, modern CNC machine tools used in in the aviation industry, the vast majority of them are equipped with systems that enable testing and compensation of the position of the kinematic center of the rotary axes based on the measurements of the standards with the use of the object probe. Product measurement probes are nowadays an indispensable equipment of a machine tool and are used not only to accurately determine the position of the product, process adaptation, or measurement of characteristics after the end of the process, but also to control and compensate machine tool errors. Machine tool compensation systems using product measurement probes can be divided into:

- dedicated, built into the CNC system, prepared by the manufacturer, e.g. Mazacheck (Mazak), 5-axis Auto Tuning System (Okuma), 3D-Quick Set (DMG), etc.
- universal, e.g., Cycle 996 (Sinumerik), AxiSet (Renishaw), MSP NC Checker (MSP) [6].

In the production company where the tests were carried out, the Mazak Integrex e-1600V machine tools used in the production process (Yamazaki Mazak Corporation, Oguchu-cho, Japan) are equipped with a dedicated error compensation system "Intelligent Mazachek" to correct the kinematic center of rotation of the C axis (table) and the B axis (tilting head). This system allows for the compensation of machine tool errors with the use of the object probe and standards in the form of calibration balls and a length standard mounted in the machine tool spindle. The system is widely used in production practice at Pratt & Whitney Rzeszów SA (PWR).

Fig. 5 shows the machine areas that are compensated by the „Intelligent Mazacheck" function.

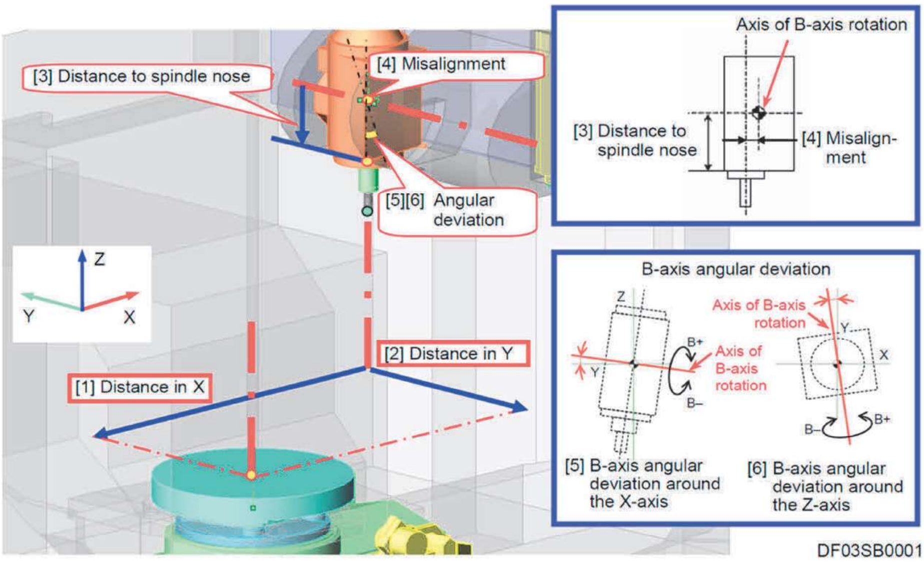


Fig. 5. Dimensions essential for maintaining high accuracy of 5-axis machining, compensated by the "Intelligent Mazacheck" function for a vertical machine tool with a tilting head [7]

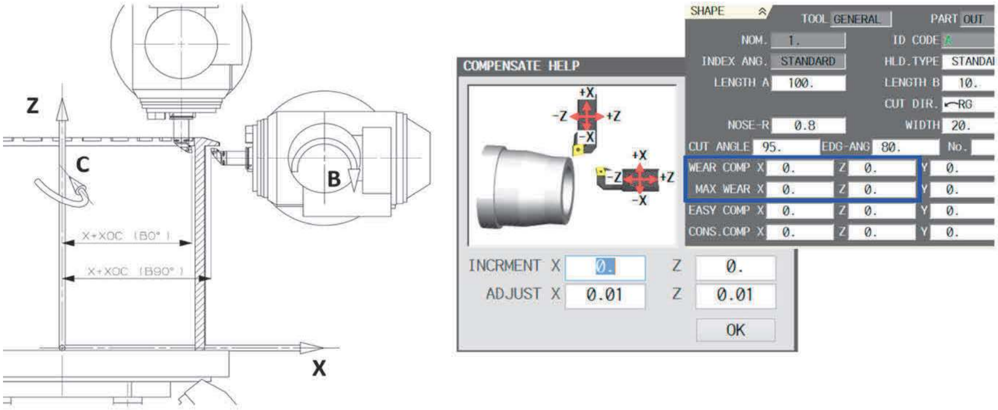


Fig. 6. Influence of XOC error a) diagram for a machine tool system with a tilting head in the B axis, b) definition, correction and control table of a turning tool (CNC MazatrolSmoothX) - allocation of XOC error in the case of lack of its compensation [9]

Despite the high efficiency of the compensation implemented by the above-described system, in production conditions there were such problems as:

1) How to compensate the error of changing the position of the center of rotation in a dynamic manner, during long-term operation of the machine tool, without interrupting the machining process, in periods of high daily temperature variation (no air conditioning)?
2) How to compensate for the error of changing the position of the center of rotation for products with variable height in order to minimize the error increase with the increase of the distance of the machining place in the Z axis from the machine tool table?
3) How to compensate the programmable center of rotation error with the real axis of rotation in turning operations?

The compliance of the software center of rotation with the actual product rotation axis is also important in turning operations. The value of the XOC error, the position of the kinematic center of rotation in the X axis (for the Mazak e-1600V machine tool system), directly affects the value of the measurement result with object probes equipped with styluses of a special shape, working in hard-to-reach areas (e.g. measuring internal / external channels), which is usually due to the possibility of using only a single point measurement along the X axis (eg Renishaw Inspection Plus, cycle O9611, O9811) [8], and also affects the value of tool wear correctors. The minimization of tool correction variability allows not only for more repeatable process performance, but also for more accurate process security in the form of the imposition of control gates with tight tolerance, both on the value of the machined diameter and on the value of the correction of the dimensions of the turning tool.

Fig. 6 a) and b) shows the influence of the XOC error on the tool value correction, for a 5-axis multi-task machine with a tilting head, for different head positions (B0 ° and B90 °) for external and internal turning.

In response to the above-described issues, research was undertaken to improve the error compensation process, and thus minimize the impact of the machine tool on the final product quality

Goal and scope of research

The aim of this article is to present the developed methodology of effective compensation of the kinematic center of rotation of the table, for the Mazak e-1600V machine tool, during product processing, for long-term processes in changing environmental conditions

and machine tool loading, without the need to interrupt the process, in an automatic cycle

with using the available technological equipment and equipment of the analyzed machine tool.

The method presented in this article has been developed and implemented in order to minimize the risk of manufacturing non-compliant aircraft turbine engine cases, stabilize the machining process, reduce maintenance costs and production downtime.

The main goals of the development of the active compensation methodology are:

- minimization of XOC and YOC displacements (Fig. 1) of the kinematic center of rotation of the table in long-term processes in order to minimize the effect of machine tool drift with a change in the environment,
- compensation of column non-perpendicularity in the XZ and YZ plane with the increase of the workpiece height workpiece up to the maximum travel range of the Z axis,
- stabilization of the variability of the correctors of turning tools performing machining in the XZ plane (Fig. 6) by minimizing the correction of the position of the kinematic center of rotation in relation to the programmable distance in the X axis,
- minimizing the measurement errors with the standard and special probe of the machined diameters in turning process.

Characteristics of the test stand

The research and tests were carried out on a 5-axis multi-task machine Mazak Integrex e-1600V (Fig. 7) installed in a production line used for machining large sheet metal cases of a turbine engine. The general characteristics of the stand are given in Table 1.

a) b) c)

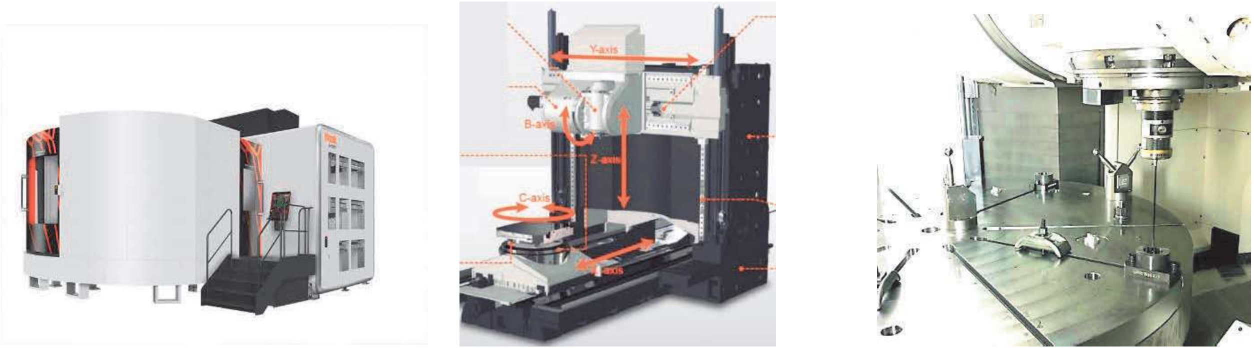


Fig.7. Mazak Integrex e-1600V 5-axis multi-task machining center:
a) General view of the machine tool [10].
b) View of the working elements of the machine tool with a description of the numerically controlled axis system and their interconnection from the machining tool towards workpiece: tool, B axis, Y axis, Z axis, X axis, C axis, workpiece [10].
c) Renishaw RMP600 strain gauge

Table 1. Basic parameters of the test stand [10]

Mazak e-1600V/10 2PC			
Capability	Max. workpiece size	ø2050x1600	[mm]
	Max. pallet load	3750	[kg]
Axis stroke	X - axis	2315	[mm]
	Y - axis	1600	[mm]
	Z - axis	1345	[mm]
	B - axis	-30 do +120	[°]
	C - axis	360	[°]
CNC Controller	Mazatrol	SmoothX	
Touch probe type	Renishaw	4xRMP600 & 3xRMP60M	
Software	Renishaw	Inspection Plus Special for PWR	

Preliminary tests

Preliminary tests were carried out on Mazak Integrex e-1600V machine tools. The data was collected for 3 machines of this type working on one production line in similar environmental conditions, over a long period of time, at least one full year.

Significant variability of the compensation parameter resulted from several conditions, the most important of which are: a

- large range of machine tool operation in the X axis, which translates into a greater variability ΔL_L of the machine bed length under variable temperature conditions, a
- high range of machine operation in the Z axis, which also translates into on the increased variability ΔL_K of the column height and the natural tendency of the column to deviate from the vertical in the Z axis, and thus the deterioration of the perpendicularity in the XZ system, as schematically shown in Fig. 1,
- the influence of radial and axial forces from the turning process directly affecting the head tilting machine tool (Fig. 6a).

The above-described factors made it necessary to look for a solution enabling the machining of large cases, engine units with the highest possible geometric accuracy, with a significant amount of machining of holes with tight position conditions, especially in the case of machining cycles with table rotation by indexing the C axis (Fig. 3b).

In connection with the periodic deterioration of the results of the conditions of the position of the holes for the machined units, measures were taken to increase

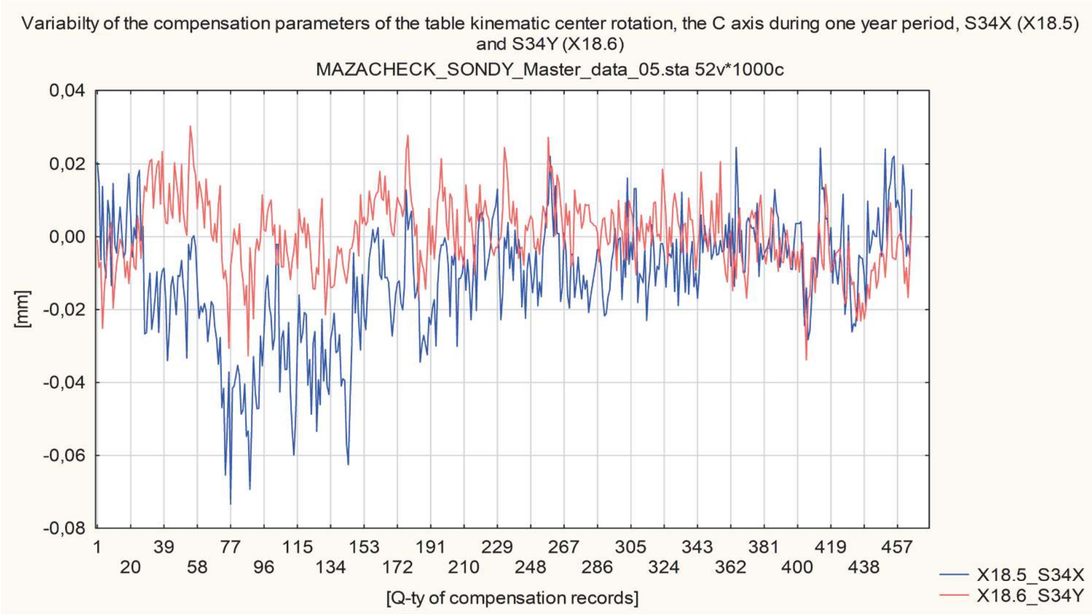


Fig 8. Analysis of the variability of the compensation parameters of the kinematic center of rotation of the table, the C axis during the 1st year, parameters S34X (X18.5) and S34Y (X18.6)

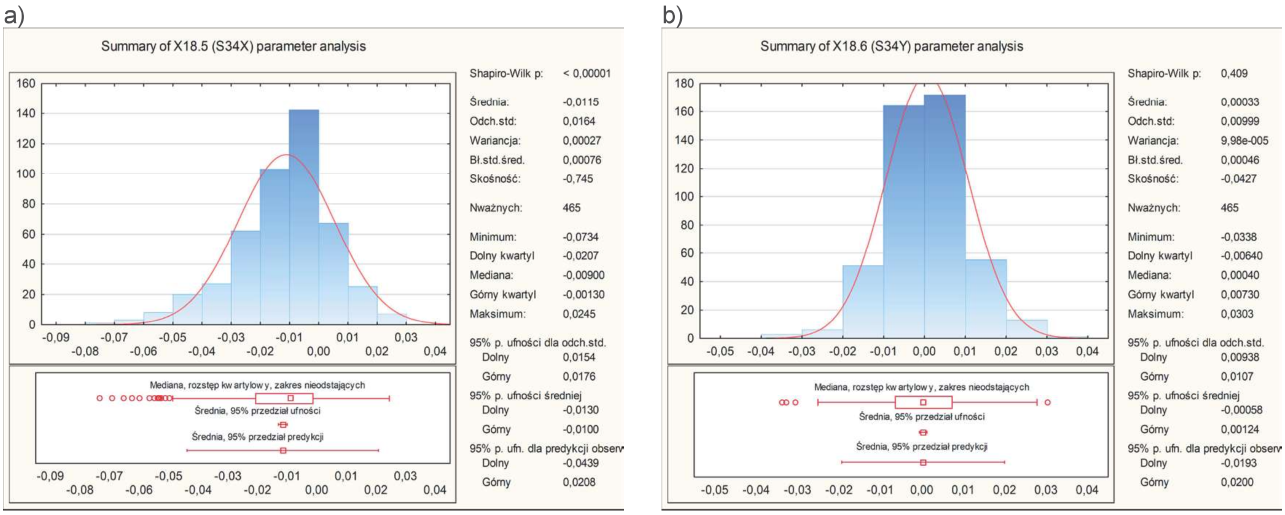


Fig 9. Analysis of the nature of the variability of the compensation parameters S34X (X18.5) and S34Y (X18.6) in the 1-year range

the frequency of machine tool compensation using the Mazacheck system with simultaneous data acquisition for a long-term (at least 1 year) analysis of the range of variability of the parameters of the position of the center of rotation of the table (S34X, S34Y), the position of the C axis relative to the programmable center in the XY system. An example of a long-term analysis is presented in the graphs Fig. 8 and 9.

Methodology of determining the position of the kinematicof thecenterrotary axis

The „Intelligent Mazacheck" software, through the G600 cycles built into the control system, corrects the position of the kinematic center of rotation of the C axis in relation to the XYZ system by updating the machine parameters of the CNC, S34X and S34Y system in real time (Table 2).

Table 2. Compensation parameters for the kinematic center of rotation of the C axis with respect to the XY system [7]

Parameters	Unit	Description
S34 (X)	0.0001 mm	Correction value (on the X axis) for the data, external correction of machine coordinates
S34(Y)	0.0001 mm	Correction value (on the Y axis) for the data, external correction of machine coordinates

Thanks to many years of cooperation with the machine tool supplier, direct access to the S34X and S34Y parameters was obtained through the # variables, thanks to which it is possible to update the parameters of the kinematic center of rotation of the C axis, and the work undertaken allowed for the development of an active error compensation methodology, the diagram of which is shown in Fig. 10 and Fig. 11.

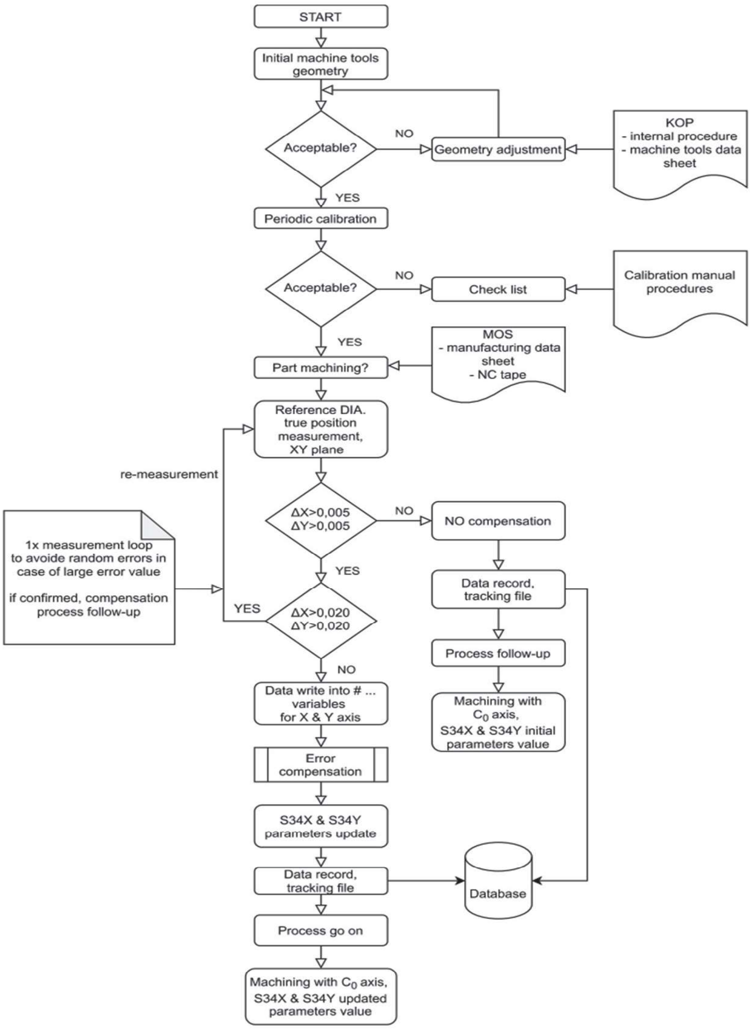


Fig. 10. The block diagram of the dynamic compensation method for analyzed machine Mazak e-1600V

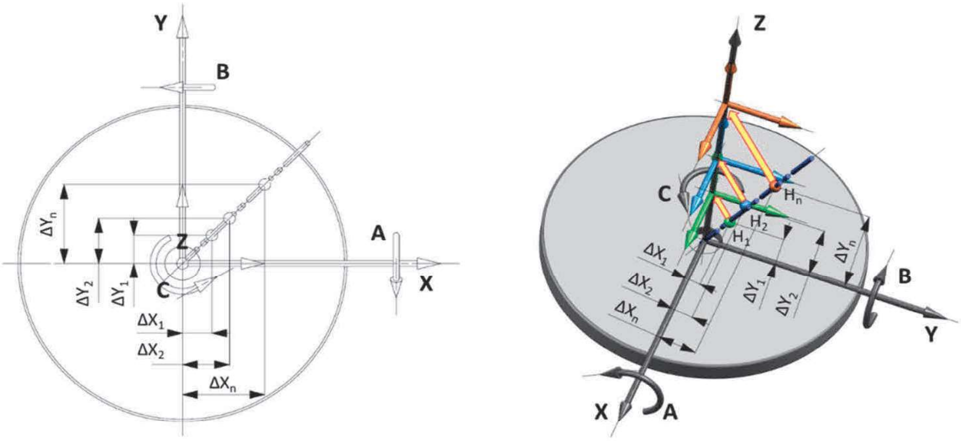


Fig. 11. The visualization of the dynamic error compensation method XOC, YOC offset kinematic center of rotation without interrupting

The diagram shows the idea of dynamic compensation and the principle of "tightening" the coordinate system of the machine tool to the real axis of rotation by continuous compensation of parameters and thus the simultaneous correction of geometric errors of the machine tool in the XZ and YZ planes along with the change of the machining height, which directly affect the XOC, YOC errors.

In the developed method, no pattern is required (it can also be used), the compensation is performed on the diameters of the machined units, bored during the multitasking operation, which become the reference elements. General requirements for introducing dynamic compensation:

- measuring probe, e.g. RMP600 by Renishaw, centered and calibrated,
- reference diameter machined with circularity <0.010 [mm],
- it is recommended to use a 4-point cycle for measuring the product, or at least 3-point with an angle opening 95 - 120 [°],
- for purely milling machining, it is possible to use reference elements from a machining fixture, provided that the tool is centered and the reference elements are centered with respect to the axis of rotation C <0.005 [mm] and the height arrangement is compatible with the machined flanges with the group of holes.

Testing and implementation results of the proposed methodology

The main goal of thetests was to confirm the assumptions of the adopted method of dynamic compensation during the process. Testing and then production implementation took place in stages and included:

- Stage one – tests using a calibration and test device developed at PWR with the possibility of direct verification of the axis position by measuring with dial gauges (a stage carried out together with the machine tool supplier), the initial state of the geometry complies with the requirements of ISO10791-1 [11], test G8V, G9V [10] ISO tolerance tightened to max. 0.006 [mm], for the 500x500 [mm] pattern.
- Stage two – tests with the PWR calibration device and the actual workpiece, fuselage - fan housing with data acquisition from the course of compensation during the process with verification of the compensated part by CMM measurement, initial geometry non-compliant for the XZ plane (G9V).
- Stage three – tests in production on an increased production sample, with the tracking of the results for each part from the measurements on the CMM, the initial geometry condition for the XZ plane (G9V).
- Stage four – production, with additional measurement of the position of 5 fixed holes with a measuring probe on the machine tool, in correlation to the CMM measurement results, the initial geometry state is inconsistent with the XZ plane (G9V), the
- Fifth stage – production, standard supervision of the part production, the initial state of the geometry in accordance with the requirements of ISO10791-1 [11], G8V, G9V ISO tolerance tightened to max. 0.006 [mm], for the pattern 500x500 [mm].

Fig. 12 shows the stages of implementing the compensation method, from testing to serial production.

a) b) c)

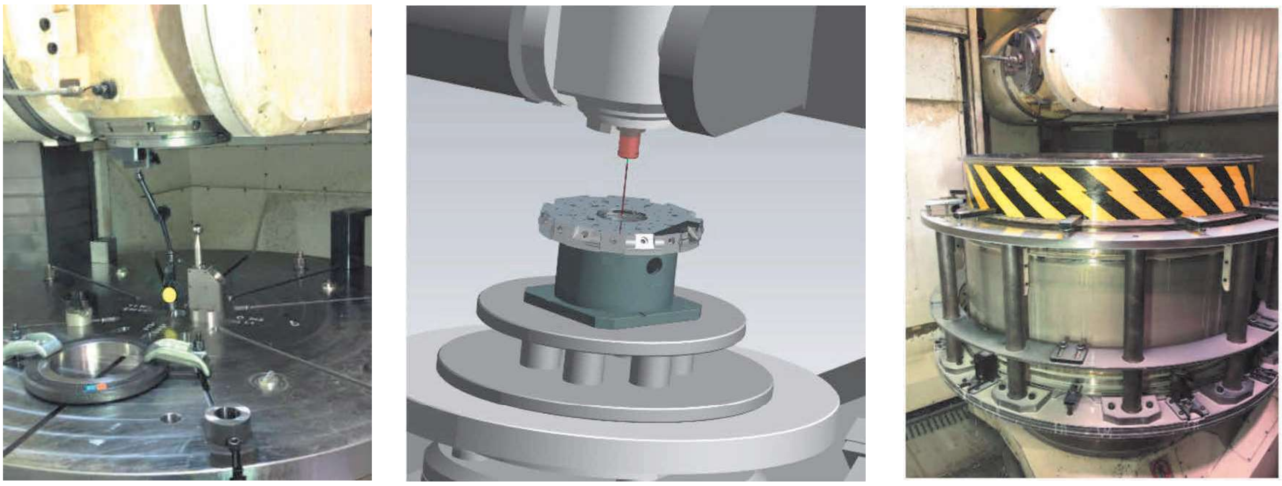
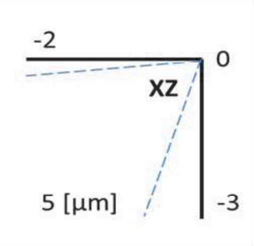
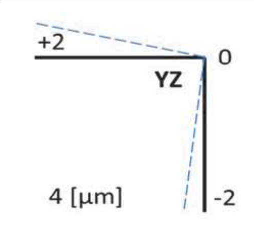
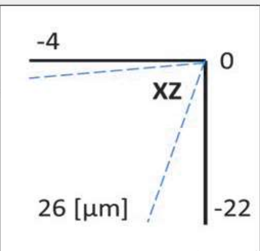
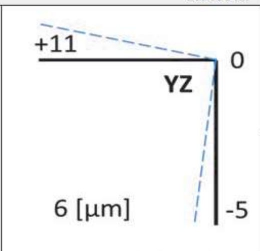
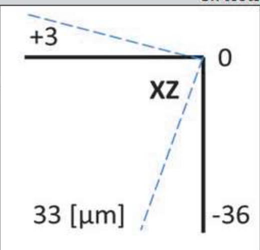
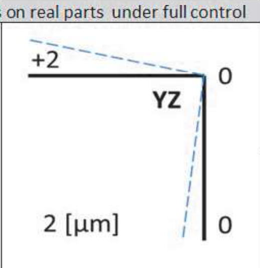
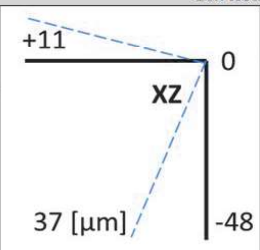
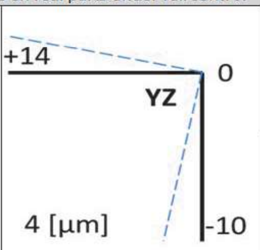
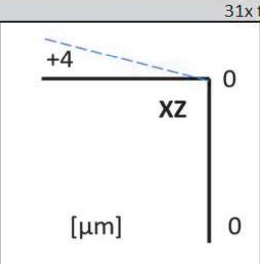
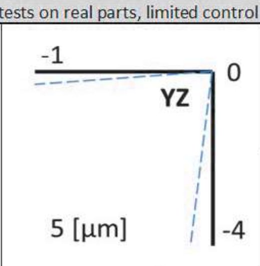


Fig. 12. Stages of testing and implementation of the active compensation methodology:
a) tests with the use of the PWR calibration device,
b) tests with the use of the PWR device, c) tests in production conditions on real products, fuselage - fan housing for a turbine engine.

A detailed summary of the results for the course of the entire test is shown in Table 3, which collectively presents the variability of the compensation range for XOC and YOC errors for 5 states of machine tool geometry in the XZ and YZ planes verified at 2 working heights.

Fig. 13 a), b) and c) show the variability of the compensation range from the height for a representative sample of machined workpieces and the amount of compensation. Fig. 13a and 13b concern the condition of the machine tool geometry not in accordance with the requirements, and Fig. 13c refer to the state of the machine geometry in accordance with the manufacturer's requirements and the ISO10791-1 standard. The graphs a) and b) clearly show shifted compensation values in the

Table 3. Summary of the compensation results in the individual study periode.

	Checking of squareness between the X/Y-axis motion and the Z-axis motion. Acc. to ISO10791-1 G8V& G9V tests, master 500x500 [mm]			C axis position compensation data relate to XYZ axis intersection point [mm]						Results conforming acc. to CMM
	Plane			Std comp. H0 = Z-1200		Comp. trial H1 = Z-950		Comp. part H2 = Z-500		
	XZ	YZ		S34X	S34Y	S34X	S34Y	S34X	S34Y	
Nominal geometry set-up			Min. [mm]	-0,0108	0,0000	0,0220	0,0117	-	-	✓
			Max. [mm]	0,0455	0,0304	0,0381	0,0154	-	-	✓
		3x tests	Δ	**0,0563**	**0,0304**	**0,0161**	**0,0037**	-	-	**0,0267**
Geometry Condition "1" 3x month set-up Jan - Mar			Min. [mm]	0,0651	0,0038	-	-	0,1334	0,0087	✓
			Max. [mm]	0,0883	0,0231	-	-	0,1959	0,0303	✓
		3x tests on real parts under full control	Δ	**0,0232**	**0,0193**	-	-	**0,0625**	**0,0216**	**-0,0023**
Geometry Condition "2" 5x month set-up Apr - Aug			Min. [mm]	0,0227	-0,0017	-	-	0,1101	0,0034	✓
			Max. [mm]	0,0876	0,0222	-	-	0,238	0,0477	✓
		10x tests on real parts under full control	Δ	**0,0649**	**0,0239**	-	-	**0,1279**	**0,0443**	**-0,0204**
Geometry Condition "3" 4x month set-up Sep - Dec			Min. [mm]	0,1112	-0,006	-	-	0,1922	0,0116	✓
			Max. [mm]	0,163	0,0454	-	-	0,3225	0,0421	✓
		31x tests on real parts, limited control	Δ	**0,0518**	**0,0514**	-	-	**0,1303**	**0,0305**	**0,0209**
Nominal geometry restore Jan - Mar			Min. [mm]	-0,0156	-0,0345	-	-	-0,0063	-0,0221	✓
			Max. [mm]	0,0298	0,0135	-	-	0,0253	0,0047	✓
		27x tests on real parts, production mode	Δ	**0,0454**	**0,0480**	-	-	**0,0316**	**0,0268**	**0,0212**

XZ plane, Δcomp. = 0.063-0.079 [mm] in relation to the lower position of the C axis rotation kinematic point. Large differences are the result of a significant deformation of the geometry in the XZ plane, which directly translates into the value of the compensation parameters. For the YZ plane, this difference is essentially constant, ΔComp. = 0.0204-0.0212 which results from the correct output perpendicularity and the observed changes in the values of the compensation parameters are the result of the influence of the environment and the variable load on the machine tool.Fig. 13d shows collectively the maximum ΔMIN. - MAX. for the entire range of the test.

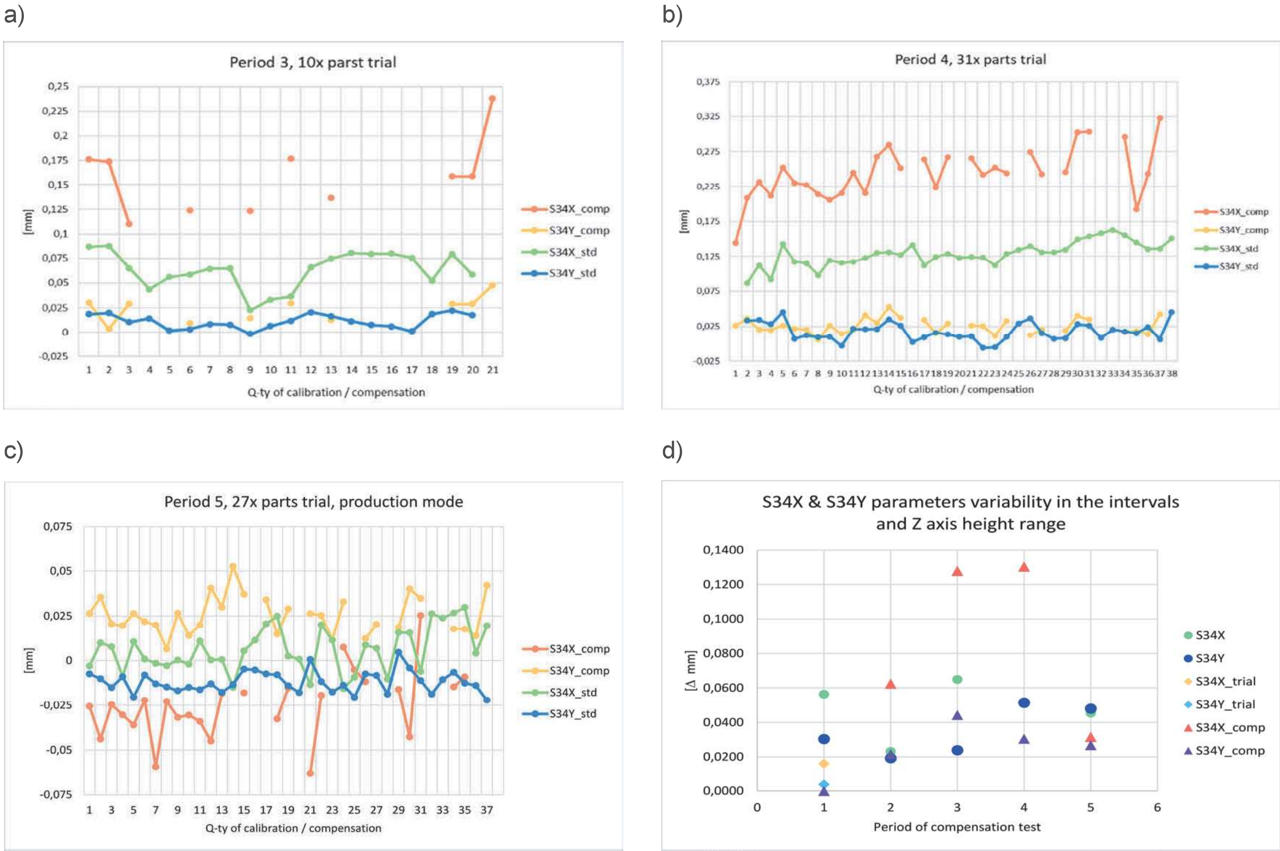


Fig. 13. The scope of changing the S34X and S34Y parameters (XOC, YOC error compensation), depending on the machining height: a) for the initial test stage 10 pcs. b) for the implementation stage 31 pcs. c) for the production stage after the machine tool geometry has been introduced, d) maximum variability of S34X and S34Y parameters in the intervals for the analyzed periods

Summary

The presented compensation methodology has found its application in production conditions for the selected machine tool park. The described method is not universal. It is a dedicated solution for machine tools with a CNC control system, in which it is possible to change the parameters of the kinematic center of rotation in real time, without the need to reset or restart the machine control system. Another important aspect is direct access to variables enabling active change of the machine tool compensation parameters. Good cooperation with the supplier of the machine tool is essential in this respect. Additionally, it should also be noticed of the risk posed by direct interference in changing these parameters, therefore the use of the described method should be individually analyzed in terms of the impact on the behavior of the machine tool, the impact on the technological process or the shape and dimensional requirements of the workpiece. It is also necessary to ensure high purity of the measured surfaces of the product and to ensure the appropriate surface quality and geometry of the measured diameters, especially with regard to the circularity condition.

The main advantages of the described method are as follows:

- the possibility of active compensation of the kinematic center of rotation by minimizing XOC and YOC errors, automatically,
- compensation at different heights of the machine in the place required by the machining process, which allows to reduce the impact of deformation of the geometry in the XZ and YZ plane on the quality of parts,
- the method does not require special equipment, it is based on the existing equipment of the machine tool,
- the compensation process is based on the parameters obtained during technological measurements carried out during the process and thus does not extend it,
- the compensation values are subject to acquisition and registration in order to monitor the variability of compensation and the state of geometry machine tools or capturing anomalies (jumps in values beyond the expected range) in a long period of work, the compensation process itself is secured in the form of control gates.

The undoubted advantage of the method is its simplicity and efficiency even in the case of significant non-perpendicularity of the axis or variability of the production environment conditions as shown in Table 3.

References

[1] Jóźwik J., Byszewski M., Study of the accuracy of positioning of rotary axes of multi-axis CNC machine tools and volumetric errors, Mechanik nr 3/2015: 144-149
[2] Turek P., Kwaśny W., Jędrzejewski J., Advanced methods of identifying machine tool errors, InżynieriaMaszyn, R. 15,1-2, 2010
[3] Schwenke H., Knapp W. , Haitjema H., Weckenmann A., Schmitt R., Delbressine F., "Geometric error measurement and compensation of machines" CIRP Annals - Manufacturing Technology, 57, 2008, 660–675.
[4] Chan J. Fast calibration and modeling of thermally-induced machine tool errors in real machining, International Journal of Machine Tools and Manufacture, Volume 37, Issue 2, February 1997, Pages 159-169.
[5] Lopez de Lacalle LN, Lamikiz A., Machine Tools forHigh Performance Machining Roz. 1.10.10, 12.5.2.4, Springer 2009.
[6] Jóźwik J. Experimental methods of error identification in CNC machine tool operation"Lublin University of Technology 2018
[7] Manual F11SB0040E, Intelligent Mazacheck, Y. Mazak 05.2015.
[8] Manual H-2000-6788-0D-A "Inspection Plus software for Mazak Integrex e-Series machines".
[9] Manual H747S30022E "Operating Manual Mazatrol-SmoothX", Y. Mazak 10.2015.
[10] Integrex eV series, Integrex e-Ramtec V series, catalog, Y. Mazak 04.2017.
[11] ISO 10791-1: 1998Test conditions for machining centers.

Grzegorz Szyszka, MSc
Pratt& Whitney Rzeszów SA
Hetmańska 120,
35-959 Rzeszów

Daniel Kwiatanowski, MSc
Pratt& Whitney Rzeszów SA
Hetmańska 120,
35-959 Rzeszów

Jarosław Sęp, Prof. PhD, Ds.C, Eng.
Faculty of Mechanical Engineering and Aeronautics
Rzeszow University of Technology
Powstańców Warszawy 8,
35-959 Rzeszów

Katarzyna Antosz PhD, Ds.C, Eng.
Faculty of Mechanical Engineering and Aeronautics
Rzeszow University of Technology
Powstańców Warszawy 8,
35-959 Rzeszów