EXPERIMENTAL STUDIES TO DETERMINE FUNCTIONAL PARAMETERS OF THE NC AXES INTEGRATING BALL SCREW ASSEMBLY

Cezara AVRAM[1], Adrian NICOLESCU[2], Eugen STRĂJESCU[3]

This paper presents the results of experimental research performed using laser interferometer ML 10 in order to determine the functional parameters of an translational numerically controlled axis, integrating a brushless dc servo motor, a belt drive intermediary transmission with 1:1 ratio, a ball screw assembly (lead screw - ball nut - bearings) and a movable element guided through a ball rail system. In this phase of the research, experimental determinations were performed in the absence of inertial load involved and the absence of a duty cycle of the driven element.

Keywords: numerically controlled axes, ball screw assembly, precision accuracy, laser interferometer

1. Introduction

Experimental researches presented in this article were performed using the RENISHAW ML 10 interferometer laser system [1], [2], [3], [5] on the experimental bench existing in MSP department - Faculty IMST (Fig. 1) [4], which materialize a translational numerically controlled axis and integrates: a FAGOR brushless DC servo motor (Nominal Torque= 9.3 Nm; Peak Torque = 46 Nm, Peak Speed = 4000 rpm) [6], a belt drive intermediary transmission with 1:1 ratio, a ball screw assembly (lead screw - ball nut - bearings) with 12 mm screw lead and a movable element guided through a ball rail system.

This study is part of the experimental research [2], [3] carried out in order to complete the PhD thesis titled "Research on structural and functional optimization of numerically controlled axes of IR in order to increase their performance" and the results are useful in the final phase for theoretical contributions validation.

[1] PhD stud, Dept. of Machine and Manufacturing Systems, University POLITEHNICA of Bucharest, Romania, e-mail: cezara.avram@yahoo.com
[2] Prof, Dept. of Machine and Manufacturing Systems, University POLITEHNICA of Bucharest, Romania, e-mail: afnicolescu@yahoo.com
[3] Prof, Dept. of Machine and Manufacturing Systems, University POLITEHNICA of Bucharest, Romania, e-mail: eugen_strajescu@yahoo.com

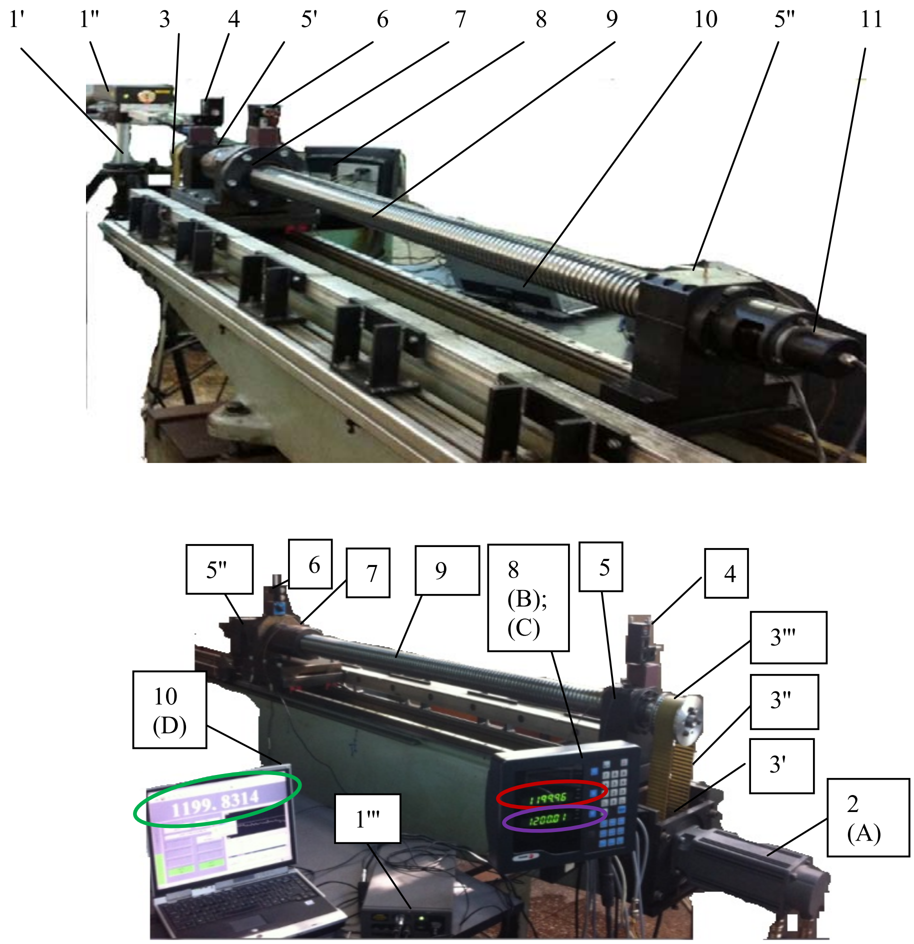

Fig. 1. The subject of the research – a translational numerically controlled axis integrating a ball screw - bearing assembly and appropriate information data-acquisition system. Exemplification for the measurements made in case of target point 1200 mm [2], [4]

1 = RENISHAW ML 10 laser equipment (1' = Tripod, 1" = ML10 Laser, 1''' = compensation unit)
2 = FAGOR brushless dc servo motor - FXM 34.40.a.e.1.000 series; 3 = belt drive intermediary transmission; 4 = Laser Beam splitter; 5 = Bearings 1; 6 = Linear reflector; 7 = Ball nut
8 = NC Fagor interface equipment; 9 = lead screw; 10 = RENISHAW Laser 10 software application; 11 = rotary encoder coupled with ball screw

2. The experimental procedure steps

The experiments performed so far have targeted:

1st stage - Determining the execution errors of the ball screw including: pitch error for each step, the cumulative pitch error on the reference length (300 mm) and the cumulative pitch error for the entire stroke (1200 mm). For this purpose, using manual driving of the screw shaft, the movable element linear displacement has been measured both, with the laser interferometer RENISHAW ML 10 as well as with a rotary encoder coupled with ball screw from 12 mm to 12 mm (corresponding to each screw rotation by 360˚) to determine the pitch error on each step, and from 300 to 300 mm (corresponding to a total screw rotation of 25 steps x 360˚) to determine the cumulative pitch error on the reference length of 300 mm, along 5 measuring ranges from zero position to the maximum stroke of 1200 mm and comparing the information provided by the rotary encoder coupled with ball screw and laser interferometer RENISHAW ML 10.

2nd stage - determining the cumulated error of ball screw execution error and the belt drive transmission execution errors, using manual driving of the screw shaft, the movable element linear displacement has been measured both, with the laser interferometer RENISHAW ML 10 as well as with the rotary encoder integrated in the DC servomotor from 12 mm to 12 mm - (corresponding to each screw rotation by 360˚) to determine the pitch error on each step, and from 300 to 300 mm (corresponding to a total screw rotation of 25 steps x 360˚) to determine the cumulative pitch error on the reference length of 300 mm, along 5 measuring ranges from zero position to the maximum stroke of 1200 mm) and comparing the information provided by the rotary encoder integrated in the DC servomotor and laser interferometer RENISHAW ML 10.

To facilitate processing of complex experimental data in the experiments were taken into account simultaneously registering of following information: the position information provided by the rotary encoder integrated in the DC servomotor, the position information provided by the rotary encoder coupled with ball screw, the position information provided by the linear transducer coupled to the movable element and, respectively, the position information on the actual movable element linear displacement measured with the laser interferometer RENISHAW ML 10. The synthesis of the results acquired from the experimental measurements performed by specific measurements sets of the actual position of the movable element, taking into account the information supplied by the RENISHAW ML 10 laser interferometer, respectively the rotary encoder coupled with ball screw (FAGOR S5000) [7], the linear transducer (HEIDENHAIN LB 326 ML 1840) [8] coupled to the movable element and respectively the rotary encoder integrated in the DC servomotor is presented below by means of Table 1, Table 2, Table 4, and respectively by means of figures fig. 1, ..., fig. 9.

Table 1

Cumulative pitch error (execution error of the ball screw) determination along the whole stroke (1200 mm) - measurements made from step to step [2]

T [mm]	E 1 [µm]	E 2 [µm]	E 3 [µm]	E 4 [µm]	E 5 [µm]	E 6 [µm]	E 7 [µm]
0	0	0	0	0	0	0	0
12	65.7	45.7	20	14.3	80	52.38	-13.32
24	22.2	22.2	0	7.8	30	27.96	5.76
36	35.2	35.2	0	14.8	50	43.96	8.76
48	25.2	35.2	-10	-5.2	20	38.76	13.56
60	35	35	0	15	50	43.52	8.52
72	47.7	47.7	0	-7.7	40	48.66	0.96
84	36.7	26.7	10	13.3	50	29.98	-6.72
96	79.4	79.4	0	-9.4	70	87.44	8.04
108	9.2	9.2	0	20.8	30	17.6	8.4
120	62.3	82.3	-20	-12.3	50	88.82	26.52
132	7.3	17.3	-10	2.7	10	19.54	12.24
144	26.8	26.8	0	-6.8	20	36.88	10.08
156	24.8	34.8	-10	-4.8	20	35.96	11.16
168	15.4	25.4	-10	4.6	20	31.6	16.2
180	77	57	20	3	80	63.2	-13.8
192	0.8	10.8	-10	19.2	20	21.8	21
204	59.2	59.2	0	0.8	60	61.48	2.28
216	16.5	16.5	0	13.5	30	23.7	7.2
228	61.2	61.2	0	-1.2	60	66	4.8
240	32.8	22.8	10	17.2	50	31.12	-1.68
252	74.8	74.8	0	-4.8	70	84.64	9.84
264	68	78	-10	-38	30	84.56	16.56
276	69.1	59.1	10	0.9	70	70.42	1.32
288	18.5	28.5	-10	11.5	30	39.14	20.64
300	66.4	66.4	0	-6.4	60	73.24	6.84
312	28.1	38.1	-10	11.9	40	41.9	13.8
324	64.4	64.4	0	-4.4	60	70.16	5.76
336	24.8	34.8	-10	15.2	40	45.32	20.52
348	79.6	69.6	10	0.4	80	76.24	-3.36
360	22.4	42.4	-20	7.6	30	47.48	25.08
372	47.9	77.9	-30	-7.9	40	81.14	33.24
384	62.8	42.8	20	17.2	80	53.44	-9.36
396	78	78	0	-8	70	87.72	9.72
408	26.9	56.9	-30	3.1	30	59.78	32.88
420	89.9	79.9	10	0.1	90	90.14	0.24
432	53	53	0	7	60	58.16	5.16
444	70.4	90.4	-20	-10.4	60	92.84	22.44
456	61.6	61.6	0	8.4	70	64.84	3.24
468	95.1	85.1	10	-5.1	90	92.1	-3
480	65.1	65.1	0	4.9	70	73.02	7.92
492	76	96	-20	-16	60	99.52	23.52
504	63.6	63.6	0	-3.6	60	72.36	8.76

Table 1 (continuation)

Cumulative pitch error (execution error of the ball screw) determination along the whole stroke (1200 mm) - measurements made from step to step [2]

T [mm]	E 1 [μm]	E 2 [μm]	E 3 [μm]	E 4 [μm]	E 5 [μm]	E 6 [μm]	E 7 [μm]
516	97	97	0	-17	80	103.6	6.6
528	46.6	66.6	-20	-6.6	40	74.08	27.48
540	101.1	91.1	10	-11.1	90	102.42	1.32
552	77.7	67.7	10	2.3	80	72.9	-4.8
564	78.2	98.2	-20	-18.2	60	105.8	27.6
576	65.5	75.5	-10	-5.5	60	78.7	13.2
588	83.6	103.6	-20	-23.6	60	106.76	23.16
600	79.5	69.5	10	-9.5	70	79.38	-0.12
612	96.2	96.2	0	-16.2	80	107.12	10.92
624	73.1	73.1	0	-3.1	70	82.34	9.24
636	109.8	109.8	0	-19.8	90	113.28	3.48
648	65.5	75.5	-10	-5.5	60	84.34	18.84
660	112	112	0	-22	90	117.28	5.28
672	92.8	82.8	10	-2.8	90	90.88	-1.92
684	92.9	102.9	-10	-12.9	80	104.66	11.76
696	76.2	86.2	-10	-6.2	70	88.56	12.36
708	98.2	98.2	0	-18.2	80	107.2	9
720	72.9	82.9	-10	-2.9	70	91.74	18.84
732	110.5	100.5	10	-10.5	100	111.58	1.08
744	82.6	82.6	0	-2.6	80	92.2	9.6
756	96.8	106.8	-10	-6.8	90	108.08	11.28
768	76.2	86.2	-10	-6.2	70	96.72	20.52
780	94.3	104.3	-10	-14.3	80	111.7	17.4
792	92.6	92.6	0	-2.6	90	94.88	2.28
804	102.5	102.5	0	-12.5	90	111.62	9.12
816	99.4	89.4	10	-9.4	90	99.76	0.36
828	114.1	114.1	0	-14.1	100	116.74	2.64
840	85.2	95.2	-10	-5.2	80	97.32	12.12
852	114.1	114.1	0	-14.1	100	117.1	3
864	87.1	97.1	-10	2.9	90	99.82	12.72
876	118.5	108.5	10	-8.5	110	119.82	1.32
888	107.3	107.3	0	2.7	110	110.06	2.76
900	104.4	114.4	-10	-4.4	100	118.92	14.52
912	93.5	103.5	-10	6.5	100	110.54	17.04
924	116.7	116.7	0	-6.7	110	127.26	10.56
936	101.5	101.5	0	8.5	110	106.54	5.04
948	111.2	121.2	-10	-1.2	110	125.84	14.64
960	97.3	97.3	0	12.7	110	104.5	7.2
972	109.6	119.6	-10	0.4	110	129.88	20.28
984	84.3	94.3	-10	15.7	100	102.42	18.12
996	128.2	118.2	10	1.8	130	128.92	0.72
1008	105.9	105.9	0	4.1	110	107.46	1.56
1020	106.6	126.6	-20	-6.6	100	128.92	22.32

Table 1 (continuation)

Cumulative pitch error (execution error of the ball screw) determination along the whole stroke (1200 mm) - measurements made from step to step [2]

T [mm]	E 1 [µm]	E 2 [µm]	E 3 [µm]	E 4 [µm]	E 5 [µm]	E 6 [µm]	E 7 [µm]
1032	99.6	99.6	0	10.4	110	109.92	10.32
1044	122.1	132.1	-10	-2.1	120	134.34	12.24
1056	112.1	112.1	0	-2.1	110	113.66	1.56
1068	116.7	126.7	-10	-16.7	100	135.42	18.72
1080	124.2	114.2	10	-4.2	120	121.68	-2.52
1092	129	139	-10	-19	110	144.84	15.84
1104	118.5	128.5	-10	-18.5	100	132.3	13.8
1116	148.4	148.4	0	-38.4	110	149.48	1.08
1128	139.5	139.5	0	-39.5	100	146.22	6.72
1140	144.3	154.3	-10	-44.3	100	165.54	21.24
1152	163.6	163.6	0	-43.6	120	166.6	3
1164	174.2	174.2	0	-54.2	120	183.08	8.88
1176	185.6	195.6	-10	-55.6	130	203.12	17.52
1188	162.6	182.6	-20	-62.6	100	186.6	24
1200	181.5	191.5	-10	-61.5	120	195.54	14.04

Value corresponding to each category of errors mentioned in Table 1 has been computed with the relations (1), (2), (3), (4), (5) and (6). For this relations the following notations have been considered:

T [mm] = TARGET;

A [mm] = position information provided by the rotary encoder integrated in the servomotor;

B [mm] = position information provided by the rotary encoder coupled to the ball screw;

C [mm] = position information provided by the linear position transducer coupled to mobile element;

D [mm] = information on the actual movement of the movable element provided by the RENISHAW laser ML 10 measurement system;

E 1 [µm] = the execution (pitch) error of the ball screw (Fig. 2, Fig. 3);

E 2 [µm] = the execution (pitch) error of ball screw cumulated with the error introduced by the limited resolution of the rotary encoder coupled to the ball screw (Fig. 4);

E 3 [µm] = the error introduced by the limited resolution of the rotary encoder coupled to the ball screw (Fig. 5);

E 4 [µm] = the error introduced by the limited resolution of the linear transducer coupled to the movable element (Fig. 6);

E 5 [μm] = execution (pitch) error of ball screw cumulated with the error introduced by the limited resolution of the linear transducer coupled to the movable element (Fig. 7);
E 6 [μm] = cumulated error from the execution (pitch) error of ball screw, execution error of belt drive transmission and the error introduced by the limited resolution of the rotary encoder integrated in servomotor (Fig. 8);
E 7 [μm] = the execution error of belt drive transmission (Fig. 9).

$$E_1[\mu m] = (T - D) * 1000 , \quad (1)$$
$$E_2[\mu m] = (B - D) * 1000 , \quad (2)$$
$$E_3[\mu m] = (T - B) * 1000 , \quad (3)$$
$$E4[\mu m] = (D - C) * 1000 , \quad (4)$$
$$E_5[\mu m] = (T - C) * 1000 , \quad (5)$$
$$E_6[\mu m] = (A - D) * 1000 , \quad (6)$$
$$E_7[\mu m] = E_6 - E_1 = (A - D) * 1000 - (T - D) * 1000 \quad (7)$$

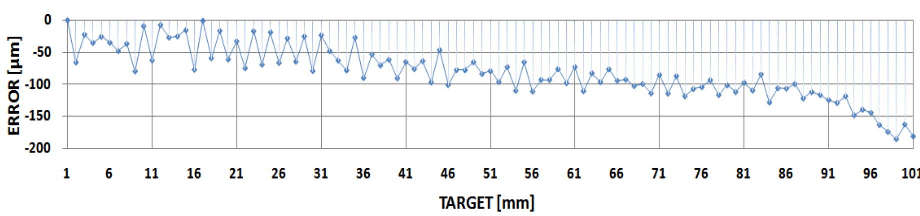

Fig. 2. Cumulative pitch error for the whole stroke (E1), measured from step to step - values calculated and provided by the laser interferometer system ML 10 [2]

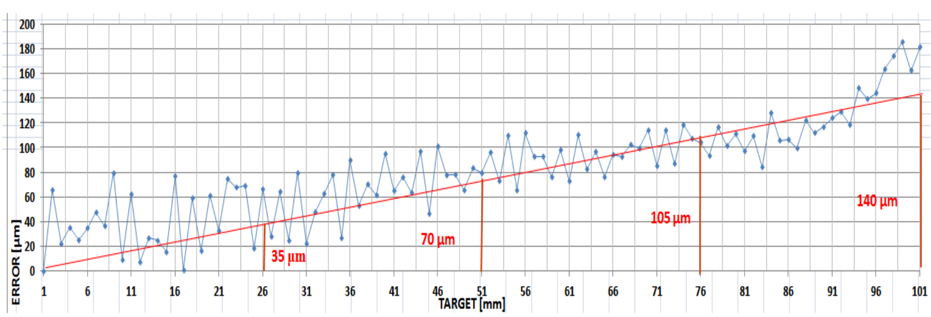

Fig. 3. The cumulative step error (E1) curve linearization [2]
Cumulative pitch error for max stroke 1200 mm (Target No.101) = 140 [μm], Cumulative pitch error for 900 mm stroke (Target No.76) = 105 [μm], Cumulative pitch error for 600 mm stroke (Target No.51) = 70 [μm], Cumulative pitch error for 300 mm stroke (Target No.26) = 35 [μm].

Table 2

Cumulative pitch error (execution error of ball screw) determination, measured on 300 mm reference length [2]

T [mm]	E 1 [μm]	E 2 [μm]	E 3 [μm]	E 4 [μm]	E 5 [μm]	E 6 [μm]	E 7 [μm]
0	0	0	0	0	0	0	0
300	46.2	46.2	0	-6.2	40	46.08	-0.12
600	64.6	64.6	0	-14.6	50	68.44	3.84
900	80.1	100.1	-20	-10.1	70	104.7	24.6
1200	115.4	115.4	0	-65.4	50	120.44	5.04

For the cumulative pitch error (execution error of ball screw) determination (Table 2) the fallowing position information were considered (Table 3):

Table 3.

Position information considered for the cumulative pitch error determination - measured on 300 mm reference length

T [mm]	A [mm]	B [mm]	C [mm]	D [mm]
0	0	0	0	0
300	299.9998	300	299.96	299.953
600	600.0038	600	599.95	599.935
900	900.024	900.02	899.93	899.919
1200	1200.005	1200	1199.95	1199.884

Table 4

Cumulative pitch error determination - measured for the whole stroke (max stroke 1200 mm) [2]

T [mm]	E 1 [μm]	E 2 [μm]	E 3 [μm]	E 4 [μm]	E 5 [μm]	E 6 [μm]	E 7 [μm]
0	0	0	0	0	0	0	0
1200	123.9	143.9	-20	-53.9	70	148.5	24.6

For the cumulative pitch error determination - measured for the whole stroke (Table 4) the fallowing position information were considered (Table 5):

Table 5

Position information considered for the cumulative pitch error determination - measured for the whole stroke

T [mm]	A [mm]	B [mm]	C [mm]	D [mm]
0	0	0	0	0
1200	1200.024	1200.02	1199.93	1199.876

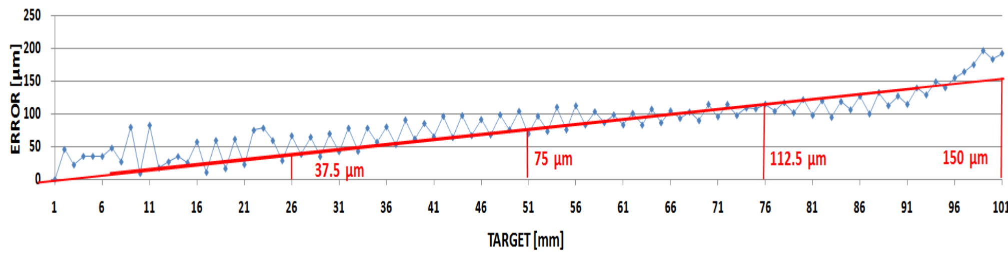

Fig. 4. The execution error of ball screw cumulated with the error introduced by the limited resolution of the rotary encoder coupled to the ball screw (E2) [2]

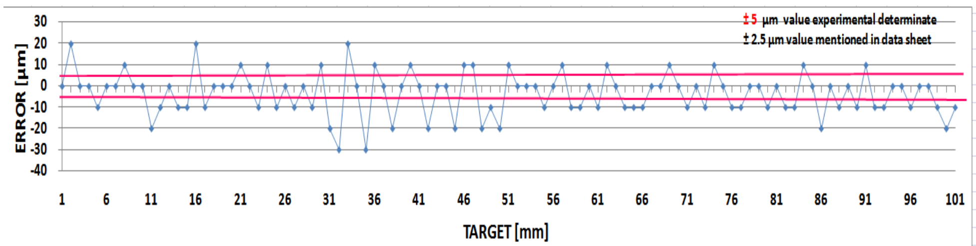

Fig. 5. The error introduced by the limited resolution of the rotary encoder coupled to the ball screw (E3) [2]

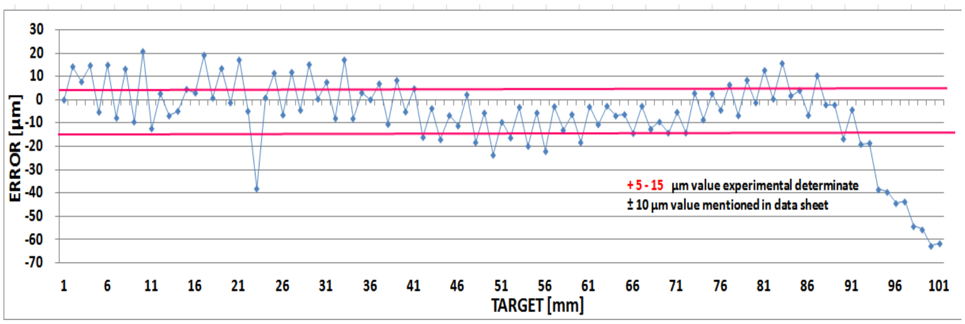

Fig. 6. The error introduced by the limited resolution of the linear transducer coupled to the movable element (E4) [2]

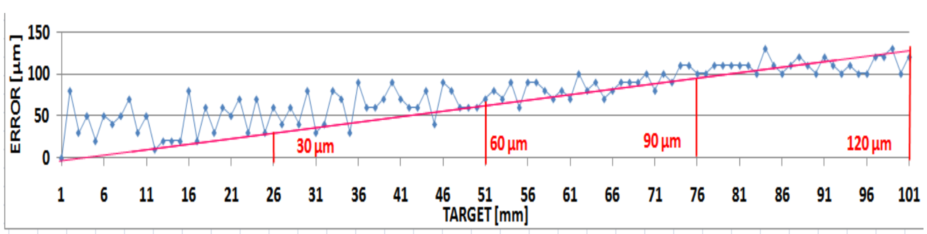

Fig. 7. The execution error of ball screw cumulated with the error introduced by the limited resolution of the linear transducer coupled to the movable element (E5) [2]

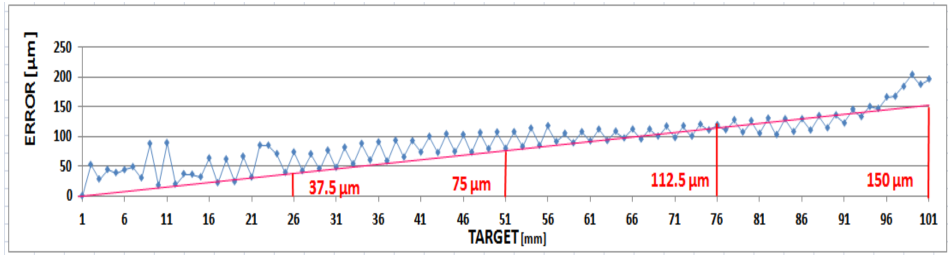

Fig. 8. The cumulated error from the execution error of ball screw, execution error of belt drive transmission and the error introduced by the limited resolution of the rotary encoder integrated in servomotor (E6) - max 157 µm [2]

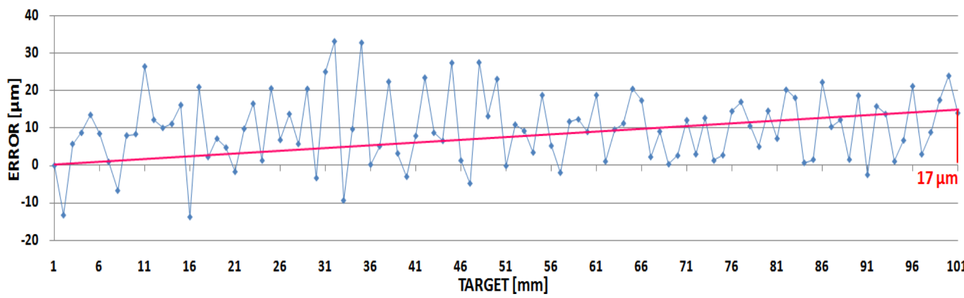

Fig. 9. The execution error of belt drive transmission (E7) - max 17 µm [2]

3. Conclusions

Determination of NC axis's functional parameters requires consideration of all categories of errors introduced by components of their structure. From this point of view, for the analyzed NC axis structure the main sources of errors are related to: errors in execution of mechanical components (ball screw and toothed belt drive) and errors introduced by the limited resolution of the position transducers associated with the mechanical components of the NC structure (rotary encoder coupled with ball screw and linear transducer coupled with the mobile element) and rotary encoder coupled with the actuator drive. In this sense, in the paper was presented the experimental procedure for the determination of the main categories of errors that affect functional parameters of the analyzed NC axis. After processing the data obtained from experimental measurements (linearization of the experimental curves) the fallowing maximum values were determined:

- the maximum value for the cumulative pitch error (E 1) resulted as being equal to 140 µm;

- the maximum value for the execution error of ball screw cumulated with the error introduced by the limited resolution of the rotary encoder coupled to the ball screw (E 2) resulted as being equal to 150 μm;
- limits of variation for the errors introduced by the limited resolution of the transducer coupled to the screw (E 3) appeared to be within ± 5 μm (versus the value ± 2.5 μm specified in transducer's data sheet);
- limits of variation for the errors introduced by the limited resolution of the linear transducer coupled to the movable member (E 4) appeared to be between +5 ... -15 μm (versus the value of ± 10 μm specified in the data sheet of the linear transducer);
- the maximum value for the execution error of ball screw cumulated with the error introduced by the limited resolution of the linear transducer coupled to the movable element (E 5) resulted as being equal to 120 μm (due to negative average value of the error introduced by the limited resolution of the linear transducer);
- the maximum value for the execution error of belt drive transmission (E 7) resulted as being equal to 17 μm;
- the maximum value for the cumulated error from the execution error of ball screw, execution error of belt drive transmission and the error introduced by the limited resolution of the rotary encoder integrated in servomotor (E 6) resulted as being equal to 157 μm.

In the NC axis performance analysis the cumulative total error over the overall NC axis must be determined by including in the calculation the belt drive intermediary transmission execution error, ball screw execution error and the error introduced by the limited resolution of the linear position transducer measuring the driven element displacement, which is the reason why the reference for the cumulative total error was considered as being the specific value error E6.

Considering the effect of reducing the amount of error introduced by the value of the cumulative average (negative) error generated by the linear position transducer limited resolution coupled to the movable element, for the analyzed NC control, it is recommend to use the position information provided by the this transducer.

Among the categories of errors identified influencing the analyzed NC axis performance parameters:

- the cumulative pitch error (E 1 = 140 μm) has the greatest influence, representing 89.17% of the cumulated error value from the execution error of ball screw, execution error of belt drive transmission and the error introduced by the limited resolution of the rotary encoder integrated in servomotor (E 6 =157 μm)
- the execution error of belt drive transmission (E 7 = 17 μm) represents only 10.83% of the total cumulative error (E6 =157 μm)

- the error introduced by the limited resolution of the rotary encoder integrated in servomotor (2,4 μm / impulse) can be considered negligible,
- the maximum performance (the minimum level of cumulative error on the entire structure) for the analyzed NC axis is 137 μm and it may be achieved for the case of measuring the mobile element displacement with the linear position transducer coupled with it.

As a completely new approach above mentioned experimental procedure allows structural and functional optimization of NC axes by simultaneously taking into account the evaluation of cumulated ball screw errors and belt drive transmission errors. The experimental measurements have been performed with RENISHAW ML 10 laser interferometer measurement system and taking into account the information supplied by the laser interferometer, the rotary encoder coupled with ball screw, the linear transducer coupled to the movable element and respectively the rotary encoder integrated in the DC servomotor. Complete details about the performed experiments are presented in [2]. Based on present approach complementary researches have been performed in looking for increasing the positioning accuracy of translational industrial robot's NC axis integrating ball screw assemblies through procedures of software error compensation [3].

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