Torque Ripple of Permanent Magnet Synchronous Torque Motor

Autor: Ing. Jan Moravec

Vedoucí: Doc. Ing. Pavel Souček, DrSc.

Abstrakt

Hlavními požadavky kladenými na pohybové osy NC obráběcích strojů jsou vysoká přesnost polohování a vysoká dynamika pohybů. Základní předpoklad pro dosažení těchto protichůdných předpokladů jsou tuhá a lehká konstrukce mechanické struktury stroje. Těmito parametry je dána výše první antirezonanční frekvence, která omezuje nastavení zesílení kaskádně uspořádaných regulátorů rychlosti a polohy. Na výsledné dynamice a přesnosti pohybu osy NC stroje se přirozeně výraznou měrou podílí přesnost samotného pohybového mechanismu, motoru a zpětnovazebního odměřování pohybové osy. Příspěvek je zaměřen na nerovnoměrnost chodu pohybové osy s prstencovým synchronním motorem s permanentními magnety, který je využíván k přímým pohonům rotačních os NC obráběcích strojů pro pohony otočných stolů, kolíbek a karuselů.

Klíčová slova

Prstencový motor, reluktanční moment, kaskádní regulace.

1. Introduction

The main requirements imposed on NC machine tools feed drive axis are high precision positioning and high dynamics. Important prerequisites for achieving these contradictory requirements are stiff and lightweight design of feed drive axis. The resulting dynamics and precision of NC machine tool feed drive axis is naturally significantly influenced by accuracy of feed drive axis mechanism, motor and feedback encoder. The contribution is focused on irregular motion of NC machine tool rotary feed drive axis with permanent magnets synchronous torque motor (PMSM), which is used to direct drives of NC machine tool rotary feed drive axis as rotary tables and carousels.

Irregular motion of PMSM is caused by its torque variation (torque ripple). Subsequently, it causes variations in speed and position of feed drive axis. This effect negatively affects the resulting accuracy of machining and surface roughness of workpiece. Torque ripple of PMSM is caused by effects resulting from the imperfect motor geometry and effects resulting from the inaccuracies of its regulation. Imperfections of the motor geometry (especially the shape and number of motor poles) cause variation of comutation angle and varying distribution of magnetic flux density around the air gap. This can be seen as fluctuations in torque (power), constant of the motor. Inaccuracies associated with the regulation are mainly given by the features of the feedback sensors which bring the information into the inputs of feedback circuits. Due to the high feedback gain of controllers at the inputs of the feedback circuit, are measured inaccuracies highlighted. The resulting inaccuracy is also influenced by assembly precision of feedback encoder and combination of different encoders for different functions in feedback loops (e.g. using one common feedback encoder for commutation, speed feedback and position feedback or using different feedback encoders for different feedbacks). Other inaccuracies are caused by kinematic deviations of the feed drive transmission mechanisms and by vibrations of mechanical structure of machine tool. These influences are presented in [1] and [4].

Further attention is focused on reluctance torque of PMSM which is called cogging. PMSM stator consists of steel poles carrying the windings. The permanent magnets with a constant magnetic flux are fixed on the rotor of PMSM. Surrounding around the air gap is thus a variable magnetic resistance, because there cycled steel poles carrying a winding with air gaps between the poles. Cogging - fluctuations in torque resulting from the transition of the rotor magnet poles through the steel stator poles (rotor permanent magnet is trying to attract a steel stator poles). This negative feature is significant in direct drives with rotary or linear motors. Especially for motors with a high numbers of poles (torque motors) working at low rotational speeds may oscillations excited by cogging lies within bandwidths of control loops and consequently degrade the precision of machining. For improving the accuracy of machining is therefore important to suppress cogging.

1.1 Indirect and direct drives

NC machine-tool feed axes can be conceiving as indirect or direct. Compared to indirect drives, direct drives (linear or torque motors) have not mechanical transmission mechanism (like ballscrew, gears, pulley, etc.) and electromagnetic motor force impact on driven mass (rotary table with workpiece, etc.) directly. Due to the low inertia, these arrangements create good assumptions for high dynamical movements of feed axes. Torque motors (fig. 1) are used for direct drives of rotary tables, milling heads, drilling heads, carousel axes, etc. Their main advantages are:

- Low moment of inertia
- High angular acceleration
- High stiffness
- High precision of positioning
- Possibility of very low speed (0.0001 rpm)
- Compact assembly

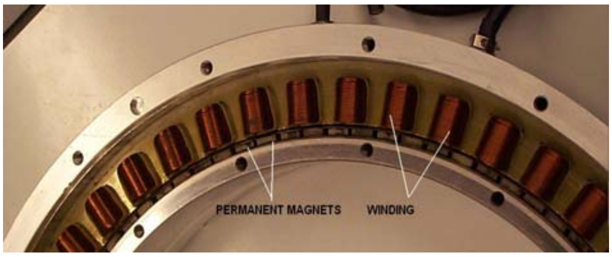

Fig. 1: *Torque motor (detail)*

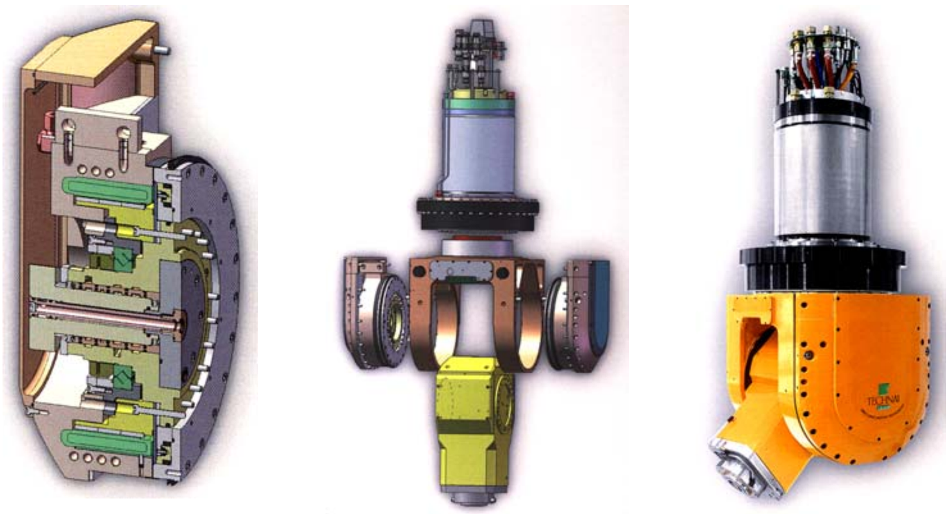

Fig. 2: *Applications torque motors in A-axis (coupled motors) and C-axis. (source [10], milling heads Technai)*

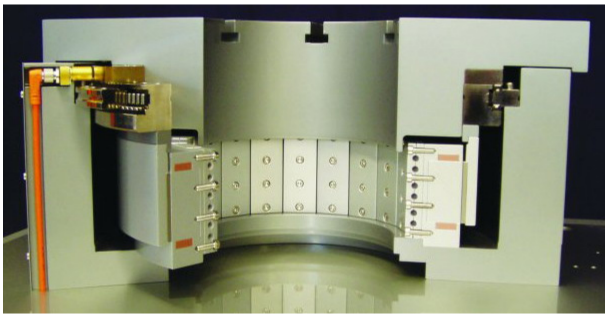

Fig. 3a: *Rotary tables equipped with torque motor [9]*

Fig. 3b: *Rotary table equipped with torque motors [10]*

2. Mechanism of cogging torque origination

Cogging is disturbing moment component, which try to align rotor permanent magnet with steel stator poles. Individual phases of cogging torque illustrate fig. 2 to fig. 5, (source [5]). For simplicity, the stator is considered as simple iron ring with rectangular poles and rotor is considered as a bar magnet.

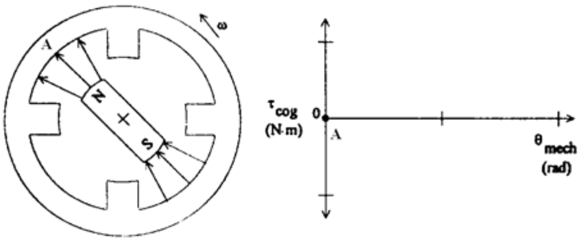

Fig. 4: *Position 'A', unstable equilibrium [5]*

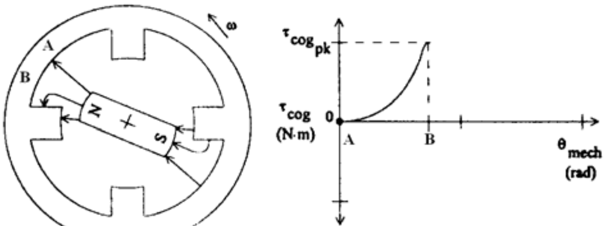

Fig. 5: *Position 'B', motor produces a torque [5]*

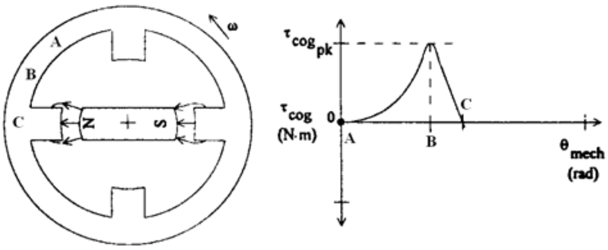

Fig. 6: *Position 'C', stable equilibrium [5]*

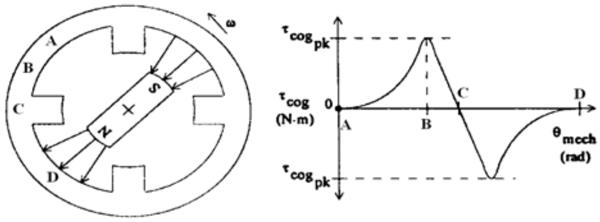

Fig. 7: *Position 'D', unstable equilibrium [5]*

Fig. 4 illustrate angular rotor displacement (position 'A'), where the bar magnet is in exact half between pole pitch. There is no torque, because the system is symmetric and magnetic fluxes (and inner moments) are balanced. System occupies a state of unstable equilibrium. Any slightest bar magnet angle deviation (position 'B', fig. 5) cause movement, because the magnetic flux starts to flow through the nearest iron pole (due to its lower magnetic resistance). Bar magnet tends to align with nearest stator pole and motor starts to produce reluctance torque - cogging. In fig. 6, the bar magnet is shown in aligned position with stator poles. Magnetic flux surrounding iron poles is symmetric, inner moments are balanced, and system occupies a state of stable equilibrium. Motor does not produce torque. If the rotor is deflected from the equilibrium by external torque, the bar magnet still tends to hold stable position. In order to allow further rotation of the rotor, the external torque must overcome the reluctance torque (in this step the reluctance torque has opposite polarity then in fig. 5). If the external torque overcome the reluctance torque, bar magnet could take a new unstable position or, in special case, new unstable equilibrium (fig. 7 analogous to fig. 4).

3. Cogging torque relationship

Surrounding around the air gap is thus a variable magnetic resistance, because there cycled steel poles carrying a winding with air gaps between the poles. Cogging - fluctuation in torque resulting from the transition of the rotor magnet poles through the steel stator poles. If a constant magnetic resistance along the air gap, the cogging torque is zero. According to [2], cogging torque depending on the rotor position and can be quantified as the additional (parasitic) component of the motor torque relationship

$$\tau_{cogg} = -\frac{1}{2}\Phi^2 \frac{dR}{d\Theta} \tag{1}$$

where:

τ_{cogg} [Nm] ...... cogging torque
Φ [Wb] ...... magnet flux crossing the air gap
R [A/Wb] ...... total reluctance through which the flux passes
θ [rad] ...... rotor angular position

Exact evaluation cogging torque τ_{cogg} using (1) depends on knowledge about the magnetic flux distribution along the air gap and around the motor poles. These depend on geometrical and material properties of motor parts. Unfortunately, these knowledge are very often unavailable due to the manufacturing secret. However, in practice the easiest way is to measure τ_{cogg}.

4. Available tools in reduction of cogging torque

Cogging suppression can be achieved by suitable design of the motor or by appropriate modification of motor control algorithm. The most common construction of motor modifications for the purpose of suppressing torque ripple are poles shape optimization, selection of the appropriate ratio of between the number of stator and rotor poles (misalignment between stator and rotor poles), skewing of stator poles, optimization of the air gap dimension, etc., for more detail see [2] and [5]. These ways lead to a constant distribution of the magnetic resistance around the air gap and thus to suppress cogging. These arrangements reduce the torque ripple, but also often reduce the torque (or forces respectively). The resulting motor design is a compromise between its accuracy and torque (or force respectively). The other way is to compensate cogging torque by usage appropriate compensative functions that provide some controlling systems (e.g. Heidenhain iTNC 530 or Fanuc in series 30i, 31i, 32i, 15i-B, 16i-B, 18i-B, 21i-B, 0i-B, 20i-B and Power Mate).

5. Research work

The aim of the research is to find a method to compensate cogging using compensation signal that can be add into the cascade control of PMSM. For easy applicability in machine-tool industry, the method must respect possibilities of commercial NC machine tool control systems. This research work is carrying out on laboratory experimental test-bed with permanent magnet synchronous motor (fig. 8). Key factors of the experimental test-bed approach to the properties of real rotary table. Due to the high moment of inertia of PMSM and negligible damping in the bearing, experimental test-bed can be considerate as a one-mass undamped system. For debugging of compensate method was created in Matlab-Simulink simulation model of a PMSM with its usual cascade control structure. This cascade control consists of three loops, the most subordinated current loop, superior speed loop and positional loop. Cogging of PMSM is add into this model in the form of a fault signal containing harmonic components related to the number of poles of stator and rotor. This signal is construct using measured current and speed irregularity of PMSM. Individual harmonic components of measured signal were obtain using the fast Fourier transform (FFT) algorithm. These components are also use for the calculation of additional current signals for compensation of cogging. Compensating signals were calculate for different rotational speeds and were stored in compensation table.

5.1 Arrangement of experimental test bed with torque motor

Fig. 8: *Arrangement of experimental test bed with torque motor ROL 530881D*

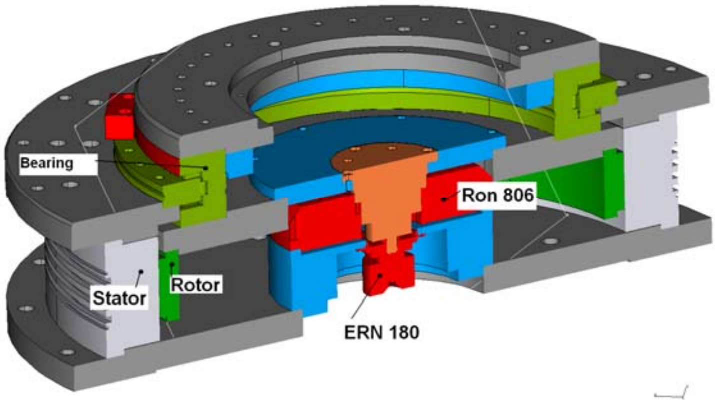

Fig. 9: *Cross-section of experimental test bed with torque motor ROL 530881D*

1 ...... experimental test bed with torque motor VUES ROL 530881D
2 ...... swichboard
3 ...... drive controller Baumuller BUS 6 VC
4 ...... analog inputs/outputs
4a ...... connecting board for analog inputs/outputs (drive controller)
5 ...... connecting block for analog inputs/outputs (AD card)
6 ...... serial communications connections (WinBASS / drive controller)
7 ...... encoder input
8 ...... PC with dSPACE 1104

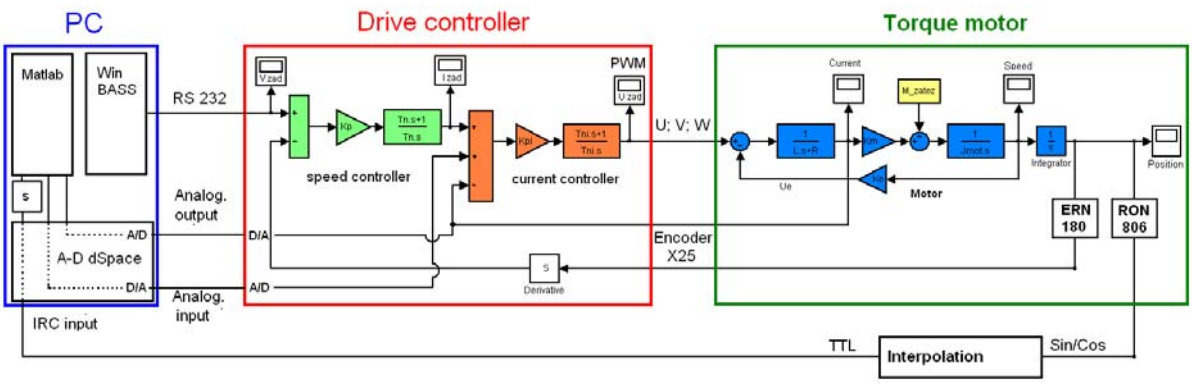

Fig. 10: *Arrangement of experimental test bed with torque motor - schematically*

5.2 Measured irregular movement of torque motor

Reluctance torque can not be measured directly, because common NC machine-tools are not equipped with torque sensor. Reluctance torque can be measured indirectly through the motor current or rotor velocity. Because of the high electromagnetic disturbance during measuring current, reluctance torque was measured indirectly through the irregular rotor velocity. Steady state rotor velocities were evaluated using Fast Fourier Transform (FFT) algorithm. As shown in fig. 11 to fig 13, the most significant influence on irregular rotor motion has harmonic component related to number of stator pole 96 and their second harmonic 192. Other significant harmonic components are related to the number of magnet poles. Compensation signal involve only these significant harmonic component.

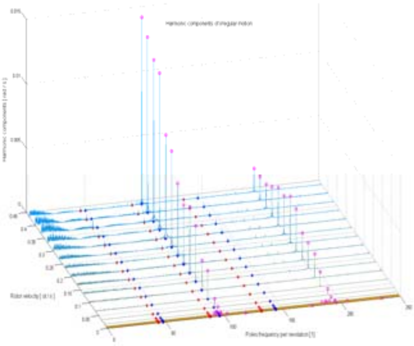

Fig. 11: *Harmonic components of irregular rotor velocities*

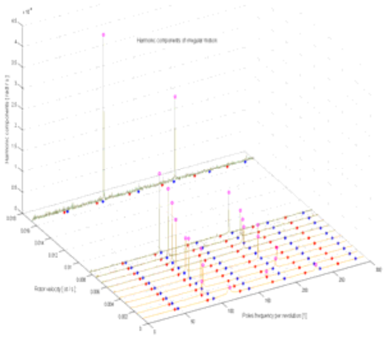

Fig. 12: *Harmonic components of irregular rotor velocities (detail)*

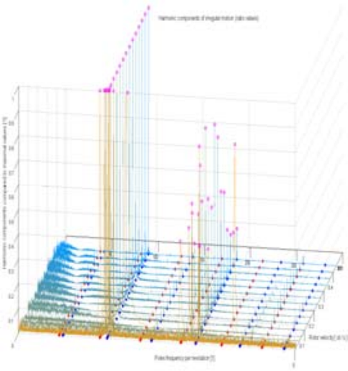

Fig. 13: *Harmonic components of irregular rotor velocities (ratio values)*

5.3 Simulation model

Simulation model for debugging of compensate method is created in Matlab-Simulink. Compared measured and simulated irregular velocities are in fig. 15. There were included only two harmonic components. Fig. 16 shows conformity between measured and simulated frequency response and step response of speed loop. Simulate model was also used for the calculation of additional current signals for compensation of cogging. Compensate signals were calculated for different rotational speeds and were stored in compensation table. As shown in fig. 17, by using the current compensation signal as additional signal in current control loop was achieved a significant reduction of amplitudes of harmonic components caused by cogging. During the experiments, there were extensive problems with electromagnetic disturbance. For good efficient of compensation method, the compensation signal must be correctly bring into phase actual rotor position. This can be guarantee by using reference pulse of feedback position sensor RON 806 and 'trigger' function in dSPACE. In despite of rigorous installation of electronic equipment (with emphasis on shielding), the problem with high electromagnetic disturbance persist and disable reliable reading of reference pulse. Other problem was relatively slow rate on analog inputs of drive controller. Next experiments will be carrying out using new drive controller Control Techniques. This drive controller is equipped with faster analog inputs and can be extend with optional programmable modules.

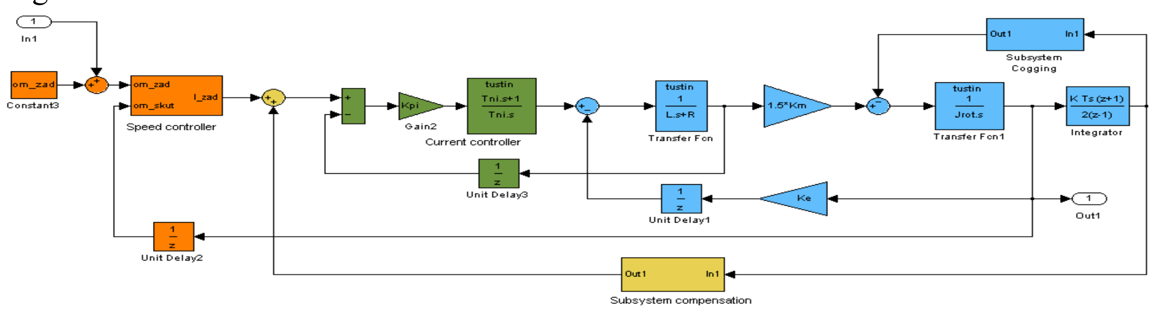

Fig. 14: *Simulation model of torque motor and its cascade control (cogging and compensation are included)*

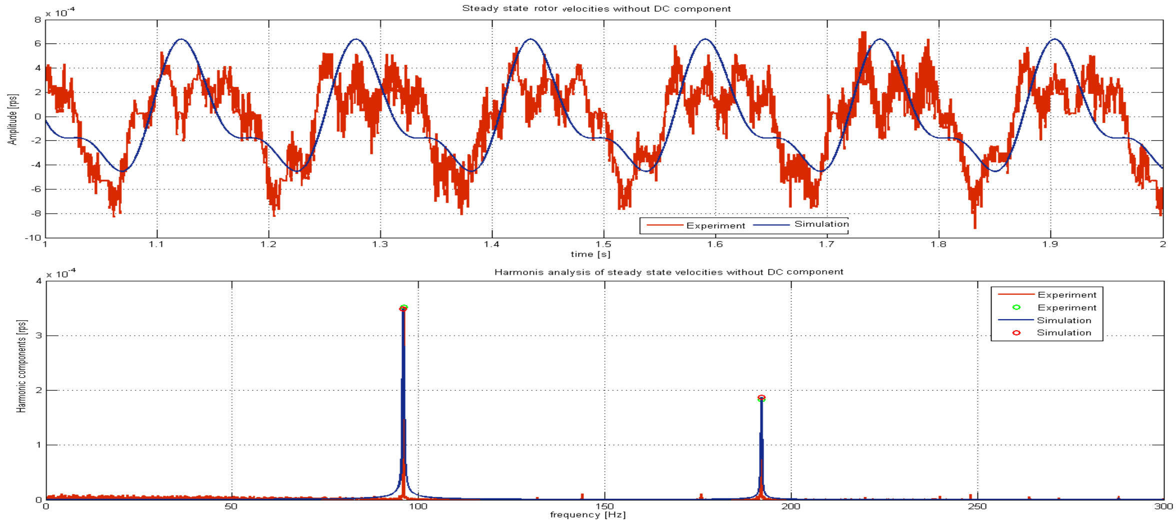

Fig. 15: *Comparison of measured and simulated irregular velocities*

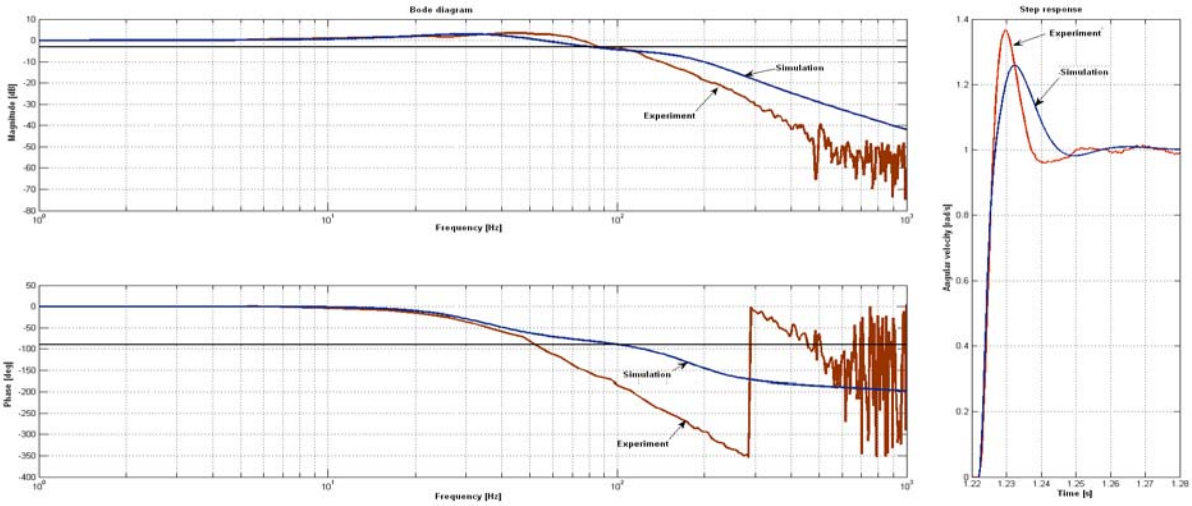

Fig. 16: *Comparison of measured and simulated responses*

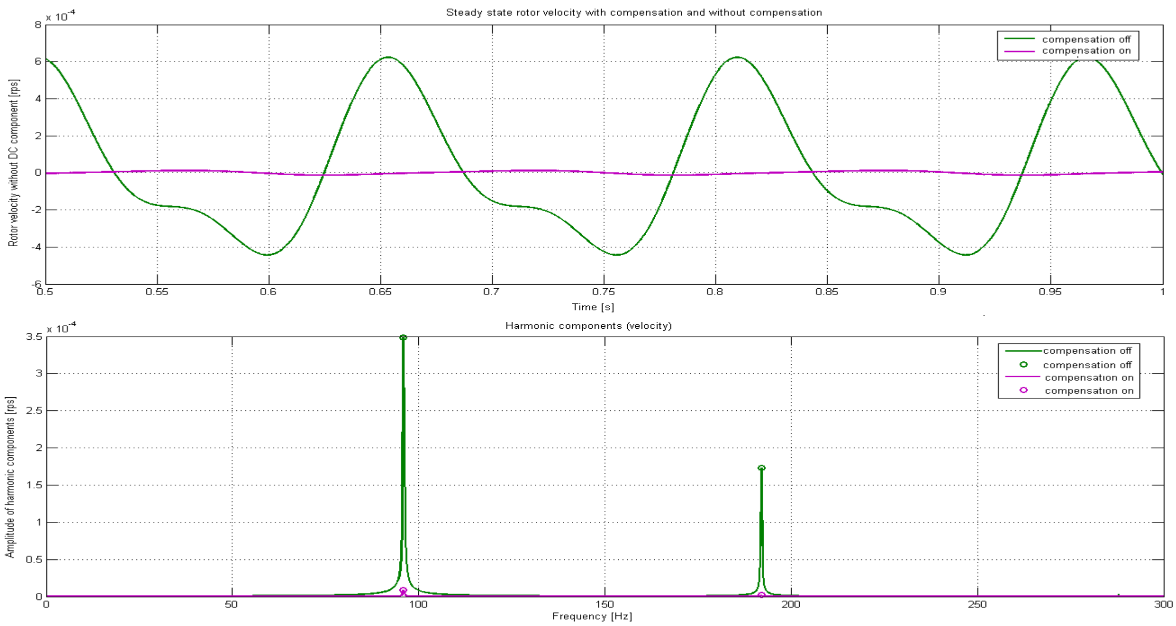

Fig. 17: *Illustration of compensation effect (simulation)*

6. Conclusion

For the purposes of modelling compensate method was created in Matlab – Simulink. Cogging torque (experimental acquired) was included. Measuring (response on testing signals) shown, that model well approximates reality. Simulation shows, that current compensation signal as additional signal in current control loop was achieved a significant reduction of amplitudes of harmonic components caused by cogging. Unfortunately, significant level of electromagnetic disturbance excluded verification of compensation method. Problem is solving by complete redesign electrical equipment and properly cable shielding. Now, the laboratorial equipment and software for the experimental verification of the chosen method are prepared.

List of symbols

τ_{cogg}	cogging torque	[Nm]
Φ	magnet flux crossing the air gap	[Wb]
R	total reluctance through which the flux passes	[A/Wb]
θ	rotor angular position	[rad]

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