Multifactorial determination of the electric drive for the force compensating manipulator

G Ya Pyatibratov and A A Danshina

Platov South-Russian State Polytechnic University (NPI), 132, Prosveschenia str., Novocherkassk, Rostov Region, 346428, Russia

E-mail: da.angela@mail.ru

Abstract. The methodology of multifactorial determination of rational parameters of transmission gear and synchronous electric motor driving by permanent magnets for the system of the vertical freight movement of the force compensating manipulator is offered. An integrated approach to the selection of the power part of this manipulator takes into account: motor speed matching and an executive mechanism of the manipulator, operation of the electric drive with a minimum possible value of the maximum torque at the movement of freight with constant speed and with acceleration at different values of the freight mass. A reasonable radius of mechanism activation is determined from accepted values with application of the compromise approach enabling to consider at the same time the performance of all limiting conditions. The electromechanical module of the manipulator is selected when a value of the activation radius provides the minimum possible required motor torque.

1. Introduction

Development of mechanization and automation means of various productions is meant to improve the manipulators serving them and robotic complexes. Nowadays, during automation of processes related to the transportation of various goods and freights, the balanced manipulators are widely used. The feature of these manipulators is compensation of links weight and load grippers by means of counter balance or springs that allows one to improve power indicators of the drive operation [1]. To increase efficiency of loading and unloading operations and the level of their automation, it is necessary to improve electromechanical systems of the long-range balanced manipulators [2]. The promising direction of improvement of manipulators and special load grippers is application of force compensating manipulators (FCM) implemented with the use of control systems of efforts which make it possible to perform the required compensation of gravity not only links, but also the freight moved by a worker [3]. Herewith, it is reasonable to assign solving of additional tasks to decrease the impact of inertia forces of transferring masses, dry and viscous friction of mechanisms to an electric drive (ED) [4].

The feature of the manipulators operation is a necessity to transport freights of various weights, which depends on the mass of the load gripper of manipulator \( \Delta m \) and freight \( m_0 \). Herewith, the minimum mass is defined by the mass of load grippers (hooks, electromagnetic, lever or pneumatic grippers and other devices) which can have the weight from 10 to 35% of the mass of the transferred freight. The maximum value of the weight is defined by the sum of masses \( \Delta m + m_0 \) of the load gripper and the mass of the transferred freight. According to the investigation, during design of power
efficient FCM, it is reasonable to apply synchronous electric motors activated by permanent magnets with nominal rotation speeds from 4000 to 6000 rpm. Herewith, the problem of determination of rational parameters of the FCM mechanism taking into account the main requirements, conditions and performance features is urgent. For the effective solution of this task, it is reasonable to apply the methodology of multifactorial determination of necessary parameters of the mechanism and ED.

The purpose of work is adaptation of a technique of the multi-factorial combined selection of rational parameters of FCM and ED mechanisms during speeds matching of motor and freight movement, value minimization of required maximum motor torque, implementation of motor alive standing with given loading moment.

2. Task description of the research
In order to improve power and mass-dimensional indicators of FCM, it is necessary to apply ED providing fulfillment of the contradictory requirements imposed on it. For this purpose, it is offered to solve a number of the interrelated assignments wholistically: to provide necessary movement parameters of the executive mechanism, to compensate freight weight and links of the manipulator, to decrease the impact of friction forces and the inertia of moving masses, to provide the required accuracy of efforts control of executive mechanisms, to improve mass-dimensional performances. By means of ED, it is possible to reduce oscillations and the dynamic efforts caused by elasticity of mechanical gears and constructions, to provide long maintenance and smooth change of torques considerable in value on the motor shaft in the mode of its standing alive. During design of FCM taking into account the listed assignments, it is necessary to select reasonably rational parameters of mechanisms and ED.

During the solving of multifactorial tasks, they are reduced to optimization of some single combined parameter [5]. When designing FCM as the combined parameter, it is offered to implement the required reduction radius that connects speed of motor rotation $\Omega_M$ and freight transferring $V_0$ with kinematic parameters of mechanical gears:

$$\rho_r = V_0 / \Omega_M = \frac{d_D}{(2i_p i_G)} = \frac{d_{GD}}{(2i_G)}$$

(1)

where $i_G$, $i_p$ – the gear ratio of the gearbox and the divisible factor of block and tackle; $d_D$, $d_{GD}$ – drum diameters in the rope drive or gear wheel in the rack and th gear drive.

Let us define acceptable values of reduction radius $\rho_{AV}$ providing coordination of movement speed of the executive mechanism and the motor; minimization of required maximum motor torque $M_M$ [6], transportation of various mass freight with maximum values of speed and acceleration [7].

3. Problem solving
We wil solve the task, based on the loading capacity of manipulator $m_0$ and parameters of the freight movement — speeds $V_0$ and acceleration $a_0$. Let us consider FCM of average loading capacity $m_0 = 150$ kg, which construction contains supplementary elements with mass $\Delta m = 15 – 50$ kg. Let us introduce a concept of an actual mass of transferred freight $m_A$ which, during the operation of FCM along with the executive mechanism in the form of the rope drive, can change from minimum value $m_{1A} = \Delta m = 15$ kg to maximum value $m_{2A} = \Delta m + m_0 = 200$ kg.

The analysis of papers [8-10] showed that in order to increase the productivity of the FCM operation, it is reasonable to have the maximum speed of freight movement equal to $V_0 = 0.5$ m/s. According to GOST 26057–84, the efforts, applied by the operator to freight, weighing up to 100 kg, should not exceed values $F_{E_{min}} = 50$ N, and weighing from 100 to 250 kg — should not exceed $F_{E_{max}} = 100$ N [11]. Taking into account these requirements, we will define possible maximum accelerations of the executive mechanism and freight:
According to the methodology presented in [5], let us define the motor capacity which provides prescribed acceleration $a_{\text{req}} = 0.5 \text{ m/s}^2$ at maximum speed $V_0 = 0.5 \text{ m/s}$ of freight movement with total weight $m_2 = \Delta m + m_0 = 200 \text{ kg}$:

$$P_{2R} = 2 k_S (\Delta m + m_0) V_0 (g + a_{\text{req}}) \frac{1}{\eta_M} = 2 \cdot 1.2 \cdot (50 + 150) \cdot 0.5 \cdot (9.81 + 0.5) \cdot \frac{1}{0.8} = 3.1 \text{ kW},$$

where $k_S = 1.2$ – the safety margin taking into account the possibility of noncoincidence of the actual reduction radius with the reduction radius providing minimum motor capacity; $g = 9.81 \text{ m/s}^2$ – the gravitational acceleration; $\eta_M = 0.8$ – the efficiency coefficient of the mechanism of the freight vertical movement system.

During the operation of FCM, the important requirement is to hold fixed hanging freight by means of ED. That is why, it is necessary to provide the mode of long standing of the motor alive at the maximum value of the steady load. According to the investigation among modern electric motors of alternating current, the synchronous motors 5DVM series produced in Russia have similar properties [12]. Selected for implementation of FCM, the high-speed motor of type 5DVM 115M has the following performance specifications: nominal capacity $P_N = 2.95 \text{ kW}$, nominal rotation speed $\Omega_N = 6000 \text{ rpm}$, nominal torque of motor shaft $M_N = 2.35 \text{ N\cdot m}$, accepted torque of long standing of the motor alive $M_0 = 4.7 \text{ N\cdot m}$, maximum torque on motor shaft $M_{M,\text{max}} = 11.75 \text{ N\cdot m}$ and inertia torque $J_M = 0.00074 \text{ kg\cdot m}^2$.

To solve the problem of multifactorial determination of the mechanism and ED CV, it is reasonable to accept reduction radius $\rho_R$ as a combined parameter [5]. To determine its rational values, we will review the impact of reduction radii which provide the required coordination of speeds of motor movement and freight $\rho_D$, define the minimum possible value of required maximum motor torque $\rho_M$, provide freight movement with constant speed $\rho_S$ and with acceleration $\rho_D$.

To solve the described problem, it is necessary to define the value of required reduction radius $\rho_R$ of the FCM mechanism which has to enter the range of its acceptable values $\rho_{AV}$ taking into account conditions and restrictions presented in Table 1.

| № | Requirement | Condition | Restriction |
|---|-------------|-----------|-------------|
| 1 | Movement speed approval of the freight and the motor | $\Omega_{MR} \geq V_0 / \rho$ | $\rho_R \geq \rho_D$ |
| 2 | Minimization of the required maximum motor torque | $M_M = M_S + M_D = \text{min}$ | $\rho_R = \rho_M$ |
| 3 | Moving of load at a constant speed; | $M_S > M_N$ | $\rho_R < \rho_S$ |
| 4 | Moving of load with acceleration | $M_{DS} = M_S + M_{DM} + M_{DL} < M_{M,\text{max}}$ | $\rho_R > \rho_D$ |

Generally, component parts of load torques depend on the direction, speed and acceleration of freight movement. During solving the described problem, it is necessary to define the greatest required
value of the motor torque which will be required for movement of freight with maximum speed and acceleration. Analytic forms for definition of motor load torques under various operating conditions of FCM can be found according to the following formulas:

\[ M_S = m_A g \rho (1 + f_{SF}) + f_{DF} V_0 \leq M_N , \]  
\[ M_{ST} = m_A g \rho (1 + f_{SF}) \leq M_0 , \]  
\[ M_{DS} = M_S + M_{DM} + M_{DL} < M_{M \text{ max}} . \]  

We will highlight a problem of multifactorial selection of the electric drive with application of the high-speed synchronous electric motor driven by permanent magnets of type 5DVM115M with the diagrams presented in Figure 1. In Table 1, in Figure 1 and in formulas (4) – (6), the following symbols are indicated: \( \Omega_{NB} \) – the required speed of the electric motor; \( M_S \) and \( M_D \) – static and dynamic load torques in the researched system; \( M_{ST} \) – the load torque in the mode of long standing of the motor alive; \( M_N \) – the rating torque of the electric motor; \( M_{DS} \) – the total maximum torque taking into account static and dynamic loads of the electric motor specified by inertia torques of motor \( J_m \) and gearbox \( J_G \): \( M_{DM} = (J_D + J_G) a_0 / \rho \) and freight weight \( M_{DL} = m_A a_0 \rho ; f_{SF} = 0.2 \) and \( f_{DF} = 0.05 \), which are the coefficients of static friction and movement. The reduction radii are: \( \rho_{SB} \) – takes into account the coordination of speeds of the motor and freight movement, \( \rho_M \) – provides a minimum value of the maximum motor torque, \( \rho_S \) – defines the motor torque during freight movement with constant speed \( \rho_D \) and with maximum acceleration, \( \rho_{AV} \) – the accepted range of required reduction radius \( \rho_{HR} \). In Figure 1, the following symbols are given: the index ‘1’ means freight weight \( m_{1A} = 50 \text{ kg} \), and the index ‘2’ is equal to freight weight \( m_{2A} = 200 \text{ kg} \).

In Figure 1, dashed lines show the limiting values of reduction radii of the FCM mechanism during application of the selected electric motor, as well as areas of their acceptable values at the minimum and maximum of the moved mass which comply with the conditions given in Table 1.

**Figure 1.** Definition of the required reduction radius of the FCM mechanism with the synchronous electric motor of type 5DVM115M.
4. Reviewing of obtained results
The review has revealed that conditions of long standing of the motor alive and during freight movement with constant speed of the considered electric motor during freight transferring are always fulfilled. Therefore, in Figure 1, motor torques and the reduction radii corresponding to them are not shown.

In case of transferring FCM of the freight of maximum weight $m_{2d} = 200$ kg, the comparison of the obtained limiting values of reduction radii showed that the acceptable range of acceptable values $\rho_{2A\Omega}$ is limited by coordination conditions of motor and freight speeds $\rho_\Omega = 0.8 \cdot 10^{-3}$ m and freight movement with constant speed $\rho_{2S} = 0.99 \cdot 10^{-3}$ m. Therefore, it is impossible to realize the ED and FCM executive mechanism with the motor of type 5DVM115M by the criterion of minimization of the required maximum motor torque equal to $M_{2M} = 2.14$ N·m because value $\rho_{2M} = 0.42 \cdot 10^{-3}$ m does not reach the range of acceptable values of reduction radius $\rho_{2A\Omega}$. In the reviewed example, when $\rho_M < \rho_\Omega$, the defining factor at the selection of rational value $\rho_R$ is the condition of coordination of motor and freight speeds. In this case, when $\rho_R = \rho_\Omega$, we will receive the minimum value of total motor torque $M_{R} = 2.5$ N·m. At the same time, it is possible to transport freight with accelerations $a_{01}$ and $a_{02}$. And the maximum value of the total torque of the motor during transportation of the freight with weight $m_{1d} = 50$ kg and acceleration $3.3$ m/s$^2$ will be 4 N·m; and with weight $m_{2d} = 200$ kg and acceleration $0.5$ m/s$^2$, the value of the torque will be 2.6 N·m that will be equal to 33% and 22% of the maximum acceptable motor torque, respectively.

5. Conclusion
Application of the methodology of the multifactorial selection of the electric drive and the mechanism of the force compensating manipulator with the synchronous electric motor of type 5DVM 115M allows making the following conclusions:

1. During development of FCM, the defining condition is specifying required reduction radius $\rho_R$ that in case of application of the high-speed motor enables the reduction of the radius of coordination of motor and freight $\rho_\Omega$ speeds to value $\rho_{2M}$ providing minimization of the required maximum motor torque.

2. In case of the given parameters of FCM, $\rho_{2M}$ does not reach the range of accepted values of reduction radius $\rho_{2A\Omega}$ that make it impossible to obtain the lowest required values of the motor torque, however the obtained value at $\rho_R = \rho_\Omega$ of the required torque is much less than the maximum accepted motor torque.

3. During development of advanced FCM, it is recommended to apply high-speed synchronous electric motors driven by permanent magnets that enables a decrease of the required capacity of the electric motor and the mass of the electromechanical unit.

Acknowledgments
The paper results are obtained with the support of project № 2878 ‘Theory development and implementation of electro-technical systems of simulators complexes and mobile objects’ executed within the framework of the basic part of state assignment № 2014/143.

References
[1] Vladov I L, Danilevskiy V N, Ionov P B and etc 1988 Balanced Manipulators (Moscow: Engineering)
[2] Sukhenko N A, Pyatibratov G Ya, Dashchina A A and Altunyan L L 2016 Prospective electromechanical control systems of industrial manipulator efforts IJPEDS 7(2) 416-21
[3] Sukhenko N A and Kravchenko O A 2003 *Rus. Electromech.* **5** 30-36

[4] Kravchenko O A, Pyatibratov G Ya, Sukhenko N A and Bekin A B 2013 *Un. News North-Caucasian Reg. Techn. Scienc. Ser.* **2** 32-35

[5] Pyatibratov G Ya, Danshina A A and Altunyan L L 2016 *The 2nd Int. Conf. on Ind. Eng. (ICIE)* vol 150, ed A A Radionov (Chelyabinsk: Procedia Engineering) pp 1403–09

[6] Myslivets N L and Sabinin Yu A 1975 *Unification Industrial Robots Actuator* (Leningrad:Electric Drive) **6(14)**

[7] Kochergin V V 1988 *Servo Systems with Direct Current Motor* (Leningrad: Energoatomizdat)

[8] Borovichi Experimental Engineering Plant 26.05.2016 Comparative table BEEP http://bomz.su/table/

[9] Gorbel 27.05.2016 Intelligent lifting devices g-force®/easy arm Gor. https://www.gorbel.com/Resources/products/intelligentassistdevices/gforce/documents/g-forcebrochure.pdf

[10] Knight Global Inc 27.05.2016 Ergonomic material handling systems KGI http://www.knight-ind.com/brochures/knight_global_product_catalog_web.pdf

[11] GOST 26057–841985 1985 *Balanced Manipulators General Specifications* (Moscow:Standartinform Publ)

[12] Electrical Company 05.04.2016 BLDC (synchronous) motors 5DVM series El. Equip. http://www.elmotor.ru/dvg1300.html