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# The Method for Control of the Energy Efficiency of Chain Transmissions

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**Abstract**
The paper suggests the method for control of the energy efficiency of chain transmissions, which is relatively easy to create. The developed method determines chain transmission performance by measuring the angular acceleration of the rotating masses during the speeding up of the chain drive. Based on the developed method, equipping an electric chain drive with a hardware and software system allows controlling the efficiency of chain transmissions in a wide range of speed and load operation modes of the chain drive. The method can be fully used for the study of chain transmission parameters influence on its performance and chain drive energy efficiency control during its production.

**Keywords:** Inertia, inertial diagnostics, Mechanical efficiency, Performance, Chain transmission

## Introduction

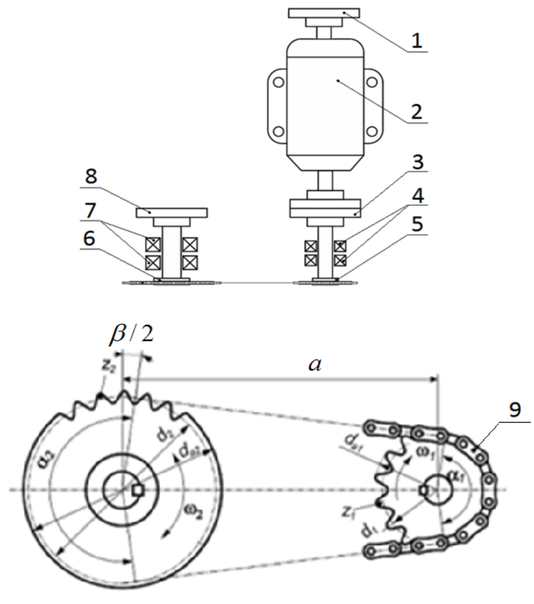
A comprehensive study of energy characteristics of chain transmissions in a wide range of speed and load operation modes is the basis for solving the problem of increasing the efficiency of chain drives. However, the majority of publications devoted to the study of chain transmissions [1-8] pay little attention to the matter of measuring their energy performance. Known methods and tools for the study of energy efficiency of chain transmissions do not allow to study most accurately mechanical losses in chain transmissions at most of speed and load operation modes, and their application is hindered by the complexity and costliness of measuring equipment [9-15]. The most commonly used method for this purpose is strain measurement, which requires a high accuracy signal measurement and calibration of strain gages. In addition, strain metering has relatively large discrecity, which is due to the time needed to restore strained state of the piezoresistor.

The present paper describes the method for control of the energy efficiency of chain transmissions in a wide range of speed and load operation modes. The developed method is free of the above limitations and determines the efficiency of chain transmissions by measuring the angular acceleration of the rotating masses during the speeding up of the chain drive.

The implementation of the method for control of the energy efficiency of an electric chain drive, which includes an induction motor and a chain transmission with parallel arrangement of the driving and driven shafts, is possible if based on the bench 'no brake' method for determining the moment of inertia of rotating masses of rotary motors.

## Materials and Method

Let us consider the implementation of the method in more detail. Figure 1 shows a diagram of a chain transmission driven by an induction motor.




1 – half-coupling for mounting a rotary body, 2 – induction motor, 3 – safety clutch of the induction motor, 4 – driving shaft support bearings, 5 - driving shaft with a driving chain-wheel, 6 - driven shaft with a driven chain-wheel, 7 – driven shaft support bearings, 8 – driven shaft half-coupling, 9 – chain

**Fig. 1. A diagram of a chain electric drive**

***The Moment of Inertia of a Chain***

Let us determine the moments of inertia of those chain parts, which are wrapped around the driving and driven chain-wheels, about the rotation axes of the respective chain-wheels. To do it, let us determine the value of the angle $\beta$:

$$\frac{\beta/2}{2}=\frac{\pi}{2}-\arccos\frac{d_2-d_1}{2a} \quad (1)$$

Where, $d_2$ is the diameter of the pitch circle of the driven chain-wheel, m; $d_1$ is the diameter of the pitch circle of the driving chain-wheel, m; $a$ is the distance between the centers of the driving and driven chain-wheels, m.

Wrap angle of the driving chain-wheel:

$$\alpha_1=\pi-\beta \quad (2)$$

Wrap angle of the driven chain-wheel:

$$\alpha_2=\pi+\beta \quad (3)$$

Driving chain-wheel wrap perimeter:

$$l_{\text{ch1}}=\alpha_1\frac{d_1}{2} \quad (4)$$

Driven chain-wheel wrap perimeter:

$$l_{\text{ch2}}=\alpha_2\frac{d_2}{2} \quad (5)$$

Knowing the specific weight of a length unit of chain $m_{ch}$ and the respective chain-wheel's pitch circle radius, we can determine the value of the moment of inertia of the chain parts wrapped around the driving and driven chain-wheels.

The moment of inertia of the chain part wrapped around the driving chain-wheel about its rotation axis:

$$J_{\text{ch1}}=m_{\text{ch}}l_{\text{ch1}}(\frac{d_1}{2})^2 \quad (6)$$

The moment of inertia of the chain part wrapped around the driven chain-wheel about its rotation axis:

$$J_{\text{ch2}}=m_{\text{ch}}l_{\text{ch2}}(\frac{d_2}{2})^2 \quad (7)$$

The total length of the chain is $L_{ch}$.

***The Moment of Inertia of the Chain Drive without Regard to the Moment of Inertia of the Chain Mesh Losses***

At the first stage, we determine the dependence of the moment of inertia on the electric motor shaft angular velocity. We determine the moment of inertia $J_1$ of the system of rotating masses of "half-coupling for mounting a rotary body 1, rotor of the induction motor 2, the induction motor bearing assemblies, safety clutch 3, driving shaft support bearings 4, driving shaft with a driving chain-wheel 5", taking into account friction losses in bearings.

Thereto, in accordance with Figure 2, we determine the dynamics of angular acceleration of the system of the rotating masses with a mounted on the driving shaft rotary body with a reference moment of inertia $\varepsilon_1(\omega)$, and then without it, $\varepsilon_2(\omega)$. Hypothesizing that the speed-torque characteristic of the electric motor remains constant at both of the motor accelerations other conditions being equal [16], the product of moments of inertia of the total of rotating masses and their angle accelerations during the first and the second accelerations can be equated to each another:

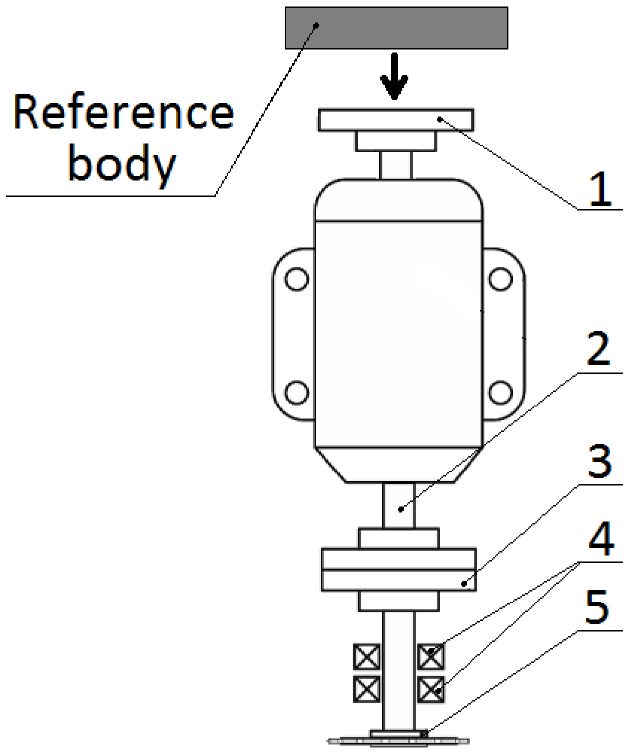



**Fig. 2. A diagram for determining the dependence of the moment of inertia of the system of rotating masses of "half-coupling for mounting a rotary body 1, rotor of the induction motor 2, the induction motor bearing assemblies, safety clutch 3, driving shaft support bearings 4, driving shaft with a driving chain-wheel 5" on the angle velocity of the electric motor shaft**

$$(J_{\text{ref}}+J_1(\omega))\cdot\varepsilon_1(\omega)=J_1(\omega)\cdot\varepsilon_2(\omega)^2 \quad (8)$$

Knowing the calculated or experimentally determined moment of inertia $J_{ref}$ of the reference body, based on the Eq. (8), we can find the dependence of the moment of inertia of the system of rotating masses under study, taking into account the friction losses in supports:

$$J_1(\omega)=\frac{J_{\text{ref}}\cdot\varepsilon_1(\omega)}{\varepsilon_2(\omega)-\varepsilon_1(\omega)} \quad (9)$$

Similarly, we define the moment of inertia $J_{im}$ of the rotating masses of "induction motor rotor, induction motor bearing assemblies, safety half-clutch". Then, having connected the induction motor to the driven shaft, we define the moment of inertia $J_{im2}$ of the rotating masses of "induction motor rotor, induction motor bearing assemblies, safety clutch, driven shaft with driven chain-wheel, driven shaft support bearings". With the known $J_{im}$ and $J_{im2}$, we can determine the dynamics of the moment of inertia of the rotating masses of "driven shaft safety half-clutch, driven shaft with driven wheel-chain, driven shaft support bearings":

$$J_2(\omega)=J_{\text{im2}}(\omega)-J_{\text{im}}(\omega)\,. \quad (10)$$

Based on the received data, we determine the moment of inertia $J_{\text{equiv}}(\omega)$ of all rotating masses of the electric drive according to the conventional methodology based on the law of conservation of energy. In this case, the moment of inertia is normalized with respect to the driving shaft rotation axis and the target value is defined without regard to the moment of inertia of the chain mesh losses:

$$J_{equiv}(\omega)\cdot\frac{\omega^2}{2}=(J_1(\omega)+J_{ch1})\cdot\frac{\omega^2}{2}+ \\ +(J_2(\omega)+J_{ch2})\cdot\frac{\omega^2}{2i^2}+E_{k1}+E_{k2} \quad (11)$$

Where, $E_{k1}=E_{k2}=\frac{L_{ch}-l_{ch1}-l_{ch2}}{2}\cdot m_{ch}\cdot\frac{\left(\omega\frac{d_1}{2}\right)^2}{2}$ is the kinetic energy of the driving and driven chain parts, respectively.

$$J_{equiv}(\omega)=J_1(\omega)+J_{ch1}+\frac{J_2(\omega)+J_{ch2}}{i^2}+ \\ +(L_{ch}-l_{ch1}-l_{ch2})\cdot m_{ch}\cdot\frac{d_1^2}{4} \quad (12)$$

Where, $i$ is the gear ratio of the chain transmission.

***The Moment of Inertia of the Chain Drive as an Assembly***

At the final stage, the chain transmission is fully assembled and the induction motor is connected to the driving shaft.

In accordance with Figure 3, we determine the dynamics of angular accelerations $\varepsilon_3$ (ω) of the whole electric drive, and the dynamics of the electric motor torque is defined in the following manner:

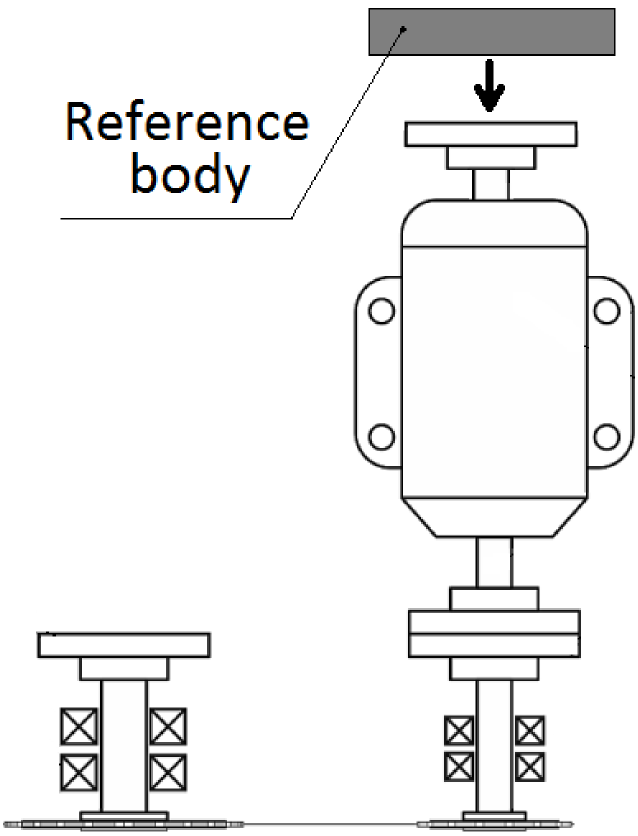



**Fig. 3. A diagram for determining the dependence of the moment of inertia of the chain electric drive on the angle velocity of the electric motor shaft**

$$M_{ChD}(\omega)=J_{ChD}(\omega)\cdot\varepsilon_3(\omega). \quad (13)$$

Where, $J_{ChD}(\omega)$ is the moment of inertia of the chain electric drive.

Then, we determine the dynamics of angular accelerations of rotating masses with the reference body $\varepsilon_4$ (ω) mounted on the driving shaft.

Whereas the speed-torque characteristic of the electric motor remains constant at both of the motor accelerations other condition being equal, the products of the moments of inertia and the angular accelerations at the first and the second accelerations can be equated to each other:

$$M_{ChD}(\omega)=(J_{ref}+J_{ChD}(\omega))\cdot\varepsilon_4(\omega)= \\ =J_{ChD}(\omega)\cdot\varepsilon_3(\omega) \quad (14)$$

From Eq. (14), we find the moment of inertia of the chain electric drive:

$$J_{ChD}(\omega)=\frac{J_{ref}\cdot\varepsilon_4(\omega)}{\varepsilon_3(\omega)-\varepsilon_4(\omega)}. \quad (15)$$

***The Chain Transmission Efficiency***

Based on the received values, we can define the dynamics of the moment of inertia of the chain mesh losses:

$$J_{chml}(\omega)=J_{ChD}(\omega)-J_{equiv}(\omega). \quad (16)$$

The dynamics of the chain transmission efficiency is defined at that as follows:

$$\eta(\omega)=\frac{P_{ChD}(\omega)-P_{chml}(\omega)}{P_{ChD}(\omega)}= \\ =\frac{M_{ChD}(\omega)\cdot\omega-M_{chml}(\omega)\cdot\omega}{M_{ChD}(\omega)\cdot\omega}= \\ =\frac{J_{ChD}(\omega)\cdot\varepsilon_3-J_{chml}(\omega)\cdot\varepsilon_3}{J_{ChD}(\omega)\cdot\varepsilon_3}= \\ =\frac{J_{ChD}(\omega)-J_{chml}(\omega)}{J_{ChD}(\omega)}=\frac{J_{equiv}(\omega)}{J_{ChD}(\omega)} \quad (17)$$

Where, $P_{ChD}(\omega)$ is the mechanical power of the chain drive; $P_{chml}(\omega)$ is the loss power in the chain mesh; $M_{chml}(\omega)$ is the brake torque in the chain mesh, which is induced by the resistance force in the chain.

It should be noted that the chain transmission efficiency is defined without regard to the friction force, which takes place in bearing assemblies of the chain transmission.

***The Instruments to Test the Applicability of the Developed Method***

In order to test the applicability of the developed method there was a test bench for chain transmissions investigation (Figure 4) assembled to determine the moment of inertia of rotating masses of the system during transitive operating modes (at the value of the angular acceleration being non zero).

The designed test bench consists of a single-phase asynchronous electric motor of power of 1100 W and rated speed of 940 rpm. The electric motor rotor shaft, through a coupling, is connected to the chain transmission driving shaft 5 with a driving chain-wheel (z = 23) assembled to it. The shaft, on which the loading flywheels 1 are mounted, is connected through a coupling to the shaft of a driven chain-wheel 3 (z = 38). Loading flywheels generate nominal force in active chain part. In order to determine the moment of inertia of the studied rotating masses system there were used wheels with reference moment of inertia 8, which can be freely removed and attached to the tail of the driving electric motor. In order to measure an angular acceleration there was used an encoder 9, which sends an analog signal corresponding by its dynamic range to the parameters measuring channel of a registration data unit 7. The personal computer with installed software 6 provides mathematical treatment of the data array and calculation of angular velocities and accelerations of the rotating motor. Based on the data of the angular accelerations obtained during the motor acceleration, both with a reference body and without it, the moment of inertia is computed.

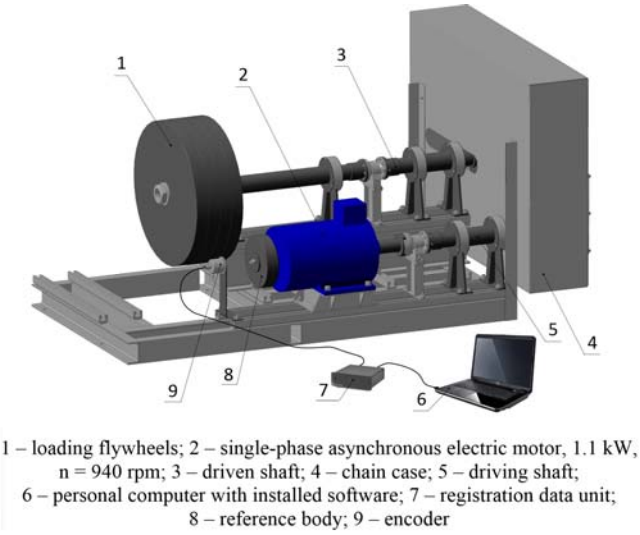



**Fig. 4. Chain Transmissions Test Bench**

Single-row drive sleeve chain with a pitch of 9.525 mm was selected as a test chain.
A reference body 8, having a known value of the moment of inertia, according to the developed method, is used to determine the moment of inertia of rotating masses system, the moment of inertia of losses in the chain transmission and the efficiency of the chain transmission.
To minimize the voltage fluctuation, which influences the measurement error, a voltage stabilizer Saturn SNE-O-10 (11 kW, 50 A) was used.

**Results**

***Experimental Substantiation of Reliability of Developed Method Measurements***

For the validation of the hypothesis that torque of certain induction motor is constant regardless of inertia mass adjoined to the motor shaft (other conditions being equal), which is the basis of the developed method, we carried out the following experiment:

1) we disconnected an electric motor from a driving shaft and determined the moment of inertia of rotating masses system ("electric motor rotor, rotating elements of motor bearing units", $J_{im}$) by the developed method;
2) we mounted an additional wheel with a known value of the moment of inertia onto the motor shaft and determined the moment of inertia of rotating masses system ("electric motor rotor, the rotating elements of motor bearing units, additional wheel with a known moment of inertia", $J_{im+}$), by the developed method;
3) we subtracted $J_{im}$ from $J_{im+}$ and got the required moment of inertia of an additional wheel $J_{add}$ and compared the obtained value with the calculated one – $J_{tv}$.

Table 1 shows average values of obtained moments of inertia and a fractional error for measurement of the moment of inertia of an additional wheel, using the developed method. At that $J_{tv}$ = 0.0110 kg·m$^2$ obtained by calculation is taken as a true value.

**TABLE 1. Determination of average value of moment of inertia for a rotary body with known value of moment of inertia using the developed method**

| **n, rpm** | **200-400** | **400-600** | **600-800** |
|---|---|---|---|
| $\overline{J_1}$, × 10$^{-4}$ *kg·m*$^2$ | 272.20 | 289.30 | 292.40 |
| $\overline{J_2}$, × 10$^{-4}$ *kg·m*$^2$ | 383.15 | 398.29 | 401.48 |
| $\overline{J_{add}}$, × 10$^{-4}$ *kg·m*$^2$ | 110.95 | 108.99 | 109.08 |
| $J_{tv}$ ×10$^{-4}$ *kg·m*$^2$ | 110.00 | 110.00 | 110.00 |
| Δ, ×10$^{-4}$ *kg·m*$^2$ | 0.95 | -1.09 | -0.98 |
| δ,% | 0.86 | -0.92 | -0.84 |

According to Table 1, there was the convergence of results obtained by the developed method and by calculation, with the maximum fractional error of 0.92%.

***Statistical Treatment of Experimental Data and Decision on the Chain Drive Performance Criteria***

According to the developed method for evaluation of chain transmissions efficiency for indication of the moment of inertia of rotating masses system it is necessary to measure an angular acceleration of the driving shaft with a reference body on it and without it. Thus, for the calculation of a systematic error of determination of the moment of inertia there were performed two series of experiments, consisting of 15 measurements of the angular acceleration each.
The fractional systematic error of the determined value of the moment of inertia is estimated as:

$$\delta J = \pm\sqrt{\left(\frac{\varepsilon_0}{\varepsilon_0-\varepsilon_{ref}}\cdot\delta\varepsilon_{ref}\right)^2+\left(\frac{\varepsilon_0}{\varepsilon_{ref}-\varepsilon_0}\cdot\delta\varepsilon_0\right)^2+\left(\delta J_{ref}\right)^2}. \quad (18)$$

Where, $\varepsilon_{ref}$ and $\varepsilon_0$ are the angular accelerations of the rotating masses with the reference body mounted on the driving shaft and without it, respectively; $\delta\varepsilon$ is the fractional systematic error of the angular acceleration measurement; $\delta J_{ref}$ is the fractional systematic error of the measurement of the reference body's moment of inertia.

Results of statistical treatment of the experimental data are presented in Table 2.

**TABLE 2. Determination of indirect measurement error**

| Value | Rotational Speed, rpm | | |
|---|---|---|---|
| | 200 - 400 | 400 - 600 | 600 - 800 |
| $\overline{\varepsilon_0}$, rad/s$^2$ | 46.833 | 71.445 | 107.494 |
| $\overline{\varepsilon_{ref}}$, rad/s$^2$ | 27.413 | 42.649 | 64.296 |
| $\overline{J_{ChD}}$, $kg{\cdot}m^2$ | 0.1341 | 0.1407 | 0.1414 |
| $\overline{J_{ref}}$, $kg{\cdot}m^2$ | 0.095 | 0.095 | 0.095 |
| $\delta\varepsilon_0$, % | 0.314 | 0.299 | 0.282 |
| $\delta\varepsilon_{ref}$, % | 0.372 | 0.329 | 0.254 |
| $\delta J_{ref}$, % | 0.1 | 0.1 | 0.1 |
| $\delta J_{ChD}$, % | 1.17823 | 1.10753 | 0.94969 |

In Table 2, we see that moment of inertia measurement error exceeds or close to 1 %. Since chain transmission performance is quite high (92 – 97 %) [17], the use of moment of inertia, which is indirectly determined value, as performance criteria for chain transmissions, is not practical.
Therefore, we offer to use direct determined value as a measure of chain transmission efficiency, which is drive acceleration time $t_{ChD}$.
At that, we transform Eq. (17):

$$\overline{\eta}(\omega) = \frac{\overline{J_{\text{equiv}}}}{\overline{J_{\text{ChD}}}} = \frac{\dfrac{\overline{M_{ChD}}}{\overline{\varepsilon_{equiv}}}}{\dfrac{\overline{M_{\text{ChD}}}}{\overline{\varepsilon_{ChD}}}} = \frac{\dfrac{\overline{M_{\text{ChD}}} \cdot t_{equiv}}{\omega_n - \omega_{n-1}}}{\dfrac{\overline{M_{\text{ChD}}} \cdot t_{ChD}}{\omega_n - \omega_{n-1}}} = \frac{t_{equiv}}{t_{ChD}}. \quad (19)$$

Where, $\overline{M_{\text{ChD}}}$ is the asynchronous chain drive torque, which is its constant characteristic; $(\omega_n - \omega_{n-1})$ is the difference between the finite and initial angular velocities of the drive shaft at chain drive acceleration period within chosen speed range; $t_{equiv}$ is the chain drive acceleration time regardless time needed to overcome friction losses within chosen speed range; it is calculated experimentally for a certain test bench and is its constant characteristic; $t_{ChD}$ is the chain drive acceleration time having regard to time needed to overcome friction losses within chosen speed range.
Chain drive acceleration time regardless time needed to overcome friction losses within chosen speed range is calculated:

$$t_{equiv} = \frac{(\omega_n - \omega_{n-1}) \cdot \overline{J_{equiv}}}{\overline{M_{ChD}}}. \quad (20)$$

***Justification of Applicability of the Developed Method for Chain Transmissions Research***

On the basis of the developed method and the technique described above, we determined the dependence of the average values of chain electric drive performance from the chain lubrication interval. According to Eq. (12), in order to get average values of efficiency for these chain electric drives, it was necessary to find the values of the moments of inertia for individual elements of rotating masses system. At that $J_{ref}$ was calculated, considering chain transmission gear ratio $i$ = 1.65. Tables 3 and 4 show the obtained values.

**TABLE 3. Obtained constant characteristics for the Assembled Test Bench**

| n, rpm | Average Values | | | | | | |
|---|---|---|---|---|---|---|---|
| | Moment of Inertia, × 10$^{-4}$ kg·m$^2$ | | | | | Time, s | Torque, N·m |
| | $\overline{J_1}$ | $\overline{J_2}$ | $J_{ch1}$ | $J_{ch2}$ | $\overline{J_{equiv}}$ | $\overline{t_{equiv}}$ | $\overline{M_{ChD}}$ |
| 200-400 | 272 | 2868 | 0.6 | 2.8 | 1331 | 0.443 | 6.28 |
| 400-600 | 289 | 2915 | 0.6 | 2.8 | 1365 | 0.284 | 10.06 |
| 600-800 | 292 | 2921 | 0.6 | 2.8 | 1371 | 0.188 | 15.20 |

**TABLE 4. Obtained Experimental Data**

| n, rpm | Average Values | | | |
|---|---|---|---|---|
| | 0 hours | 8 hours | 16 hours | 24 hours |
| | $\overline{\eta_{ChD}}$,% | $\overline{\eta_{ChD}}$,% | $\overline{\eta_{ChD}}$,% | $\overline{\eta_{ChD}}$,% |
| 200 – 400 | 97.2 | 95.4 | 93.5 | 91.8 |
| 400 – 600 | 96.5 | 93.8 | 92.7 | 91.1 |
| 600 – 800 | 96.2 | 93.2 | 92.5 | 91.0 |

**Discussion**

Experimental data obtained let us estimate results validity and the effectiveness of the introduced method. According to Table 1, there was the convergence of inertia moment values obtained by the developed method and by calculation, with the fractional error of less than 1%. These values are comparable to fractional error of measurement of chain electric drive inertia moment presented in Table 2. For reasons given, we can gather that the hypothesis that the speed-torque characteristic of the electric motor remains constant at both of the motor accelerations (with and without the reference body) when other conditions being equal is valid.
It is well known, that chain transmission efficiency is quite high and can reach 97%, and consequently, in that case efficiency control is not practical while fractional error of efficiency criteria measurement is more than 1%. Therefore, we offer to use the chain drive acceleration time as a performance criteria, at that measurement error is practically adds up to accidental error, which is within 0.25 and 0.40%. From our point of view, such level of error is practice-relevant during control and investigation of the chain transmission efficiency.
Measuring the chain drive acceleration time, we can monitor efficiency changes due to different operating conditions, as in the presented graphs (Figure 5) we can observe that chain drive efficiency changes due to change of lubrication interval.

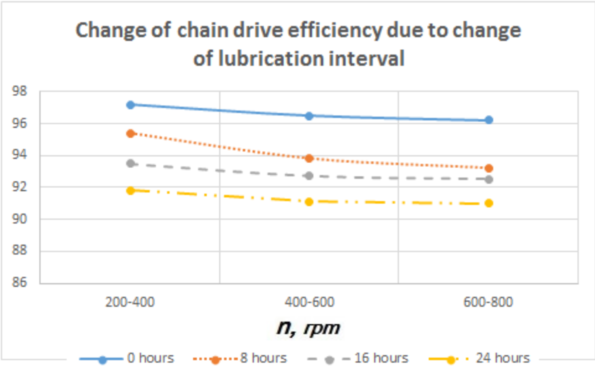



**Fig. 5. Change of chain drive efficiency due to change of lubrication interval**

Based on the obtained data we can conclude that the usage of the developed method for chain transmissions reflects a vivid picture of energy efficiency changing in mechanical systems, and it allows indicating the state of chains and an impact of individual factors on the efficiency of chain transmissions.

## Conclusion

Introduced method and technique for control of the energy efficiency of chain transmissions uses the acceleration time of asynchronous electric motor attached to the chain transmission as energy efficiency criterion. The acceleration time is influenced by amount of energy consumed to overcome friction forces in couplings of chain gear elements and is measured directly. Thus, accuracy of chain transmissions efficiency control and the rate of response to change of chain transmission efficiency when speeding up are considerably higher than using known methods. The developed method makes it possible to resolve the problem of determining friction losses in chain gearing itself, i.e. developed method for energy efficiency control makes it possible to determine chain transmission performance without taking into account friction loses in bearings of chain drive under study.

Therefore, having equipped the asynchronous electric motor with hardware and software system for registration of acceleration time and determination of the moment of inertia of a chain electric drive as well, you can easily measure the chain transmission performance and control the influence of individual factors on the energy efficiency of chain transmissions by identifying the acceleration time in a wide range of speed and load modes.

The developed method can find its application at plants manufacturing chains and chain drives. At the level of technical control department, having determined the tolerance for the acceleration time of asynchronous electric motor attached to the chain transmission under the study with the developed method, there is a possibility to control its energy efficiency that is influenced by assembling quality of chain gears, materials used and lubrication quality. It should be noted that the performance of chain transmissions is crucial characteristic of their energy perfection. It is a criterion of chain transmission working capacity and its reliability as friction condition impacts degradation processes rate, such as wear and back-to-back endurance, and therefore it effects chain transmission lifetime.

The developed method can be applied at plants manufacturing lubricants for chain drives as well. Study of factors influencing the chain transmission performance at different conditions and types of lubricants helps to improve their quality and to determine their use limit more accurately.

If to mention about the developed method further perspectives, it can be fully applied for control and study of belt, toothed, worm and other kinds of mechanical transmissions, which targets detection of change their energy performance.

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## References

[1] J.C. Conwell and G.E. Johnson, “Design, construction and instrumentation of a machine to measure tension and impact forces in roller chain drives,” Mechanism and Machine Theory, 31(4), pp. 525-531, 1996.

[2] J.C. Conwell and G.E. Johnson, “Experimental investigation of link tension and roller sprocket impact forces in roller chain drives,” Mechanism and Machine Theory, 31(4), pp. 533-544, 1996.

[3] J. Huo, S. Yu, J. Yang and T. Li, “Static and Dynamic Characteristics of the Chain Drive System of a Heavy Duty Apron Feeder,” The Open Mech. Eng. J., 7(2013), pp. 121-128, 2013.

[4] S.-P. Liu, K.W. Wang and S.I. Hayek, “Modeling and analysis of chain drive systems,” J. Acoust. Soc. Am., 87, pp. 136-S136, 1990.

[5] N. Srivastava and I. Haque, “A review on belt and chain continuously variable transmissions (CVT): Dynamics and control,” Mechanism and Machine Theory, 44(1), pp. 19-41, 2009.

[6] I. Troedsson, and L. Vedmar, “A Method to Determine the Static Load Distribution in a Chain Drive,” ASME J. Mech. Design, 121(3), pp. 402-408, 1999.

[7] E.V. Usova, “Povyshenie dolgovetshnosti i sovershenstvovaniye tekhnitsheskogo obsluzhivaniya tsepnykh peredatsh selskokhoziaystvennogo naznatsheniya,” (Unpublished Doctoral dissertation), Azov-Black Sea State agro engineering Academy, Zernograd, Russia, 2007.

[8] L. Zhang, C. Zhang, J.-H. Horng and Z. Chen, “Study on Simulation of the Chain Transmission Mechanism,” Advanced Materials Research, 593 (6), pp. 797-800, 2012.

[9] M. Doppelbauer, “Accuracy of the Determination Of Losses and Energy Efficiency of Induction Motors

by the Indirect Test Procedure," EEMODS, 2011, Washington, USA, 2011.

[10] A. Irimescu, L. Mihon and G. Pädure, "Automotive transmission efficiency measurement using a chassis dynamometer," Int. J. Automotive Technology, 12(4), pp. 555-559, 2011.

[11] M.M. Katsman, "Laboratornye raboty po elektritsheskim mashinam i elektroprivodu," Izdatelskiy centr "Akademia," Moscow, 2004.

[12] N.V. Mevsha, "Metody issledovaniya i otsenki tekhnicheskogo sostoyaniya tsepnykh peredatsh," (Unpublished master's thesis), Kuban State University of technology, Krasnodar, Russia, 2005.

[13] J. B. Spicer, "Effects of the Nonlinear Elastic Behavior of Bicycle Chain on Transmission Efficiency," J. Appl. Mech, 80(2), 2013.

[14] Spicer, J. B., C. J. K. Richardson, M. J. Ehrlich, J. R. Bernstein, M. Fukuda and M. Terada, 1999, "Effects of Frictional Loss on Bicycle Chain Drive Efficiency," J. Mech. Design, 123(4), pp. 598-605.

[15] J. B. Spicer, C. J. K. Richardson, M. J. Ehrlich, J. R. Bernstein, M. Fukuda and M. Terada, "On the efficiency of bicycle chain drives," Tech. J. of the IHPVA, 50(2000), pp. 3-9, 2000.

[16] Y.F. Arkhiptsev, "Assynkchronye elektrodvigateli," Energoatomizdat, Moscow, 1986.

[17] N.V. Vorobyev, "Tsepnye peredatshi," 4th Edn, Mashinostroeniye, Moscow, 1968.