Research of the impulse forces interaction in synchronous electromagnetic impact machines

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Abstract. The paper describes the process of the impulse forces interaction in the synchronous electromagnetic impact machines. The research issue is an actual one as it is necessary to estimate kinetic energy loss in mechanical systems of synchronous electromagnetic machines for accurate synthesis of mathematical models. The relationship between the kinetic energy transferred to deformed medium and kinetic energy returned to the mechanical oscillatory system is determined. The second one depends on deformed medium properties and the impact systems parameters. The new dependences reflecting the head bounce factor and the head initial velocity with kinetic energy loss on deformation and recovery of incomplete impacting volumes are established.

1. Introduction
The synchronous impact electromagnetic machines are applied in different industries and technological processes [1–5]. Tendencies of application of linear impact electromagnetic machines are considered in [6–9]. Synchronous impact electromagnetic machines have higher energy indicators [10, 11] than other ones. The impact mass oscillations frequency is multiple of power line frequency [10, 11].

The electromagnetic machine development and design methods are mainly based on static approaches [12–21] which are difficult for analysis and synthesis tasks. Static approaches are used because the dynamic design requires taking into account many factors including velocity, frequency, non-linearity of steel magnetic characteristics, power loss and other factors [22–27].

2. Problem statement
The analysis of the force impulses interaction for a partially elastic impact is important in the impact system simulation as additional kinetic energy loss takes place in the mechanical system [24].

If periodic impulses are generated, the motion of the striker impact mass is significantly influenced by the bounce factor and the striker velocity recovery factor. These factors describe the effectiveness of power transmission to deformed medium.

It is clear that if an impact is partially elastic, only a portion of the striker kinetic energy is transferred to the operating tool. A part of the striker kinetic energy returns to the mechanical oscillatory system during the striker reverse. The other part of kinetic energy is spent on deformation and heating of bodies during the impact and considered as additional power loss. An amount of energy transferred to deformed medium and energy returned to the mechanical system depends primarily on the mechanical system parameters of the impact electromagnetic machine.
Figure 1 contains the construction diagram of the electromagnetic impact unit with the head two-side free running-out [9].

Reciprocated motion of the head 1 appears as the result of its periodical interaction with the magnetic field of the coil 2. The travel of the head 1 is performed by the electromagnetic forces of the coil 1 and the elastic forces of the return spring 3. The reverse of the head 1 is caused by the electromagnetic forces of the coil 2 and partly by the head kinetic energy when the head is bouncing from the tool 4. The force impact impulse from the tool 4 is transferred to the deformed medium 6.

The cylinder head 1 and the magnetic core 5 with the coil 2 inside form the configuration of the electromagnetic motor magnetic system.

The coil 2 is powered from a 50 Hz single-phase voltage source through a half-period rectifier.

The impact unit total operating cycle takes two periods of the source voltage, providing the head impact synchronous frequency \( n_i \) and the operating cycle duration \( t_c \):

\[
n_i = \frac{60f}{2p} = 1500 \text{ min}^{-1}; \quad t_c = \frac{2p}{f} = 0.04 \text{ s},
\]

where \( 2p = 2 \) is the number of voltage periods during the operating cycle.

The operating cycle with the head two-side free running-out is implemented by the single coil which provides the acceleration of the head impact mass by electromagnetic forces in both directions.

![Figure 1](image1.png)

**Figure 1.** Electromechanical vibratory impact system with electromagnetic excitation.

![Figure 2](image2.png)

**Figure 2.** Synchronous impact electromagnetic machine with inertial striker reverse.

The head is freely running out when there is a pause between current pulses. The running down head alternates the direction of the spring squeezing and the operating tool impact [9].

The construction diagram of the two-coil synchronous electromagnetic machine with inertial striker reverse is presented in figure 2 [11].
The operating process is implemented by the system of the travel coil 1 and the reverse coil 2 in the removable stator with the magnetic core sections 3, 4. The coils accelerate the striker 5 by electromagnetic forces in both directions. The striker periodically interacts with the operating tool 6 and the massive inertial actuator 7. The massive inertial actuator stops the striker and accelerates its reverse. If the striker impacts the inertial actuator, the impact energy exchange takes place that additionally accelerates the striker. A part of the kinetic energy is converted to the potential energy when the spring 8 is squeezed. Other part of the kinetic energy is spent on impact body deformation.

After the impact, the striker is accelerated towards the operating tool by electromagnetic forces of the reverse coil. Then the cycle repeats.

The impact unit operating cycle corresponds to one voltage period providing the impact impulses synchronous frequency $n_{im}$ and the operating cycle duration $t_c$:

$$n_{im} = \frac{60}{2p} f = 3000 \text{ impacts/min}, \quad t_c = \frac{2p}{f} = 0.02 \text{ s},$$

where $2p = 1$ is the number of voltage periods per operating cycle, $f$ is the power line frequency.

The impact unit produces work if the striker motion is completely synchronized with the voltage impulses applied to the system of coils.

3. Theory

The effectiveness of energy transfer to deformed medium and influence of the electromechanical oscillatory impact system on energy transfer are analyzed with the design scheme of the impact interaction between the striker and the operating tool presented in figure 3. The impact interaction between the striker and the inertial actuator is shown in figure 4.

![Figure 3: Design diagram of the impact interaction between the head and the tool.](image1)

![Figure 4: Design scheme of the interaction between the striker and the inertial actuator.](image2)

With respect to material elastic and dissipative properties it is supposed, that bodies physical properties are changed by an impact because of deformation and incomplete volume recovery.

The direct central impact of two bodies consists of two steps: before the impact and after it. Such process division allows deriving the expressions for the head and tool mass centers velocities after the partially elastic impact:

$$\begin{align*}
\bar{v}_1 &= \bar{v} + k_r (\bar{v} - \bar{v}_1), \\
\bar{v}_2 &= \bar{v} + k_r (\bar{v} - \bar{v}_2),
\end{align*}$$

where $\bar{v}_1, \bar{v}_2$ are correspondingly the head and tool mass centers velocities before the impact; $\bar{v}_1, \bar{v}_2$ - are correspondingly the head and tool mass centers velocities after the impact; $\bar{v}$ is the velocity of the mass center if the impact is perfectly inelastic; $k_r$ is the velocity recovery factor.

With respect to the momentum conservation law the mass center velocity for the perfectly inelastic impact is:
\[
\bar{v} = \frac{m_1 v_1 + m_2 v_2}{m_1 + m_2}.
\]  

(2)

If it is assumed that the tool velocity \( v_2 \approx 0 \) at the impact moment, then with respect to (1) and (2), the head and tool mass center velocity after the impact is:

\[
\begin{align*}
\bar{v}_1 &= v_1 - \frac{m_2}{m_1 + m_2} \left( \frac{m_k}{m} - k_i \right), \\
\bar{v}_2 &= v_1 - \frac{m_1}{m_1 + m_2} \left( 1 + k_i \right).
\end{align*}
\]

The impact causes the head reverse. Hence the head bouncing from the tool has the velocity \( \bar{v}_1 \leq 0 \).

The head bouncing factor is a function of the impact system parameters with respect to the velocity sign:

\[
k_b = \frac{-\bar{v}_1}{v_1} = \frac{m_2}{m_1 + m_2} \left( k_i - \frac{m_1}{m_2} \right).
\]

The influence of the parameters of the impact system with the kinetic energy loss on deformation is described by the function \( k_b = f \left( \frac{m_1}{m_1}, k_i \right) \) plotted in figure 5.

The plot shows the head velocity after the impact (bouncing velocity) relative to the head velocity before the impact.

When the head is bouncing, the kinetic energy returned to the mechanical system is:

\[
T_1 = \frac{m_1 \bar{v}_1^2}{2} = \frac{m_1 v_1^2}{2} \left[ \frac{m_2}{m_1 + m_2} \left( k_i - \frac{m_1}{m_2} \right) \right]^2.
\]

The effective work produced by the electromagnetic motor is impulsive. If the recovery factor is constant, it can be estimated through the head kinetic energy transferred to the tool during the impact by:

\[
T_2 = \frac{m_2 \bar{v}_2^2}{2} = \frac{m_2 v_1^2}{2} \left[ \frac{m_1}{m_1 + m_2} \left( 1 + k_i \right) \right]^2.
\]

The kinetic energy loss during the impact is:

\[
\Delta T = T - T_1 - T_2 = \frac{m_2 v_1^2}{2} \left[ 1 - k_b - \frac{m_1 m_2}{(m_1 + m_2)^2} \left( 1 + k_i \right)^2 \right],
\]

where \( T = \frac{m_1 v_1^2}{2} \) is the head kinetic energy before the impact.

The impact energy efficiency with respect to the kinetic energy loss on deformation is:

\[
k_e = \frac{T - T_1}{T} = 1 - \frac{m_2}{m_1 + m_2} \left( k_i - \frac{m_1}{m_2} \right)^2.
\]

The function \( k_e = f \left( \frac{m_1}{m_2}, k_i \right) \) describing the amount of energy transferred to the deformed medium relative to the total head kinetic energy over the operating cycle is stated in figure 6.
Figure 5. Bouncing factor function
\[ k_b = f \left( \frac{m_i}{m_1}, k_e \right) \]

When the impact energy exchange takes place and the elastic unit is squeezed, the kinetic energy of the inertial mass \( m_3 \) is transformed to the potential energy. Then the potential energy is transformed to the reverse kinetic energy (Figure 6).

The mass centers velocities projections at the end of a partially elastic impact (Figure 6) are:
\[ \vec{v}_1 = \vec{v} + k_e (\vec{v} - \vec{v}_1) = \vec{v} (1 + k_e) - k_e \vec{v}_1; \]
\[ \vec{v}_3 = \vec{v} + k_e (\vec{v} - \vec{v}_3) = \vec{v} (1 + k_e) - k_e \vec{v}_3, \]

where \( \vec{v}_1, \vec{v}_3 \) are the velocities of the striker mass center and the inertial actuator at the start of an impact; \( \vec{v}_1, \vec{v}_3 \) are the velocities of the striker mass center and the inertial actuator at the end of an elastic strike; \( \vec{v} \) is the mass center total velocity of the completely non-elastic impact; \( k_e \) is the velocity recovery factor (\( 0 \leq k_e \leq 1 \)).

The mass center total velocity projection for the absolutely non-elastic impact is:
\[ \vec{v} = \frac{m_1 \vec{v}_1 + m_3 \vec{v}_3}{m_1 + m_3}. \]

The solution of the equations (3), (4) and (5) gives the projections of mass center velocity at the end of the elastic impact through the velocities at the start of the impact:
\[ \vec{v}_1 = \vec{v}_1 - (1 + k_e) \frac{m_3}{m_1 + m_3} (\vec{v}_1 - \vec{v}_3), \]
\[ \vec{v}_3 = \vec{v}_3 + (1 + k_e) \frac{m_1}{m_1 + m_3} (\vec{v}_1 - \vec{v}_3). \]

The impact impulse of the bodies’ interaction over the elastic impact period can be expressed as:
\[ S_2 = S_1 + S_u = (1 + k_e) S_1. \]
where $I_{S}$ is the impact impulse of the impact first phase, corresponding to the maximal bodies deformation, $I_{S''}$ is the impact impulse of the second phase, $k_{i} = \frac{S_{ii}}{S_{i}}$.

With respect to the impulse-momentum theorem, the impact impulses for the impact first phase are:

$$\begin{align*}
    m_{1}(\bar{v} - v_{1}) &= -S_{i}, \\
    m_{2}(\bar{v} - v_{2}) &= S_{i}.
\end{align*}$$

The impact impulse for each impacting mass (Figure 6) based on (5), (8) and (9) is:

$$S_{z} = (1 + k_{i}) \frac{m_{1}m_{3}}{m_{1} + m_{3}}(v_{1} - v_{3}).$$

The average values of impulses caused by the forces interaction between the striker and the inertial actuator at the end of the elastic impact are:

$$N_{i} = \frac{m_{1}\bar{v}_{i}}{v_{1}}, \quad N_{i} = \frac{m_{3}\bar{v}_{3}}{v_{3}}.$$  

The accumulated kinetic energy of the striker during the impact energy exchange is important for energy transformation. With respect to (6) and inertial masses motion in the opposite phase the striker kinetic energy at the end of the elastic impact depending on velocity projections is:

$$T_{z} = \frac{m_{1}}{2} \left[ v_{1} - (1 + k_{i}) \frac{m_{3}}{m_{1} + m_{3}}(v_{1} + v_{3}) \right]^{2}.$$  

It is possible to express the ratio of the striker kinetic energy at the end of the elastic impact to the kinetic energy at the impact start from the last equation as:

$$\frac{\bar{T}_{i}}{T_{1}} = \left[ 1 - \left( 1 + k_{i} \right) \left( 1 + \frac{v_{3}}{v_{1}} \right) \right]^{2},$$

where $T_{i} = \frac{m_{1}v_{i}^{2}}{2}$ is the striker kinetic energy at the impact start.

With respect to (10) the influence of parameters of the impact system with the kinetic energy loss on deformation for $k_{i} = 0.9$ is shown on the diagram in Figure 7.

As the energy conservation law is not valid for the impact of partially elastic bodies because of deformation kept after an impact, the kinetic energy loss is:

$$\Delta T = \left[ \frac{m_{1}v_{i}^{2}}{2} + \frac{m_{3}v_{3}^{2}}{2} \right] - \left[ \frac{m_{1}\bar{v}_{i}^{2}}{2} + \frac{m_{3}\bar{v}_{3}^{2}}{2} \right],$$

where the first two terms describe the impact masses kinetic energy at the impact start and other two terms describe the impact masses kinetic energy at the end of the impact.

Substitution of (4) and (5) to (9) with following transformations gives the impact bodies kinetic energy loss expressed by velocities at the impact start:

$$\Delta T = (1 - k_{i}^{2}) \frac{m_{1}m_{3}(v_{1} - v_{3})^{2}}{2(m_{1} + m_{3})}. $$
Figure 7. Ratio of striker kinetic energies for impact energy exchange.

Figure 8. Kinetic energy loss on bodies deformation.

Transformation of (12) to dimensionless values of the impact masses kinetic energy and velocities projection gives

$$\Delta T^* = \left(1 - k_i^2\right)^2 \left( \frac{1 + \frac{v_2}{v_1}}{m_1 + 1} \right)^2 \left( \frac{m_3}{m_3 + \frac{v_3}{v_1}} \right).$$

(13)

The kinetic energy loss on the bodies deformation for $k_i = 0.9$ is shown in figure 8.

4. Discussion of results and conclusion

The simplification of the equations for electromechanical impact system parameters limits capabilities of the exact dynamical analysis and synthesis of such systems only in transient modes with respect to kinetic energy loss.

The dependences reflecting parameters of the impact system with the kinetic energy loss on deformation and incomplete volume recovery are established.

References

[1] Usanov K M, Moshkin V I and Ugarov G G 2006 Linear Impulse Electromagnetic Drive of Machines with Self-Contained Power Supplies (Kurgan: KSU) p 284

[2] Zhuravlyov Y N, Mateевич S G and Kochevin F G 1998 Low-frequency electrodynamic vibrator with magnetically suspended movable part The 4th Int. Conf. on Motion and Vibration Control (Zurich) vol 3 pp 1063–1067

[3] Simonov B F, Serdyukov S V and Cherednikov E N 1996 Results of research and field work on the rose-oil sheniyu vibroseis method Oil Industry [in Russian – Neftyanoe Choziaystvo] 48

[4] Oparin V N and Simonov B F 2010 Nonlinear deformation-wave processes in the vibrational oil geotechnologies J. Min. Sci+ 46 95–112
[5] Sattarov R R and Ismagilov F R 2010 Research of vibro-impact mode of reactive electromechanical actuators Proc. of Institutions of Higher Education. Electromechanics [in Russian – Izvestiya Vysshikh Uchebnich Zavedeni. Electromekhanika] 23–27

[6] Ryashentsev N P, Ugarov G G and Lvitsin A B 1989 Electromagnetic Presses (Novosibirsk: Science) p 216

[7] Kuchankov S N and Timoshenko E M 1998 Nonsteady thermal conditions of electromagnetic motors in shock-type equipment J. Min. Sci+ 34(2) 148–152

[8] Ivashin V V and Pevchev V P 2012 Electromagnetic drive for impulse and vibro-impulse processes Proc. of Institutions of Higher Education. Electromechanics [in Russian – Izvestiya Vysshikh Uchebnich Zavedeni. Electromekhanika] 1 72–75

[9] Ryashentsev N P, Timoshenko E M and Frolov A V 1970 Theory, Calculation and Design of Electromagnetic Impact Machines (Novosibirsk: Science) p 260

[10] Neyman L A, Neyman V Yu and Shabanov A S 2017 Vibration dynamics of an electromagnetic drive with a half-period rectifier The 18th Int. Conf. of Young Specialists on Micro/Nanotechnologies and Electron Devices (Novosibirsk: NSTU) pp 503–506

[11] Neyman L A, Neyman V Yu and Obukhov K A 2017 New method of the synchronous vibratory electromagnetic machine mechatronic module control The 18th Int. Conf. of Young Specialists on Micro/Nanotechnologies and Electron Devices (Novosibirsk: NSTU) pp 516–519

[12] Pevchev V P 2009 Principal dimensions of the short-stroke electromagnetic motor for a seismic wave generator J. Min. Sci+ 45 372–381

[13] Gordon A V and Slivinskaya A G 1960 DC Electromagnets (Moscow Leningrad: Gosenergoizdat) p 447

[14] Kazakov L A 1978 Electromagnetic Units of Radio Electronic Equipment (Moscow: Soviet radio) p 187

[15] Simonov B F, Neyman V Yu and Shabanov A S 2017 New conception of an electromagnetic drive for a vibration source in hole The 18th Int. Conf. of Young Specialists on Micro/Nanotechnologies and Electron Devices (Novosibirsk: NSTU) pp 507–510

[16] Tatevosyan A A and Tatevosyan A S 2014 Calculation of magnetic system of the magnetoelectric machines Proc. Dynamics of Systems, Mechanisms and Machines (Dynamics 2014) 7005698

[17] Chen H S and Tsai M C 2008 Design considerations of electromagnetic force in a direct drive permanent magnet brushless motor J. Appl. Phys. 103 07F117

[18] Tatevosyan A A and Tatevosyan A S 2014 Calculation of optimal parameters of electromagnetic vibratory drive Proc. of Tomsk Polytechnic University 325 121–132

[19] Ryashentsev N P and Ryashentsev V N 1985 Electromagnetic Drive of Linear Machines (Novosibirsk: Science) p 153

[20] Malov A T et al 1979 Electromagnetic Hammers (Novosibirsk: Science) p 269

[21] Pevchev V P 2010 The use of Micro-CAP software to simulate operating processes of electromechanical impulse devices Russian Electrical Engineering 81(4) 213–216

[22] Neyman L A, Neyman V Yu and Shabanov A S 2016 Simulation of processes in an electromagnetic converter with energy loss in the massive magnetic core The 17th Int. Conf. of Young Specialists on Micro/Nanotechnologies and Electron Devices (Novosibirsk: NSTU) pp 522–525

[23] Neyman L A and Neyman V Yu 2016 Dynamic model of a vibratory electromechanical system with spring linkage 11th Int. Forum on Strategic Technology (Novosibirsk: NSTU) Pt. 2 pp 23–27

[24] Manzhosov V K et al 1985 Dynamics and Synthesis of Electromagnetic Generators of Power Pulses (Frunze: Ilim) p 119

[25] Usanov K M et al 2017 Strike action electromagnetic machine for immersion of rod elements into ground IOP C. Ser.: Earth Env. 032050
[26] Moshkin V I et al 2014 Mathematical simulation of electromagnetic pulse linear motors Conf. Proc. 2014 Int. Conf. on Actual Problems of Electron Devices Engineering (APEDE 2014) pp 348–352

[27] Tatevosyan A S, Tatevosyan A A and Zaharova N V 2018 Calculation of non-stationary magnetic field of the polarized electromagnet with the external attracted anchor J. Phys.: Conf. Ser. (Mechanical Science and Technology Update MSTU 2018) 012086