Control of a reversible electric machine included in the vehicle suspension

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Abstract. The relevance of the work is due to the constantly growing requirements for the ride comfort of automobiles. The purpose of the study is a rational choice and combination of principles for constructing an algorithm for controlling an electric machine, replacing a hydraulic damper in the design of a vehicle's suspension system. The study of the behavior of suspension, depending on the applied control algorithms, was carried out by the method of mathematical modeling. In this work, the control of the suspension of one wheel was considered. The angular and longitudinal oscillations of the body were not the subject of this study. In this regard, the applied design scheme is two-mass. The positive and negative aspects of various principles for calculating the target force generated by an electric machine are considered, and an algorithm for calculating the magnetic flux and armature current of an electric machine necessary for the implementation of the target force under various conditions is developed. It is shown that the calculation of the target force should be based on a combination of several principles, since this allows significant expanding of the suspension operating conditions range.

1. Introduction
Due to the high competition among high-class cars, the requirements for the level of properties affected by the car's suspension system are constantly growing. Existing solutions in this area gradually exhaust their potential, and there is a need to introduce new solutions. One of the promising areas is the use of an electric machine instead of a hydraulic damper [1–4]. This opens up a wide range of possibilities for controlling the suspension, because in addition to dissipative forces, it is possible to create active ones. It is possible to use such system to counteract rolls, as well as to isolate the sprung part from disturbances from road irregularities.

The latter option requires the most dynamic control, large and rapidly changing currents in the windings of the electric machine. The purpose of this study is to develop a control algorithm that implements this option.

2. Problem statement
In this paper, we abstract from the problem of counteracting the roll of the body and focus on the problem of isolating the sprung part from disturbances from road irregularities. The design scheme for which arguments, calculations and graphs will be given is two mass (Figure 1). A detailed description and justification of the mathematical model is given in [5].
When controlling a reversible electric machine that replaces the damper in the suspension system, the following tasks must be solved:

- Determination of the force to be generated by the electric machine;
- Automatic selection of the operating mode of the electric machine (engine or generator);
- Calculation of the control action on the electric machine, which will result in the desired force.

3. Results

The main issue when drawing up an active suspension control algorithm is determining the principles on which the calculation of the target force that an electric machine should create will be based. We call the force a target force, because it will not always be possible to implement it due to the limitations imposed by the system's capabilities.

In foreign studies [3, 6] the skyhook control is often applied. It is the principle of active suspension control, which simulates the connection of the sprung part through a damper with a point fixed in the vertical direction in space. The target force of the damper is calculated using the feedback principle based on the absolute vertical velocity of the sprung part (1).

\[
F_{skh} = k_{skh} V_{body}
\]

Where:
- \(F_{skh}\) - force generated by the damper;
- \(k_{skh}\) - feedback coefficient;
- \(V_{body}\) - absolute vertical speed of the sprung part.

The widespread use of this method is quite justified, since it was shown [3, 6] that a high ride comfort level is achieved when using it.

However, it is known [7] that when the operating speed of a tracking control system is important, preference should be given not to the feedback principle (Figure 2a), but to the compensation principle (Figure 2b).
Figure 2. Functional schemes of control systems: a - on the principle of feedback; b - on the principle of compensation. \( x_3(t) \) – stimulus; \( y(t) \) – control action; \( x(t) \) – output value; \( z(t) \) – external disturbing action.

The compensation principle implies that it is possible to calculate the necessary change in the control action to compensate the external one. To implement this, a mathematical model of the influence of external and control actions on the output value is required. In our case, the output value is the vertical acceleration of the sprung part, and its target value is zero. The control action is the force generated by the electric machine. The external disturbance is a force created by an elastic device. This force can be measured directly or calculated through suspension deformation and elastic characteristic.

It is easy to show that in order for the acceleration of the sprung part to remain zero, the force generated by the electric machine must be equal in modulus and opposite in direction to the force of the elastic device.

The disadvantage that does not allow using this method in its pure form is the lack of feedback on the vertical speed of the body. In combination with the purpose of the control system to maintain zero acceleration of the sprung part, this leads to self-oscillation from one extreme position of the suspension to the other (Figure 3).

Fortunately, there is no contradiction in the two principles of calculating the force generated by an electric machine described above – they can be applied together. Then, the expression for calculating the target force will look like this:

\[
F_{EM} = -F_{sp} + k_{sh}V_{body} \tag{2}
\]

Where:
- \( F_{EM} \) - target power of the electric machine;
- \( F_{sp} \) - the force of the elastic device.
Figure 3. The process of self-oscillation from one extreme position of the suspension to the other on a flat surface (initial vertical speed of the sprung part: 0.01 m/s).

The collaborative application of these principles combines the responsiveness to forces of an elastic device, and the absence of self-oscillations. When the ride on a dynamometric road and a smooth paved cobblestone is modeled, this approach provides a fairly high smoothness of the ride. However, on poorer roads, problems arise due to the lack of energy absorption capacity of the suspension. Using an electric machine in engine mode to isolate the body from disturbance leads to the phenomenon that the work on deforming the suspension is performed not by the road roughness, but by an electric machine. When hitting a high bump, the suspension will first be compressed to the limiter without accelerating the sprung part, but then a bottoming out will occur (Figure 4).

Figure 4. Bump overcoming with the suspension bottoming out.
The second problem is the suspension "hanging" in some position (not static) caused by the lack of feedback on the suspension deformation. A natural approach to solving this problem is to introduce feedbacks on the suspension deformation and the suspension deformation rate. This reduces the chance of a bottoming out, but impairs ride comfort on good roads. A compromise may be to apply progressive characteristics to these feedbacks. Painstaking selection of coefficients and degrees of feedback allows combining smoothness on small bumps and energy absorption capacity on large ones.

The second problem is the deviation of the established suspension position from the static one after passing the roughness (Figure 5). This is due to the small contribution of feedback on suspension deformation to the calculation of the target force.

![Figure 5. Bump overcoming with the "hanging" of the sprung part in a position that does not correspond to the static one.](image)

This problem can be solved by adding feedback on the filtered road profile. If the acceleration of the unsprung part is known, the trajectory of its movement can be tracked. Exposing this data to low-frequency filtering and taking it as a macro profile, feedback on the deviation of the trajectory of the body from the macro profile of the road can be organized. This approach not only returns the suspension to a static position (Figure 6), but also reduces the probability of suspension bottoming out.

From the experience of working on a mathematical model, the following can be recommended:

- Set the feedback on the vertical speed of the body to be degressive.
  This allows quick suppressing of deviations of the body speed from zero when they are small, but at the same time not restraining too much the movement of the body when overcoming large irregularities.

- Set a progressive feedback characteristic for the deformation and strain rate of the suspension.
  This will increase the energy absorption capacity of the suspension, almost without compromising the ride comfort on relatively good roads. To improve the ride comfort on bad roads, the feedback characteristic should be limited from above.
Figure 6. Bump overcoming with feedback on the macro profile of the road.

In accordance with the above, the target force of an electric machine is calculated as follows:

\[ F_{EM} = -F_{sp} - F_{frict} + F_{skh} + F_{stiff} + F_{damp} + F_{macro} \]  

(3)

Where:
- \( F_{frict} \) - the friction force in the suspension guide device;
- \( F_{stiff} \) - component of the target force of the electric machine, determined by feedback on the suspension deformation;
- \( F_{damp} \) - component of the target force of the electric machine, determined by feedback on the speed of deformation of the suspension;
- \( F_{macro} \) - component of the target force of the electric machine, determined by feedback on the deviation of the trajectory of the sprung part from the filtered road profile.

To calculate the components of formula (3), the following values must be measured or calculated:
1) The force of the elastic device. This requires either a force sensor or a suspension position sensor and a reliable elastic characteristic.
2) The value of the friction force in the suspension. This force may depend on the direction, speed of deformation of the suspension, its position, force, and other factors. The exact type of dependencies is supposed to be determined experimentally.
3) Vertical speed of the sprung part. To determine this, the integration of accelerations received from the accelerometer of the sprung part is required.
4) Deformation and deformation rate of the suspension. To determine this, the data from accelerometers or the suspension position sensor can be used.
5) Vertical coordinate of the macro profile. To do this, you need to use the accelerometer data of the unsprung part: they need to be integrated twice and passed through a low frequency filter.

Now that we have decided on the method for calculating the target force of an electric machine, it is necessary to organize the selection of its operating mode and the calculation of the control action.

The algorithm for selecting the operating mode is based on a simple idea: the generator removes energy from the mechanical system, that is, the work of the electric machine takes negative values,
and the engine supplies energy, that is, the work of the electric machine is positive. Therefore, if the 
target force of an electric machine is directed in one direction with the speed of relative movement of 
the sprung and unsprung parts, then the engine mode should be used, if they are directed in opposite 
directions, then the generator mode should be used.

4. Synthesis of control influence

There are certain difficulties in controlling a reversible electric machine. When connected to the same 
voltage, the rotor speed is limited from above when operating in engine mode, and from below when 
operating in generator mode.

In the engine mode, this is due to the fact that the electromotive force (EMF) of induction on the 
rotor winding becomes equal to the supply voltage. As a result, the armature current tends to zero, as 
does the electromagnetic moment.

Limiting the minimum speed of the rotor in the generator mode is due to the fact that up to a 
certain speed, the EMF of induction on the rotor winding is less than the storage voltage, which is why 
it cannot be charged. As a result, there is no current in the armature winding, as well as the moment of 
resistance of the generator.

The following solutions to this problem can be suggested:

1) Separation of charging and power circuits. When operating in engine mode, the electric 
machine is connected to a power source with a relatively high voltage, and in generator mode it is 
connected to an energy storage device with a relatively low voltage. This allows increasing the speed 
range in both modes.

2) Control of the magnetic flow of an electric machine. Due to this, it is possible to reduce the 
induction EMF at high speeds. In generator mode, this will help to reduce the drag force, and in engine 
mode – to expand the speed range.

Synthesis of the control action involves solving the following tasks:

1) Creating an algorithm for selecting the circuit to which the electric machine will be connected: 
the power supply circuit or the energy storage circuit.
2) Synthesis of the magnetic flux control algorithm.
3) Calculation of the required armature current.

The circuit selection algorithm is based on the algorithm for selecting the operating mode of an 
electric machine. In generator mode, the electric machine should be connected to a low-voltage energy 
storage circuit, and in engine mode, to a high-voltage power supply circuit. This algorithm should be 
supplemented with a description of the operation of the machine in a situation where the energy from 
the oscillating system should be removed, but the speed of rotation of the rotor is insufficient to 
overcome the charging voltage of the storage device. Under these conditions, a possible method of 
removing energy is to dissipate it as heat. This is possible either when the armature winding is 
connected to the dissipation circuit (heat is released on the resistance of this circuit), or when 
connected to a power source (counter-connection), in this case the heat is dissipated on the anchor 
winding.

The condition of the dissipation circuit switching can be formulated as follows: if the maximum 
possible induction EMF at a given angular velocity is less than the voltage at the terminals of the 
energy storage device, the storage device cannot be charged and energy should dissipated as heat. The 
maximum possible EMF of induction at a given angular velocity of the rotor is determined by the 
maximum $k\Phi$ value of the electric machine, where $k$ – is the design coefficient, and $\Phi$ is the magnetic 
flux.

Changing the magnetic flux in the regenerative mode is used as one of the methods for regulating 
the damping force. In active mode, there is an optimal value of the magnetic flux. To calculate the 
required magnetic flux, the values of the following parameters must be set:

- Selected operating mode;
- Power supply or energy storage voltage;
- Angular velocity of the rotor;
- The target electromagnetic torque;
- Resistance of the armature winding in the generator mode.

For both the motor and generator modes, expressions for calculating the magnetic flux are derived from formulas (4, 5, 6) known from electrical engineering [8]:

\[ M = k\Phi l \]  
\[ E = k\Phi \dot{\phi} \]  
\[ l = (U - E)R^{-1} \]

Where:
- \( M \) - electromagnetic moment;
- \( l \) - current in the armature winding;
- \( E \) - induction EMF;
- \( \dot{\phi} \) - angular speed of rotation of the rotor;
- \( U \) - the voltage of the power source or energy storage to which the armature winding is connected;
- \( R \) - resistance of the armature chain.

In regenerative mode, the \( \Phi \) calculation formula is derived using transformations from the above expressions (4, 5, 6) and looks like this:

\[ \Phi = 0,5U\dot{\phi}^{-1} + (0,5U\dot{\phi}^{-1} + MR\dot{\phi}^{-1})^{0,5} \]  

In active mode, the optimal value of \( k\Phi \) for the maximum torque for a given rotor speed is calculated. Differentiating expression (4) by \( k\Phi \) and equating the derivative to zero, we get:

\[ k\Phi = 0,5U\dot{\phi}^{-1} \]

The calculation of the required armature current is relevant only for the engine mode, since in the generator mode this current is determined by the value of the magnetic flux and the speed of rotation of the rotor. For known values of the electromagnetic moment and magnetic flux, its calculation is quite simple and follows directly from expression (4):

\[ l = M(k\Phi)^{-1} \]

5. Conclusions

In this paper, we considered aspects of constructing an algorithm for controlling an electric machine that replaces a damper as part of a single-wheel suspension. The issues of angular vibrations were not considered – these are problems for future research, where the joint functioning of such electric machines in the suspension of each wheel will be considered. However, for the control algorithm for each individual electric machine, this will only mean entering another term in the expression for calculating the target force.

The main problem is the combination of ride comfort and energy absorption capacity with limited suspension travel. As a result of working with the mathematical model, we can conclude that the use of such a system allows for high ride comfort and sufficient energy absorption capacity. An important point is that the shift towards ride comfort or energy absorption capacity is determined by the control algorithm, so further improvement of the means and methods for collecting and processing information about the road profile, as well as algorithms for calculating the target force of an electric machine, can ensure greater efficiency of the system described in this article.

The next stage of this research is an experimental study of the suspension with an electric machine and its control algorithms.
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