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Rear earth and high temperature superconducting permanent magnet synchronous tube motor/generator optimization for the components of the car suspension system

Thesis of the Ph.D. work

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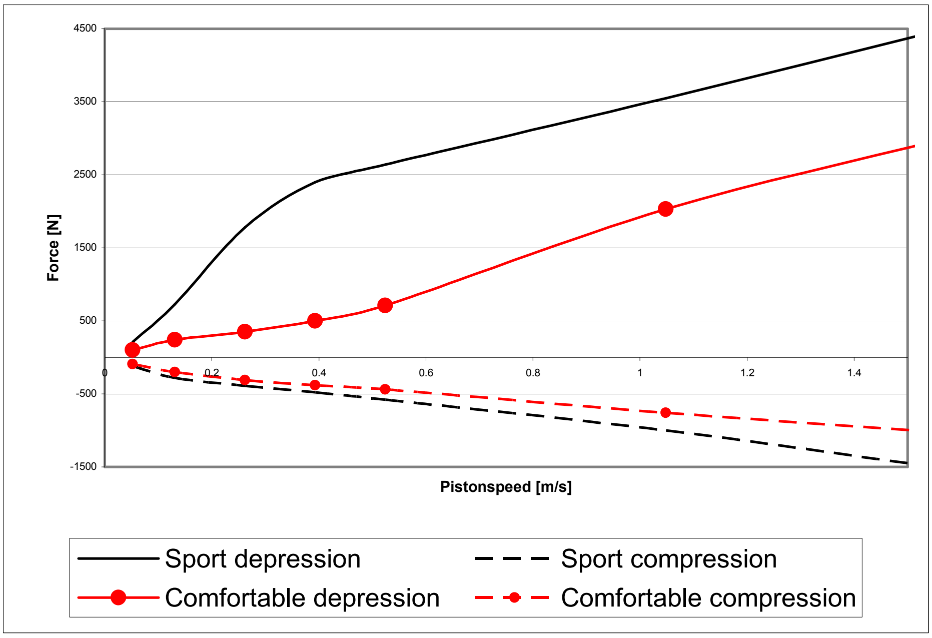
1. Introduction

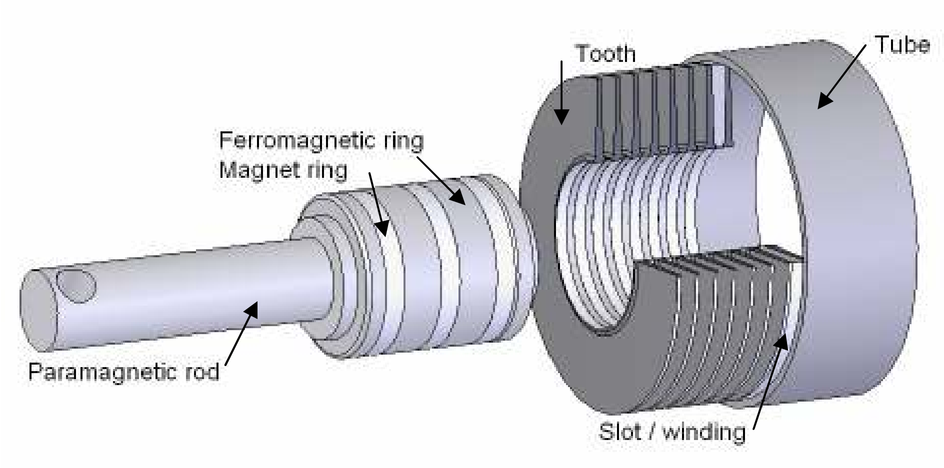
Today's vehicles are equipped with an extended range of actuators, sensors and softwares are controlling all dynamics. It is still a difficult problem for the suspension system to solve simultaneously holding the body of the car in comfort and the execution of the requirements of other safety systems like ABS, ESP, steer-by-wire, etc systems. As passive suspension systems are unlikely provide solution, the introduction of semi-active suspensions in practice is urgent. In today's vehicles shock-energy is converted into heat by a hydraulic shock absorber having a reacting force that is not controllable. Furthermore, the reacting force depends on the direction where the piston is moving at, as well as the speed of displacement. Classical hydraulic shock absorbers can operate on a predefined characteristic, which is a compromise between the safety (big reaction force) and the comfort (low reaction force) ability



1. ábra: Passive shock absorber characteristics

The control units for these classical systems are very complicated and expensive, and many ways not fast enough. Even more and more research of the world works on different controllable shock absorbers, which are pneumatic, hydraulic, rheologic and electronic systems. A possible solution for new generation shock absorbers could be a permanent magnetic (PM) or superconducting magnetic (HTS) synchronous tube machine, which operates as a controllable shock absorber. Like a tubular machine– used as an actuator (motor) – it is capable to act as an active element in the suspension (shaft displacement, vehicle tilting). When it is used as a generator it can also act as a semi-active element. Proper electronic control allows continuously variable acting force between F_{min}(~0N) and F_{max}, which is covered by switching the stator windings between short-circuit and open-loop. When it is used in generator mode, such a configuration produces electrical energy that may be dissipated or recuperated to the vehicle power system. By storing this energy via charging the batteries, the tubular generator behaves as a shock absorber at the same time. There is only one company in the world, called BOSE, they are working on full electronic shock absorber, which is mainly a permanent magnetic linear synchronous motor. With this system they can realize the active suspension system of a personal car, so it can operate against the spring element of the suspension. With this system it is possible (in generator mode) to convert mechanical (oscillation) energy into electrical energy. It is impossible to find concept description or any information about the system, and it is not patented. There is 4 prototype on a test vehicle which is working, but it won't be the future system (consulted with specialists), because of the complexity and high costs.

After collecting the information from this area, I thought that if I can design a permanent magnetic linear generator, I would decrease the prices, and with semi-active operation and energy recuperation it would be a good choice for the vehicle industry. More and more permanent magnetic devices and electronics are placed on vehicles, because they are even cheaper. These PM machines are optimal because they have big energy density and efficiency. The built up of such a machine is the same as the rotary machines, but the rotor moves in linear direction. A typical built up of a PM linear synchronous machine is shown on figure 2.



2. ábra: Permanent magnetic synchronous tube machine (schematic draw)

Nowdays the tube machines are working in motor mode in small places as linear actuators. I made a tube machine design model to engineer the shock absorber specific optimization.

High temperature superconducting magnets (HTSC) are adaptable on the rotor side of such a machine as a magnet, and hypothetically on the stator side as a HTS coil, but this is not realistic, because of the big magnetic fields and AC usage. In my simulations I used HTSC magnets on the rotor side, because it has bigger energy density than the PM. I simulated and measured unprecedented the contra-polar HTS magnets in linear motor usage on the rotor.

In my PhD work I made a PM synchronous tube machine designer software to optimize it for personal car shock absorber usage. It can realize the full time control parallel with the recuperation. I analyzed the HTS usage on the rotor side, which is possible on 77 K. I made the designer method through analytic (magnet circuit) and FEM method. I optimized the influence of the radial and tangential parameters of the machine. Input parameters were the maximal geometry of the shock absorber and the maximal energy density point of the used magnets. The purpose of the model was to find the geometry which gives the maximal reaction force from this parameters. I analyzed the cyclic worked machine heat transients, which is important from the viewpoint of the efficiency and lifecycle. Before the HTS magnet usage on the rotor, magnetization, demagnetization and relaxation measurements were made. The magnetization of the MHS magnets depends on the magnetic field of the environment, and it decreases in time (relaxation). I analyzed the effect of the parameters to the relaxation, and the magnetic field between the contra-polar MHS magnets. The analytic and FEM models were implemented for HTS calculations. The biggest difference between the PM and the HTS machine, is the shaft material. At HTS machine, it is made of ferromagnetic material because of the lower resistance of the magnetic circuit.

Another calculation is introduced for permanent magnetic suspension design. With this theory, any optional spring characteristic could be realized with contra-polar used permanent magnets. It is possible to change the quantity of the magnets and the ferromagnetic environment, which will manipulate the magnetic resistance of the magnetic circuit. If the magnetic resistance is low, the surface induction of the permanent magnets will be higher, so the repulsive force too.

This work discusses about the analytical and a FEM designer and optimization model, which was validated by prototypes measurements. The models can calculate the electric, magnetic and shock-absorber specific optimal (maximum energy) geometrical parameters of a PM or HTS synchronous tube motor/generator fitted into the possible shock-absorber space.

2. Methodology of the research

As a first step of my research, I made measurements on different models of rear earth magnetic systems. I validated the measurements with finite element method (with Quick Field software). I met the correlation between the moving magnets and the coils, so the breaking force which comes from the electromagnetic field of the eddy currents. I made analytic model (magnetic circuit model) which gives the geometrical parameters of the machine from the input parameters. The geometrical parameters were put in finite element model, which was made in MatLab environment. The model calculates two-dimensional model where the rotor moves with discrete steps. This model gives induced voltage, short-circuited current, reaction force and many calculated parameters. The results were validated in a prototype, which was designed and measured by me. After validation, I made the machine and the shock absorber specific optimization.

I made experimental measurements with HTS magnets to analyze the usage on rotor side of linear motor, so the relaxation and the demagnetization. I changed a few things in the analytic and in the FEM model to simulate the HTS magnet machine, to make the comparison based on the same maximal geometrical space.

With this two model and with the parameters of the used materials, it is possible to calculate the geometrical parameters of the machine which gives the maximal reaction force from the input maximal geometrical parameters. It is possible to calculate the induced voltage, short circuited current and the reaction force of PM or HTS magnetic linear synchronous machine.

3. New scientific results

1. Thesis:

With measurement-validated models, I confirmed that with the same overall dimension with the same construction and with the same air gap induction synchronous tube machine we get the maximal power, if on the rotor used contra-polar oriented permanent magnets are working on the maximal energy density point. [1]

The working point of the magnets comes from the magnetic resistance of the magnetic-circuit. I analyzed the effect of the working point to the reaction force. I compared the parameters where the maximal geometry was always the same. Because of the contra-polar oriented usage of the magnets on the rotor, the flux of the pole comes from the flux density of the magnets and the geometry of the ferromagnetic ring, plate. I analyzed the context between the used ferromagnet (B-H curve), the number of the poles of the rotor and the geometry of the tooth and slots on the stator. I analyzed and optimized these effects from the viewpoint of the reaction force. Parallel with the simulation, I measured on the prototype these effects, to validate the theory. There is another important part of the simulation, to calculate the velocity of the magnets. These (NdBFe) magnets are still very expensive.

2. Thesis:

I made mathematical content between the breaking force of the synchronous PM generator and the geometrical and active material parameters of the machine, to digest the possible usage as a vehicle shock absorber. Based on this simulations and the measurements I demonstrated in vehicle, as shock absorber used 3 phase, N35 permanent magnetic tube machine, which has 80 mm diameter, 300 mm long and +/- 60 mm amplitude, after optimizations we get the possible realized maximal reaction force in generator mode by the sub-thesis of this thesis.

At first I made an analytic model with the magnetic circuit theory. The input parameters of the model are the composition (ring, plate or radial magnetized magnets), maximal geometry, used air gap, radial ratio of the stator and rotor, phase number, ferromagnetic material (B-H curve) and the working point of the magnet. This parameter comes from the characteristic of the used (neodymium) magnet, which is linear, so the maximal energy density point is on 0.6 T flux density and 420000 fields straight. I controlled the analytical results with the QuickField (FEM) software. This analytic model gives that geometry, where the pre-defined parameters are realized together. These geometrical parameters will be the input for the FEM model, which was made in MatLab 6.5. The target of this model was to calculate the reaction force of the motors on different piston speed, to compare the geometries. Input parameters were the B-H curve of the ferromagnetic material, the construction (ring or plate magnet), the short circuit type (coils alone or in phase), methodology of the cogging force minimization (pole twist, fraction slot), the material of the slot end, the speed of the piston (0-1 m/s) and the maximal length of the stator and rotor. The model calculates dynamical effects from discrete steps of the rotor, which is moving. It results the short-circuited current in the coils, the induced voltage, inductivity, resistance and the flux density map of the machine. From these parameters, the model can calculate with the Maxwell's stress tensor the reaction force that will break the rotor movement.

2.1 Based on the 2. thesis we get the maximal reaction force if the length of the stator and the rotor is the same, because of the short circuited current and the contacted poles. [2], [3]

There was a question at the mounting of the first prototype: which length of the rotor and stator will be optimal. It is important, because there are coils on the stator, which are not active, so do not have contact with the poles of the rotor. It means there are coils in the phase, which are just resistances, so decrease the current in the phase. If the current is lower, the reaction force will be lower too. The construction needs +/- 60 mm amplitude, and there is just 420 mm maximal length for the system, so the rotor could be maximal 180 mm. If the length of the rotor changes the reaction force will be changing, because the phase resistance and the contact poles will be different. The length of the stator was changing from 100 mm up to 300 mm. It results different reaction forces depending on the piston position.

2.2 Based on the 2. thesis considering the results of the simulations we get the maximal reaction force if the rotor diameter is the half of the whole machine diameter. [4]

I analyzed the reaction force of the generator when the radial ratio of the machine (R_{stator}/R_{rotor}) is changing. It means if the predefined maximal diameter of the motor is fixed, the ratio of the diameter of the rotor and the stator could be different. The results of the simulations give maximal force at many constructions approximately at 50%.

2.3 It is possible to increase the reaction force of the tube generators with ~40%, if we use special form teeth on the stator side to keep the induction always on the same value in radial direction. It is possible with trapezoidal form teeth, to get bigger place for coils. [3], [5]

Regarding to the efficiency of the machine it is important to fill the slots with copper as much as possible. It is possible to increase the copper percent in the slots if we use trapezoidal teeth on the stator. It means the tangential parameter of the teeth is decreased in out direction of the radius. In this construction, the cross section of the teeth is always constant in radial direction. It means the flux density in the teeth will be always the same in radial direction, with the consideration of the dispersal. It results bigger place for coils in slots, so the copper percent could be bigger to increase the power of the generator.

2.4 If we use the same geometrical parameters, but we use in one-phase copper rings instead of coils (considering the armature reaction) the reaction force will be ~ 50% higher. [6]

It is known, that if the copper percent increases in the slots, the power will be higher. It means if the reaction force still not enough, it would be possible to use copper rings in the generator. It gives 100% copper in the slot, and it gives a piston speed dependent reaction force, which is not controllable. With this construction, it is important to calculate the effect of the reaction of the armature. Copper rings could be used under the coils or in one of the three phases. With this technology, it is possible to realize much higher reaction force, but the controlled area will be smaller.

3. Thesis:

Based on analytical and FEM simulations I demonstrated and confirmed with measurements, that in vehicle as shock absorber used, 3 phase up to 77 K cooled tube generator, with (Jc-B marked) high temperature superconductor magnet (YBCO) on the rotor side, the realized reaction force is the same as with (B-H curve marked) permanent magnetic rotor tube generator on this temperature. [1], [7]

I convert the simulation models (analytic and FEM) to calculate HTS magnetic tube generator parameters. It is possible to simulate ferromagnetic or non-magnetic construction on 77 K temperature. HTS is marked with Jc-B curve, and the technical relaxation in contra-polar usage is considered based on measurements. I compared these generators with 300 and 200 K temperature permanent magnetic tube generators. I used always the same maximal geometry and materials. The main difference between the constructions is the material of the piston rod. The MHS marked with shield currents, so the rod is made of ferromagnetic material to decrease the magnetic resistance of the magnet-circuit. The magnet circuit of these generators are the same, so the excitation of the active materials (PM or HTS) are too. It means the control of the short-circuited current, to block the reaction of the armature will be almost the same. It affects nearly the same reaction force.

3.1 Based on measurements I demonstrate that between two high temperature superconductor magnets (30 mm diameter and 10 mm length YBCO) in contra-polar position the fall of the static repulsive force (5 mm up to 10 mm distance) is always the same. [7]

These measurements were made in Germany in Jena at the HTS laboratory of IPHT research center. I magnetized the HTS magnets with FC methodology with ~1T magnetic field. I used two HTS magnets to put them in a pot in contra-polar composition to measure the static repulsive force. The force was measure with a strain gauge based force sensor in static position on a measuring arm. A computer fastened the force in fix periods. The target of this measurement was to analyze the HTS magnets in contra-polar position. There is no information in literature about the contra-polar relaxation, just about the simple HTS relaxations. This complex relaxation is proportional with the repulsive force fall, because of the flux density change of the HTS magnet.

4. Thesis:

With the size and quantity of the permanent magnets and with the optimal choose of their magnetic environment, it is possible to realize any spring characteristic.[6]

It is possible to realize magnetic spring, with two contra-polar oriented permanent magnets. It has no stabile levitation; it needs some drive system, for example a tube. By moving magnets, an eddy current will flow in them. It will give a damping force parallel with the spring force characteristic. I used the strongest rear earth magnets (neodymium) for the measurements and for the simulations. To get the repulsive force between two permanent magnets I made measurements, analytic and FEM simulations. The first step was to realize different spring characteristics in simulation with pieces of permanent magnets. In this system, the reaction force between two magnets (on fix distance) is the same, but with many pieces of magnets, different shapes of characteristic could be realized. The shape of the characteristic is changing if we use different ferromagnetic environment, for example a stator of a tube machine. It gives a lower magnetic resistance in the magnet circuit which results a different working point of the magnet so a bigger magnetic flux density on the surface area of the magnet. It results a bigger repulsive force between the magnets, which means on 0.25 mm distance an approximately 40 % bigger force versus on air operation system. At this system, it is also possible to recuperate the electrical energy with the coils on the stator, as it was presented in that part of this document. If we put our permanent magnetic system with the drive paramagnetic tube in a ferromagnetic tube, the reaction force will be approximately 40% more bigger on 0.25 mm magnet distance. It gives much higher surface flux density on the surfaces of the magnets. It means that it is not possible to recuperate the electrical energy to the network of a vehicle.

4. Possible applications

After many optimizations, the results show that the performance of a hardest conventional shock absorber (4000 N on 0.7 m/s) can be reached with a tubular LSM. It needs 1.5 times the volume, but it suits in the McPherson suspension system. With these models (analytical, FEM) it is possible to find the best geometry fitted to the arbitrary, available shock-absorber space, which will give the maximum possible reaction force. With a correct control electronic, it is possible to realize the semi-active or the full active suspension together with the energy recuperation feature. The only limit of these systems is the price of the permanent magnets (NbFeB) which gives a high priority at new investments.

5. Conclusion

The main area of my work is the possible usage of the magnets in vehicle suspension. The fields of research contain 3 parts. At first, I analyzed the possibility of a synchronous tube machine as a shock absorber by vehicles. I made models and measurements to optimize the machine for shock absorber usage. I analyzed the magnetic, electric and temperature stress, and the effect of the build-up to the reaction force. Because of this work, I demonstrate that the same reaction force is realistic with tube machine from the classical shock absorber geometry. It converts the mechanical energy into electrical, so it is possible to realize the fast control parallel with the recuperation, battery charging.

I analyzed theoretically the high temperature superconductor magnet usage in tube machine on the rotor side. Based on measurements I studied the parameters, property and the possible magnetizing solutions. After the measurements, I made a simulation to calculate the reaction force of this machine too. I confirmed it is not necessarily to use HTS magnets on the rotor side on this (77 K) temperature, because the PM rotor machine has the same power.

I analyzed also the PM levitation in vehicle suspension, so as a spring unit. I made analytic and FEM simulation parallel with measurement. I confirmed that any vehicle spring characteristic could be realized with PM. The parameters, which we have to change, are the ferromagnetic environment, and the quantity of the magnets. It is possible to use a tube machine stator as a drive unit for the magnets, so we can damp the oscillation of the vehicle with the coils and parallel realize the spring unit.

6. Publications in theme

[1] Zádor István– Dr. Vajda István, „Állandó mágneses illetve szupravezetős fél-aktív lengéscsillapító tervezési lépései", Tavaszi Szél konferenciakiadvány, old. 147-152, Budapest, 2007

[2] Istvan Zador – Daniel Horvath – Dr. Istvan Vajda, „PM Tube machine designed for a controlled vehicle shock-absorber suited for energy recuperative operation", XVIIth International Conference on Electrical Machines Conference (CD) Chania, 2006.

[3] Istvan Zador –Dr. Istvan Vajda, „Development of a permanent magnetic semi-active shock-absorber", International Review of Electrical Engineering, Vol. 2 N. 4, pp. 579-586, Italy, July-August 2007

[4] Istvan Zador - Daniel Horvath - Dr Istvan Vajda, „PM synchronous tube machine optimization for vehicle shock-absorber", 13th Biennial IEEE Conference on Electromagnetic Field Computation Conference Proceeding (CD), Athen, Greece, 2008.May.

[5] Istvan Zador – Bence Falvy – László Dr. Palkovics, „Electro-mechanical suspension actuator with energy recuperative feature", World Automotive Congress (CD), Yokohama, 2006.

[6] Istvan Zador - Thomas Naber, „Elektromagnetische Komponente für Federung und Dämpfung im Fahrzeug", Fahrwerk vertikaldynamik (CD), Deutschland, 2007.

[7] Istvan Zador - Denes Kiraly - Dr Istvan vajda, „Synchronous tube machine optimization for vehicle shock absorber using permanent or superconducting magnets", Applied Supercunductivity Conference proceeding (CD), USA, 2008.