Maglev Concepts as Proposals to Reduce the Global Climate Problem

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ABSTRACT: Three concepts of maglev transport: electromagnetic controlled suspension, super conductive electrodynamic repulsion, and levitation based on the Magnetic Potential Well (MPW) phenomenon are considered as forms of technology addressed to challenges posed by global climate change. The MPW, free-body dynamics stability and main characteristics of MPW-levitation are presented in greater detail.

1 INTRODUCTION

During the industrial age (approximately from 1750) human activity has caused a steady, upward trend in global temperature and this can result in catastrophic consequences in the foreseeable future [1]. Another global problem is natural resource depletion, particularly oil and gas. The power industry, transport industry and the ancillary industries devoted to repair and maintenance are major consumers of energy and contributors to CO_2 emission.

Currently, maglev transport technologies developed in Germany and Japan [18], [19] are based on two classical concepts to achieve free body hovering: automation applied to conventional "warm" electromagnets attracted by steel rails (electromagnetic suspension concept), and movement of a superconducting magnet along an electrically conducting medium (electrodynamic repulsion concept). The automated levitation results in prodigious electrical losses into electromagnets estimated at one kilowatt per suspended ton of mass. The electrodynamically levitated transport does not operate at stops and low speeds, hence it requires wheels and corresponding guideways etc. In order to answer the demands of a truly resource saving high-technology of the future, maglev technologies must be improved in the area of energy consumption.

Therefore versions of maglev transport reducing energy consumption can be of some interest and possible utility. One such version is based on the Magnetic Potential Well (MPW) phenomenon [6]-[10], [11], [12] and [17].

2 THE MPW PHENOMENON

2.1 Simple explanation

One can imagine MPW as the interaction of two magnets in a manner analogous to mechanical spring action yet acting through space. The MPW means that two-magnet potential energy as a function of spacing has a local minimum. This is demonstrated in Figure 1 by magnetic lines of force for two coaxial super conductive rings, one fixed and the second capable of occupying three positions: top, middle, and low. The key fact underlying MPW is Faraday's electromagnetic induction law on the basis of which the full magnetic flux (linkage) Ψ coupled with any zero resistance closed loop is constant in magnitude. In outer heterogeneous magnetic fields, electric current in such a loop at its different positions assumes various magnitudes to provide Ψ-constancy (frozenness). As an example, constant linkage of the upper ring in Figure 1 is supposed to be equal to 5 magnetic lines of force.

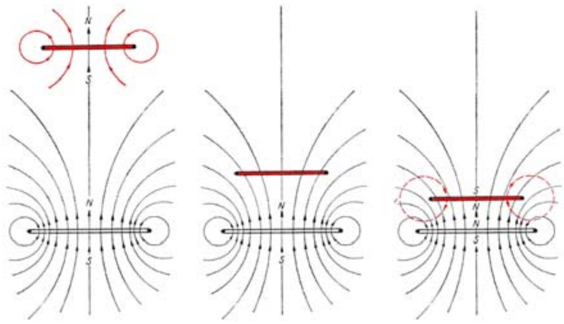

Figure 1. The MPW-demonstration by magnetic lines.

At the top position, for Ψ = 5 lines, the electric current in the upper ring must originate 4 magnetic lines piercing the upper ring area in addition to one line of the outer field generated by the lower ring electric current. Unidirectional electric currents in both rings result in magnetic attraction between them.

At the middle position, the magnetic force between rings is zero because 5 magnetic lines piercing the upper ring area are created by the lower ring outer field. Therefore electric current in the upper ring and magnetic force between the rings must be zero.

At the low position this current must change direction and originate two lines (shown by dotted lines in Figure 1) to eliminate superfluous outer field's magnetic lines piercing the upper ring area. This results in opposite currents and repulsion between the rings.

Thus, we derive the MPW-manifestation: two approaching magnets spontaneously change magnetic attraction into magnetic repulsion due only to a decrease in the spacing between them. This result is a consequence of the fact that a closed zero resistance loop's electric current can change both magnitude and direction to satisfy Faraday's law and, by placing this loop at different positions in heterogeneous outer magnetic fields.

The correct MPW-theory was first derived by Kozoriz [6]. He discovered MPW and established the MPW-manifestation condition for two zero resistance closed loops

$$\Psi_1 \Psi_2^{-1} = L_{12}(x_0)\, L_2^{-1} \qquad (1)$$

where the left part of (1) is ratio of loop's frozen magnetic linkages, $L_{12}(x_0)$ is loops' mutual inductance magnitude at the MPW-position, and L_2 is self-inductance magnitude of a loop whose frozen linkage is Ψ_2. Since mutual inductance is always less than self-inductance, MPW can occur if the loop linkage ratio (a parameter that the user can choose) satisfies the inequalities $0 < \Psi_1 \Psi_2^{-1} < 1$.

2.2 Magnetic force law in the MPW-direction

Instead of the classical monotonic law for two-magnet force as a function of linear spacing, the MPW-case results in two unusual characteristic positions (see Fig. 2). At one of them (x_0) magnetic

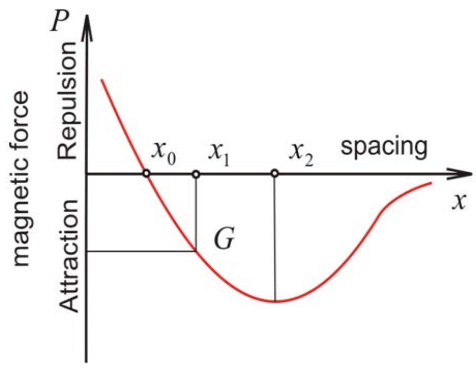

Figure 2. Force-spacing characteristics in MPW-direction.

force is zero (MPW-position). At the second (x_2) magnetic attraction assumes maximal magnitude. In the range $x_0 < x_1 < x_2$ suspension by magnetic attractive force is obviously stable. This assists yet does not guarantee a free position stability or levitation.

2.3 MPW-levitation

The MPW-levitation problem must be investigated by taking into account all degrees of freedom (six in the case of one free solid body). As an example, we consider a free vehicle motion with MPW-manifestation in gravity direction. The vehicle is described by six degrees of freedom. Three of them are Cartesian coordinates of the vehicle mass center. Others (x_4, x_5, and x_6) are roll, pitch, and yaw angles determining the vehicle space orientation relative to an immobile two-wire dc line magnetically supporting the vehicle. Common simplifications and known methods of analytical mechanics [14] and electromechanics [16] allow us to construct a dynamic model in the form of ordinary differential equations of the 12th-order. As showed by Kozoriz [10], this system decomposes into three subsystems. The first of them is vertical oscillation, the second is uniform motion along the two-wire line or equilibrium, and the third is a lateral-orientational dynamic subsystem of the 8-th order. The last can be written down as

$$\frac{d^2 x_2}{dt^2} = -b_2 x_2 - b_{24} x_4 ,$$

$$\frac{dn_1}{dt} = -b_{42}x_2 - b_4 x_4,$$

$$\frac{dn_2}{dt} = \frac{C_2 - C_1}{C_1} n_3 n_1 - b_5 x_5,$$

$$\frac{dn_3}{dt} = \frac{C_1 - C_2}{C_1} n_1 n_2 - b_6 x_6, \qquad (2)$$

$$n_1 = \frac{dx_4}{dt} + x_6 \cdot \frac{dx_5}{dt},$$

$$n_2 = -x_6 \cdot \frac{dx_4}{dt} + \frac{dx_5}{dt},$$

$$n_3 = x_5 \cdot \frac{dx_4}{dt} + \frac{dx_6}{dt}.$$

Here x_2 is non-dimensional lateral displacement of the vehicle mass center; C_1, C_2 are vehicle central inertia moments with respect to long and transverse axes respectively; b_2, b_4, b_{24}, b_{42}, b_5, and b_6 are constant non-dimensional rigidities; n_1, n_2, and n_3 are non-dimensional angular velocity components along central inertia axes, and t is non-dimensional time.

The subsystem (2) is too complicated to be analyzed by known analytical methods. Analysis based on Maple12 [21] software proves to be capable of solving the Cauchy problem and building phase portraits. An example of a Maple-solution looks as follows

$restart; with(plots):$

$e_1 := \frac{d}{dt} x_2(t) = y_2(t):$

$e_2 := \frac{d}{dt} y_2(t) = -b_2 \cdot x_2(t) - b_{24} \cdot x_4(t):$

$e_3 := \frac{d}{dt} n_1(t) = -b_{42} \cdot x_2(t) - b_4 \cdot x_4(t):$

$e_4 := \frac{d}{dt} n_2(t) = \left(C_2 C_1^{-1} - 1\right) \cdot n_3(t) \cdot n_1(t) - b_5 \cdot x_5(t):$

$e_5 := \frac{d}{dt} n_3(t) = \left(1 - C_2 C_1^{-1}\right) \cdot n_1(t) \cdot n_2(t) - b_6 \cdot x_6(t):$

$e_6 := n_1(t) = \frac{d}{dt} x_4(t) + x_6(t) \cdot \frac{d}{dt} x_5(t):$

$e_7 := n_2(t) = \frac{d}{dt} x_5(t) - x_6(t) \cdot \frac{d}{dt} x_4(t):$

$e_8 := n_3(t) = \frac{d}{dt} x_6(t) + x_5(t) \cdot \frac{d}{dt} x_4(t):$

$b_2 := 10 : b_{24} := 0.5 : b_4 := 2 : b_{42} := 5 : b_5 := 4 :$

$b_6 := 10 : C_1 := 1 : C_2 := 10 :$

$s := dsolve\left(\{e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8, x_2(0) = 0.1, y_2(0) = 0, x_4(0) = 0.2, x_5(0) = 0.05, x_6(0) = 0.1, n_1(0) = 0, n_2(0) = 0, n_3(0) = 0\}, \{x_2(t), y_2(t), x_4(t), x_5(t), x_6(t), n_1(t), n_2(t), n_3(t)\}, type = numeric\right):$

$odeplot\left(s, [[t, (x_4(t))], [t, x_6(t)]], 0..10, numpoints = 500, color = black\right);$

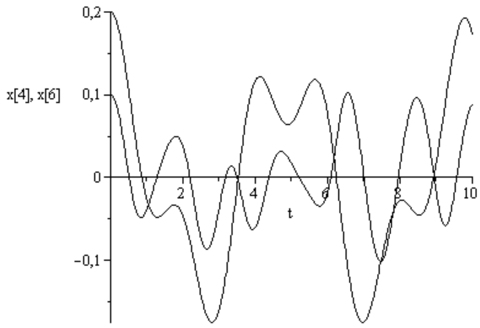

Figure 3. Roll-time (x_4) and yaw-time (x_6) dependencies.

$odeplot\left(s, [y_2(t), x_4(t)], 0..50, numpoints = 500, color = black\right);$

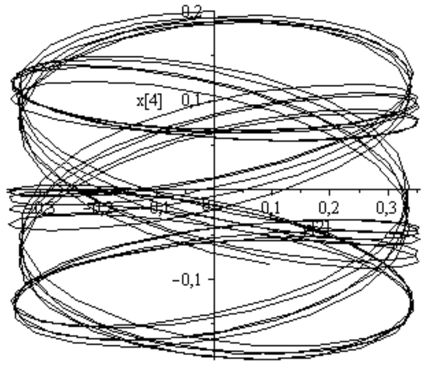

Figure 4. Lateral speed-roll angle (y_2, x_4) phase portrait.

$odeplot\left(s, [y_2(t), x_2(t), x_4(t)], 0..50, numpoints = 500, axes = BOX, color = black\right);$

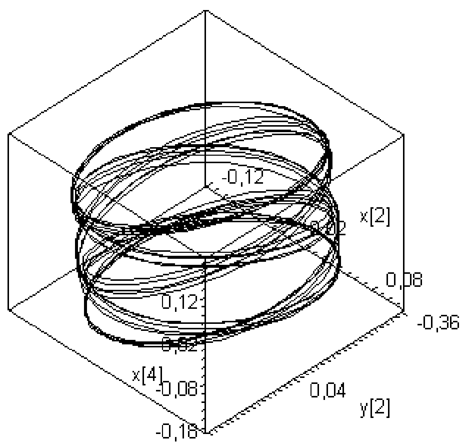

Figure 5. Lateral displacement (x_2)-lateral speed (y_2)-roll angle (x_4) phase portrait.

$$odeplot\left(s, \left[t, x_2(t), x_4(t)\right], 0..30, numpoints = 500, axes = BOX, color = black\right);$$

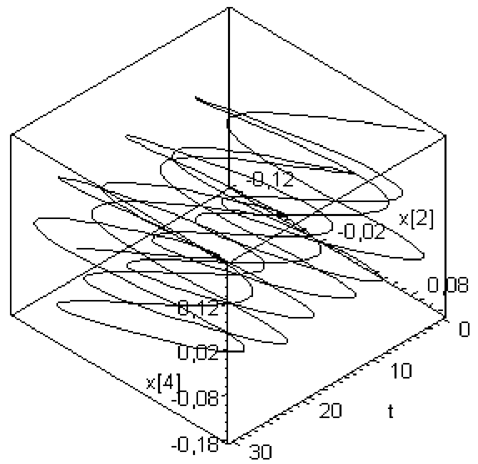

Figure 6. Lateral displacement-roll angle-time (x_2, x_4, t) phase portrait.

Other parameter choices and initial conditions demonstrate also the ability of the free vehicle dynamic behavior to be stable. Thus, in theory, the MPW-levitation with zero electrical losses can be considered as a real technology.

3 KNOWN MAGLEV CONCEPTS

Forty years ago Germany and Japan bravely began the development of a novel technology in transportation wherein a vehicle like a car without wheels or a plane without wings is held and moved in the free hovering configuration relative to guideway by means of magnetic forces. The problems of climate change and the crisis of energy which we face today were less perceptible then, and the idea of magnetic levitation seemed like utopian fantasy. Nevertheless these countries converted seemingly absurd idea into workable technologies that are at present viable in the marketplace – Germany and China have built the Shanghai-airport maglev line that from 2004 operates as public transport [19]. Other projects based on the German maglev are being considered for implementation in the USA, Germany and other countries. Meanwhile, Japan builds a high-speed maglev-line Tokyo-Osaka in parallel to the existing high-speed railroad.

Many groups are working on the development of maglev. For example, Swissmetro project [4], [18] provides for a metro throughout the country (and in the future over Europe in the dreams of its developers) with magnetically levitated vehicles inside vacuum processed tubes. Maglev technology is being developed in Brazil, Canada, China, South Korea, UK, Ukraine and USA. Powell [15] proposed maglev technology as a new mode of space transportation capable of significantly reducing the cost to launch bodies into outer space. Some maglev concepts are based on permanent magnets [5, 20], and some on low or high temperature superconductors [13].

Generally speaking, there are two well-known concepts to achieve practicable magnetic levitation [13], [17]-[19]. The first called electromagnetic levitation (EML) is reduced to feedback-controlled attraction between "warm" electromagnets and steel rails. Transistor and solid-state power electronics enhanced this concept. Distinguishing features of EML-system are relatively small gap, high energy consumption, massive guideway, and feed-back control (without feed-back control EML is impracticable). The second concept called electrodynamic levitation (EDL) inspired by the availability of high current density superconducting wire is reduced to magnetic repulsion between vehicle's super conductive magnets and electric conductor mounted in the guideway. Distinguishing features of this system are zero electric losses in superconducting magnets, relatively big gap, and operation over speeds of approximately 150 km/h (at lower speeds this system is impracticable). The second concept has been developed in Japan.

4 MPW-CONCEPT AND RESOURCES SAVING

There is also a third less known concept of maglev based on the MPW [7]-[12], [17]. It operates without feed-back control, with zero electric losses, and irrespective of speed.

MPW-levitation has the lowest energy consumption. EML concept requires no less than one kilowatt per suspended ton brought about by the Joule effect into "warm" windings of supporting, guiding and driving coils. This level of EML-electric loss is comparable with friction loss of high-speed trains at speeds over 300km/h yet looks unattractive for urban transport. EDS is a type of maglev with zero electric loss into coils on board only. During operation there are enormous energy losses in other coils made of normal conductor that are provided for levitation, guiding and driving. Together with aerodynamics, EDS-electric losses are equivalent to energy efficiency no greater than that of modern aircrafts.

Another constitutive problem of EDS is the presence of wheels. Wheels as safety feature are problematic at high speeds. In reality, planes taking off and landing at 200 km/h have occasional blowouts, racing cars going around tracks at 320 km/h change tires every 400 km. EDS-vehicles must always be able to instantly land on wheels at speeds of 500 km/h and more - this presents a great source of danger. In addition, the rolling surface cannot end after lift-off, instead it must continue to the next station.

The new maglev levitation uses super conductive magnets operating in the persistent current mode. In this case, energy consumption to support low temperatures as a requirement of superconductivity state can be reduced to 100 W for a hundred-ton vehicle.

New levitation can operate at 50 to 200 mm of spacing. This is much more than 10 mm of EML technology made for small spacing requiring extremely precise arrangement and massive guideways.

Automated electromagnetic suspension is restricted from above by approximately 2.5 Tesla caused by magnetic saturation of commercial soft-magnetic materials. Eddy currents of EDS generate magnetic fields less powerful compared to super conductive magnets field that sufficiently decreases levitation magnetic forces. The best permanent magnets as a source of high-temperature superconductor levitation magnetic field [5, 13, 20] operate at no more than 1 Tesla. The MPW-levitation guarantees the highest force and rigidity levels. It is caused by the fact that only MPW-levitation can operate at 10 or even 20 Tesla magnetic fields.

Therefore, levitation force characteristics that are in square proportion to the magnetic field level, in the MPW-case are unachievable for all other maglev concepts.

MPW-levitation operates without automation and irrespective of speed.

5 CONCLUSIONS

The perpetual motion machine is forbidden by physical laws. Yet these laws allow us to create machines that asymptotically approach the achievable limits imposed by reality. One avenue towards this dream is superconductivity, particularly high-field superconductors with today's upper critical field of approximately 60 Tesla [2]. Superconductivity in high magnetic fields is of both fundamental and technical interest. Large-scale superconducting devices comprise magnets, motors, generators, and cables using zero resistance superconducting windings. Typical values of current density used in superconducting coils are 10^9 A/m^2 or more - about two orders of magnitude higher than values used in normal conductors. Superconducting magnets allow the utilization of higher fields in large volumes at lower costs in capital investment and energy expenses. As an example, the bubble chamber magnet at CERN would require a power of 70 MW with conventional coils, while the superconducting version consumes less than 1 MW [1]. The MPW conditioned by the upper critical field and properties of commercial superconductor materials properties allows free hovering. These features result in three and more orders of magnitude increase in levitation force characteristics relative to all known maglev concepts.

The enormous challenges posed by global climate change and shortages of natural resources especially non-renewable ones like oil and gas are a major source of scientific challenges and concern. The conventional power industry and transport operating as heat engines are major sources of problems which must be replaced with forms of technology that are less resource and energy intensive. In comparison with heat energy, electrical energy is much more efficient form of energy to be converted without exhaust into kinetic energy.

An obvious bottleneck to improvements in transportation as one of the main consumers of energy is the presence of wheels as a source of friction, wear, and noise. Maglev technology is one of the best solutions to these problems. Based on superconductivity and levitation phenomenon MPW, this technology can be improved towards the dream of transportation with zero operation losses. Then maglev technologies will be able to answer all the demands of a truly resource-saving high-technology adequate for the future.

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