Advanced Maglev Projects Based on the Magnetic Potential Well Phenomenon

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ABSTRACT: Some projects based on a new magnetic levitation phenomenon are proposed. This phenomenon called Magnetic Potential Well (MPW) adds up to a local minimum for the magnetic potential energy considered as function of separation between two spaced magnets. MPW manifests itself when at least one of two superconducting magnets operates in the persistent current mode, and some geometrical conditions are satisfied. Projects relate to transportation, high-speed acceleration, magnetic bearing, docking in outer space, and inertial navigation.

1 INTRODUCTION

Brandt considers several physical mechanisms that can cause a body to freely float [1]. As for floating by magnets, Gilbert [3] examined the problem as early Brandt considers several physical mechanisms that can cause a body to freely float [1]. As for floating by magnets, Gilbert [3] examined the problem as early as 1600. Later Earnshaw proved the theorem [4] according to which free particles interacting by the inverse square distance force law cannot constitute a stable equilibrium configuration. Nowadays this result is usually considered as the fundamental principle forbidding attempts to levitate a body by forces of magnets without artificial force changes. Only one well-known exception to this theorem discovered by Braunbeck in 1939 [2] exists. The "Magnetic Potential Well" (MPW) phenomenon discovered by Vasyl' Kozoriz in 1976 [5] can be considered as the second less known exclusion from the "instability rule". MPW-exhibition requires zero electric resistance. Diamagnetism and zero electric resistance as two macroscopic demonstrations of superconductivity attract attention because both assist with levitation stability although do not guarantee it. So called Meissner repulsive magnetic levitation [16] based on superconductor diamagnetism, and MPW-levitation based on zero resistance of a closed current-carrying loop are two versions of superconducting levitation based on different physical mechanisms leading to free equilibrium stability. The repulsive levitation is restricted from above by the lower critical field excluding magnetic field penetration inside the superconductor. The maximal field for niobium is no more than 1.5 Tesla at 4 K, this corresponds to a pressure of approximately 10^4 N/m^2, which is too small in magnitude to be competitive with the pressure required for many applications. The MPW-levitation can use e.g. niobium-titanium or niobium-tin wire keeping zero electric resistance up to critical fields of 8 Tesla and 23 Tesla respectively resulting in $3 \cdot 10^7$ N/m^2 and $2.6 \cdot 10^8$ N/m^2 pressure respectively – these are appreciable magnitudes and can lend themselves to many applications. Some of them are considered here.

2 THE MPW PRESENTATION

The main ideas of the proposals explained below form a group around the maglev technology based on the Magnetic Potential Well (MPW) phenomenon [6]-[15], [18].

MPW is a property of two magnets to change attraction into repulsion by only decreasing the spacing between them. In other words, MPW corresponds to the local minimum for the two-magnet potential energy as function of distance. Finally, MPW is equivalent to the statement about similarity between two-magnet and mechanical spring force laws.

To visualize these ideas, some curves are shown in Figure 1 where P is magnetic force, x is spacing, U is magnetic potential energy, x_0 is the spacing corresponding to the MPW-position; the upper and lower curves at the left show MPW-interaction and the other four figures on the right demonstrate the "classic" magnetic case.

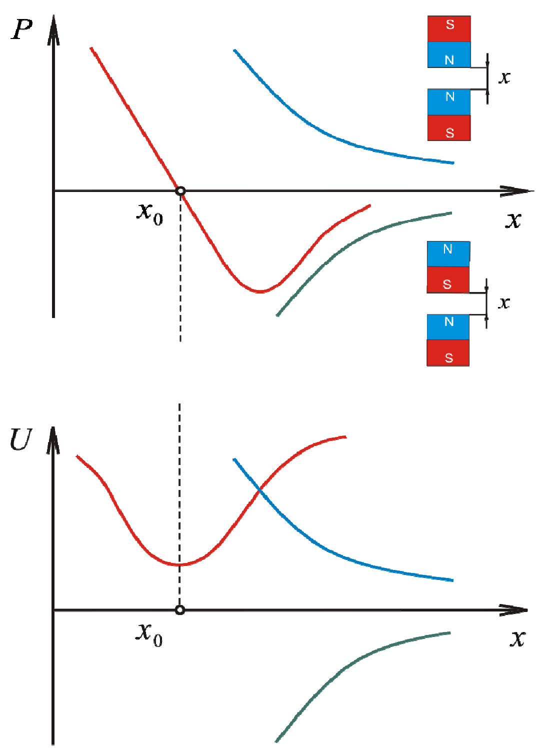

Figure 1. The MPW-presentation

Prima facie, MPW seems to be at odds with physics. MPW runs counter to the classical conception of monotonicity of magnetic interaction. Among the interactions known in nature (gravity, electromagnetic, nuclear, and weak), only pairwise nuclear potential energy has a local minimum. Others including magnetic interaction are imagined as monotonically changing functions of distance. For example, the inverse cubic distance in law of two-dipole potential energy satisfies this monotonicity.

The MPW was first discovered and substantiated by Vasyl' Kozoriz [5]. His proof was based on the fundamentals elaborated by White & Woodson at MIT (see [17], chapter 1). In accordance with their energy conversion concept, the magnetic energy expressed in terms of magnetic linkages (full magnetic fluxes) and coordinates is the potential energy U. For two current carrying loops the last can be represented by the expression

$$U=\frac{1}{2}\left(L_{22}\Psi_1^2-2L_{12}\Psi_1\Psi_2+L_{11}\Psi_2^2\right)\left(L_{11}L_{22}-L_{12}^2\right)^{-1} \quad (1)$$

where Ψ_1 and Ψ_2 are magnetic linkages coupled with loops whose self-inductances and mutual inductance are L_{11}, L_{22} and L_{12} respectively. In this formula linkages Ψ_1 and Ψ_2 must be considered as some constants in consequence of closed loops' zero resistance. Self-inductances L_{11} and L_{22} are constants also. Only the mutual inductance L_{12} is a function of one mechanical coordinate x.

Therefore, in accordance with the above explanations, the magnetic force P can be derived as the negative first partial derivative of energy (1) with respect to the coordinate x

$$P=-\frac{\partial U}{\partial x}=-\frac{\partial U}{\partial L_{12}}\frac{\partial L_{12}}{\partial x}=$$
$$=-\frac{L_{12}\left(L_{22}\Psi_1^2+L_{11}\Psi_2^2\right)-\left(L_{11}L_{22}+L_{12}^2\right)\Psi_1\Psi_2}{\left(L_{11}L_{22}-L_{12}^2\right)^2}\frac{\partial L_{12}}{\partial x}. \quad (2)$$

The numerator of the first multiplier can be equal to zero, if

$$L_{12}=L_{22}\Psi_1\Psi_2^{-1} \quad (3)$$

or

$$L_{12}=L_{11}\Psi_2\Psi_1^{-1}. \quad (4)$$

Any of these conditions can be the necessary condition of the MPW-existence. By loops numeration we must choose one of them to satisfy inequalities $L_{12} < L_{11}$ and $L_{12} < L_{22}$ (mutual inductance is always less than any self-inductance). Then, if for example we choose (3), the second partial x-derivative of the magnetic potential energy (1) calculated at "point" (3) results in

$$\frac{\partial^2 W}{\partial L_{12}^2}=\frac{\Psi_2^2 L_{22}^{-1}}{L_{11}L_{22}-L_{12}^2} \quad (5)$$

i.e. the second x-derivative of the potential energy is positive at point (3), because $L_{11}L_{22} > L^2_{12}$, $L_{12} > 0$.

So, a repetition of the MPW-proof conducted in [5] satisfies the necessary and sufficient conditions for the U-minimum existence.

3 ZERO ELECTRIC LOSS LEVITATION

The novel magnetic force phenomenon demonstrating an analogy between two-magnets and mechanical spring forces assists levitation without automation, irrespective of speed, and without electric losses. This can dramatically improve well-known maglev transportation technologies [16] based on other physical principles to levitate, particularly in the matter of energy consumption. As a first step, the development and demonstration of the working model with 2 to 5 tons of mass freely suspended without electric losses at approximately 50mm spacing is proposed.

The overall strategy aimed to realize the main objective is restricted by some conditions. The main objective of this project is to demonstrate the electric lossless suspension of a mass comparable to a modern car in the free stable equilibrium (levitation position) at high spacing, without using automation or diamagnetic materials as tools to achieve the free hovering stability. This will demonstrate the possibility to create energy-saving transportation systems operating at practically convenient levitation spacing, at speeds ranging from zero to 1000 km/h and higher, zero consumption of oil resources, without exhaust and wear, and with a very low level of noise. Such systems, we believe, will sufficiently help to reduce CO_2 emission directly and by implication, the heating of the Earth caused by operating transport systems and by industries connected with their manufacture, repair and maintenance.

There are two conditions which must be allowed to gain a better understanding of our partners and customers. The first is total disbelief in the existence of a new magnetic levitation phenomenon. As many years' experience demonstrates, any quick-witted student who has grasped the rudiments of electricity validates MPW after the simplest arguments and MPW-demonstration. By contrast, experts are usually of the opinion that MPW is an absurdity or something similar without due consideration. The second is a doubt about stable free equilibrium because MPW assists stability in the free position yet does not guarantee it.

Therefore, the overall strategy at the beginning provides for diverse versions of the MPW-manifestation by tests which can be carried out for magnetic force levels up to 100s of Newton. The cheapest way to do this is to test MPW by using available super conductive magnets. Only after demonstration of the MPW phenomenon at different levels of persistent currents and spacing, with and without magnetic shields etc. will remove grounds for doubt.

The project provides for new eventualities to improve the design of superconducting magnets as key enablers of levitation. The main challenge here is the constraints on load-bearing elements of superconducting magnets. On the one hand, they must be thick and short to securely transmit sizeable magnetic forces from the "warm" zone to the cold one. Each magnet must be a tightly coupled system. Force effectiveness of interacting magnets and the desire to have big levitation spacing necessitate small design dimensions surrounding the superconductive coils. On the other hand, load-bearing elements (and other ones) of the design must be thin and long, and manufactured from super heat-insulating materials to minimize heat losses that are direct energy losses caused by operation of the superconducting system. To the main problem facing conventional superconducting magnet design we must add the optimal current-carrying geometrical configuration of the MPW-levitation as a new design element peculiar to this new levitation phenomenon.

New eventualities planned to be investigated focus on unusual current-carrying coil configurations, new heat-insulating materials with thermal conductivity and tensile strength fifty times lesser and no less than corresponding parameters for stainless steel respectively. Novelties in design will keep thin and long load-bearing elements that will work in tension and at the same time design dimensions surrounding parts of superconductive coils producing levitation magnetic forces will be smaller than for traditional designs of force superconducting magnets. An oddity in our concept of the evaporated helium liquation is refrigeration with minimal and maximal temperatures of thermal cycle between 4 K to no more than 15 K. This allows us to maintain zero electrical resistance conditions for some high current density superconductors such as niobium-tin windings that enables the use of super rigid magnetic bearings based on the MPW [10]-[13] in refrigerant compressors and expanders. The last will result in considerably higher thermodynamic efficiency of refrigeration and unparalleled energy efficiency of the superconductive magnets operation in general.

Validation of the MPW-manifestation and magnet design will be conducted together with theoretical researches of magnetic forces and stability of the MPW-levitation. The novel features of this problem require us to take into account the arbitrariness of the free body location using modern computer software. Our experience allows us to transform the MPW-levitation problem into a precise mathematical framework and to derive solutions instead of using expensive tests to find levitation conditions.

After validation of the free position stability, researches of the free magnetically levitated body dynamics are scheduled. This part of the works is important to study dynamic behaviour of the free vehicle and how parameter values have an impact on this behaviour. Investigations of this very complicated mathematical problem will be based on mathematical models of dynamics derived *a priori* and corrected by testing.

Finally, the plan provides for making and testing the working model, validation of the MPW-levitation parameters, and demonstrations of levitation for a suitable range of parameter values.

4 HIGH-SPEED ACCELERATION/BRAKING

The exact solution of the optimization problem to minimize a frictionless motion time between two points with zero initial velocity reduces to the motion with constant maximal acceleration. Figure 2 demonstrates this conclusion graphically. The area S of OABL-rectangle representing the work of the accelerating force P at the acceleration interval L is maximal.

Many practicable acceleration technologies fall well short of this optimal solution. For example, a real shot is realized with force-distance dependence represented by the curve l. The area between curve l and horizontal axis in Figure 2 is much less than that of the OABL-rectangle. Therefore, the kinetic energy of a bullet or shell as a part of this area and outgoing velocity as this kinetic energy measure are much less than the corresponding parameters, which could be obtained with the maximal area S.

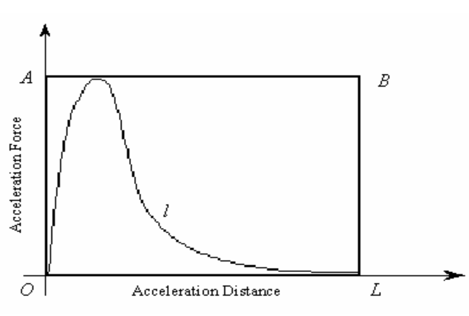

Figure 2. Acceleration force versus distance

This drawback is entailed by the operating principle of the “classical” shooting because burning reaction transient comparable with motion times generates a gas pressure that decreases with increasing gas volume during motion.

The use of burning reaction with curve l approaching to the rectangle is possible for missiles. But in this case energy efficiency of acceleration process is very low. Moreover, the fuel and oxidizer must be accelerated together with accelerated body. Therefore the missile principle to accelerate is also ineffective from the shortest acceleration time viewpoint indicated.

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The electromagnetic acceleration of a body possessing electrical conductivity by non-periodic discharge of a RLC- circuit results in force-distance dependence similar to curve l in Figure 2. This is far from optimal as well.

Another problem is friction. One-dimensional motion of a mass m accelerated by the constant force P = ma (a is acceleration) under the presence of a friction force F that with coefficient k is proportional to the velocity V and is described by the differential equation

$$m\frac{dV}{dt} + kV = ma \; . \tag{6}$$

If at zero time V = 0, this equation has the solution

$$V = ma\frac{1-\exp(-kt/m)}{k} \tag{7}$$

In the case of frictionless motion (k = 0) this gives V = at denoting an indefinite increase as a function of time t. Motions with friction restrict V by the value am/k. It means that beginning from some velocity the energy is converted into friction heat loss instead of being used to accelerate. Therefore, elimination of friction is paramount for high-speed acceleration.

The maglev technology is the best solution to minimize friction. However, it is not a panacea for high-speed acceleration. Its realization entails some novel problems that are quite different from traditional kinematics with friction. Particularly it is important to guarantee non-contact hovering during the acceleration process. This condition places active constraint on the magnetic levitation stiffness. In other words, the heat release problem in usual kinematic pairs with friction that arise at high velocities transforms into the problem of providing with some magnetic force parameters for non-contact kinematic pairs.

Any magnetic levitation concept is restricted by the stiffness level. This restriction depends on many factors, particularly on the level of levitation magnetic fields. The MPW-levitation guarantees the highest level of field. It can operate in fields of 10-20 Tesla. Other versions, e.g. automated electromagnetic suspension are restricted by approximately 2.5 Tesla that corresponds with magnetic saturation of magnetically soft materials. The best rare-earth permanent magnets used for high-temperature super conductive magnetic levitation are even more restricted. By contrast, the MPW-levitation is capable of providing 10^8 N/m^2 of operating magnetic pressures and more. Such levels can guarantee stiffness sufficient for non-contact acceleration with outgoing velocities greater than 10^3 m/c.

Magnetic levitation as a tool to practically eliminate friction is only a part of the problem of high-speed acceleration. A problem of no less importance is making a compact mover of high power capacity and constant accelerating force or, in other words, conversion of the curve 1 to the horizontal segment AB in Figure 2.

There are two well-known classic versions of the mover, represented by asynchronous linear motor (ALM) and synchronous linear motor (SLM). The ALM is capable of operating regardless of synchronism between velocities of the accelerated body and magnetic field generating by three-phase winding. Its drawback is low levels of accelerating forces caused by low levels of both generating and generated magnetic fields.

The SLM can use powerful on-board super conductive magnets operating in the persistent current mode and three-phase winding or individual magnets on the ground. This substantially increases the level of accelerating forces but requires synchronism between the vehicle magnetic field and one running along the direction of acceleration. Therefore LSM needs a smooth frequency converter. The last is an additional bulky device transferring energy required to accelerate a body. This substantially lowers the energy transformation efficiency. In the case of individual accelerating magnet along the direction of acceleration, rapid switching of powerful electromagnets must be provided for. This is a complicated technical problem because its realization involves considerable release of heat and undesirable side-effects like short circuits. Practically this case transforms the smooth frequency converter problem into the short energy evacuation problem applied to powerful inductive energy storages.

We have experience in developing a new linear accelerator/decelerator that uses powerful individual superconducting magnets and SQUID- automation.

The energy efficiency of this linear drive in accelerating mode can be no less than 90%. We tested various experimental models of the new drive with 2000 N force and demonstrated energy efficiency of 92%.

The analysis above shows the problem of high-speed acceleration requires attention to new ideas because “classical” principles demonstrate disadvantages as a result of an ineffective force law. On the other hand, there exist many practicable results in applied superconductivity particularly in the design of compact, powerful super conductive magnets. These magnets can be used as super-effective inductive storage with energy loss only to compensate cold leakage - this is a very small part of useful magnetic energy.

We develop a new approach in acceleration to some practicable applications, particularly to the “Aircraft Take-Off and Landing System” (ATOLS).

An aircraft taxis a very long time before take-off and after landing. A descending flight takes a long time. Energy efficiency is no more than 30% on any part of the flight. The kinetic energy of the aircraft and the energy for braking are wasted during landing. Aircraft engines are sources of air pollution and noise. Aircraft comfort and new modes of lift-off are limited by engine power. There seem to be limits to the power of engines given the size and mass constraints for contemporary flight.

ATOLS can realize unprecedented improvements in aircraft transport because it is capable of executing mutual transformation between magnetic and kinetic energies of billions of Joules directly, with more than 90% efficiency, quickly, and without contact. By means of ATOLS, the takeoff and landing time and runway can be reduced to 20 s and 300 m respectively and landing speed can be 500 km/h and higher. During ATOLS-acceleration the magnetic energy stored in advance by immobile super conductive magnets is converted into the kinetic energy of the aircraft directly, without sliding contacts, and practically without energy losses. During ATOLS-braking of the aircraft along runway its kinetic energy in a like manner is stored in the form of magnetic energy by immobile super conductive magnets with the possibility to be reused e.g. to reaccelerate the aircraft. ATOLS eliminates the problems of carrying capacity, sufficiently decreases spatial requirements and essentially reduces pollution around the airport.

5 RIGID MAGNETIC BEARINGS

Magnetic bearings have become very important elements for many applications [16]. We develop superconducting versions of them based on the MPW that have been invented by Vasyl' Kozoriz [10]-[13].

The majority of devices using commercial bearings operate with radial stiffness of 10^7 N/m to 10^8 N/m. In order to compete with them, non-contact bearings must demonstrate comparable parameters. But, known magnetic bearings fall short of these required values of stiffness. Analysis conducted by Moon [16] shows that achieved stiffness for electromagnetic controlled bearings is on the level of 10^5 H/m and this is due to operation in the field near to the magnetic saturation of soft-magnetic materials. Superconducting passive bearings based on diamagnetism demonstrate lower operation stiffness. MPW-bearing (a version is shown in Figure 3) where

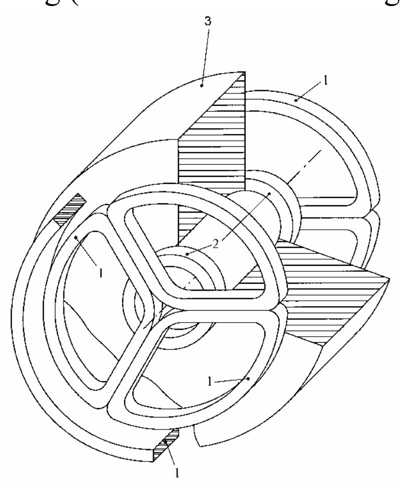

Figure 3. MPW-bearing

stator superconducting coils 1 and rotor superconducting coils 2 operating in the persistent current mode are capable of suspending the rotor 3 in the free state at working magnetic fields of approximately 10 Tesla and higher demonstrate radial stiffness no less than 10^7 N/m.

Moreover, current carrying elements as levitation enablers, instead of typical winding technology can be fabricated on the basis of planar technology. This allows the use of brittle materials, particularly CuO-based high-temperature superconductors with upper critical field of 30 Tesla to 200 Tesla instead of 20-30 Tesla for niobium-based low-temperature ones (see [16], table 3-3). This means that MPW-bearings of super high stiffness can be realizable with low and high temperature superconductor materials. An additional way to improve force characteristics is the topology of current-carrying elements (Fig. 4) when rotor or stator part of bearing 1 has big loops 2 responsible for the supporting magnetic force level and small loops 3 dramatically increasing levitation stiffness.

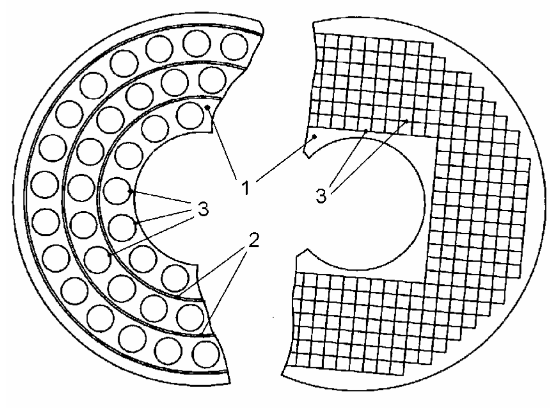

Figure 4. Current-carrying elements

Analysis of the super rigid MPW-bearing shows they can operate with working radial stiffness of about 10^{13} N/m; that is sufficient to guarantee fail-safe operation of a flywheel energy storage kinetic energy density of which is comparable with petrol burning energy density.

6 SUPER PRECISE INERTIAL NAVIGATION

In these applications the MPW-phenomenon provides for a lossless energy super conductive levitation of a sensitive element. The idea of the controlled multidirectional MPW-suspension of a single free sensitive element is used. This free element is fully immobile relative to the device frame. In order to attain the space immobility, SQUIDs fix three displacements of the sensitive element mass center and three angles of its space orientation relative to the frame. Any change of fixed parameters causes currents and corresponding magnetic forces in the controlling coils. These forces compensate any linear and/or angular displacements of the sensitive element that may arise during motion of the frame. Exact and full information about currents in controlling coils measured by SQUIDs is sufficient for the most precise solution of the inertial navigation problem. As an example, the aircraft MPW-navigation system is capable of determining location relative to the runway at the end of 10-hour flights with no more than a few centimetres of error.

7 DOCKING IN SPACE

Instead of complicated conventional docking operations, the ability of MPW-force to change attraction at big spacing into repulsion at small ones is used. This ability is the best executor of docking operations: to orient distant spaceships, to accelerate them for approach, and to slow them down to touch without impact. The MPW-docking realizes these operations as “direct and full manifestation” of the MPW.

The distant spaceships launched separately into their outer space nearness spontaneously change their relative orientation to one when magnetic attraction between super conductive magnets of the spaceships takes effect. As a result, the spaceships begin to approach one another.

The spaceships’ superconducting magnets are energized on the Earth before launch under conditions of the MPW-manifestation between them. Subsequently these magnets operate in the persistent current mode up to docking end and possibly longer. During approach, the magnetic energy accumulated by super conductive magnets turns into the kinetic energy of the spaceships directly and without losses. Accordingly to MPW-manifestation, approach of spaceships results in change of magnetic attraction into magnetic repulsion caused only by the decrease in spacing between superconducting magnets of spaceships. Therefore in the approach process the spacing arises at which attractive magnetic force between super conductive magnets is zero. At this spacing conversion of the magnetic energy into spaceships kinetic energy ends. Nevertheless, spaceships continue to approach by inertia.

As the MPW- manifestation, after zero magnetic force spacing repulsive magnetic forces emerge between super conductive magnets. These magnetic forces increase in magnitude as the spaceships get closer causing them to slow down. Such braking is not caused by energy dissipation or a similar process. It is a natural consequence of the process of direct conversion of the relative motion kinetic energy of the spaceships into magnetic energy of their super conductive magnets operating in the persistent current mode.

At some minimal spacing between the spaceships their relative motion kinetic energy runs out and turns completely into magnetic energy. In this moment it is necessary to turn on coupling locks because the spaceships can begin to move in opposite directions as a result of magnetic repulsive forces between their super conductive magnets.

The described mechanism of docking is a self-executing process and does not need any other movers, sources of energy supply or complex control systems. The energy accumulated in the super conductive magnets can be kept after docking or be utilized to uncouple spaceships.

We have elaborated the theory of the MPW-docking and executed simulations confirming the effectiveness of this proposal.

8 CONCLUSIONS

Some technical proposals represented above and developed by Vasyl’ Kozoriz and his group are based on a new magnetic force phenomenon “Magnetic Potential Well” (MPW) requiring zero electrical resistance of a closed current carrying loop to be manifested. This condition successfully meshes with properties of available high current density superconductors capable of surely operating in high magnetic fields. Additionally, MPW does not require automation to levitate at rest or during motion. Working parameters of MPW-devices demonstrate some properties and parameters unachievable for known technologies. As we face challenges of global warming and resource depletion, particularly of non-renewable sources of energy, new possibilities can be sources of immense hope and profit.

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