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AMLEV: A NEW ALTERNATIVE OF MAGLEV

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Keywords

Abstract

Herein is provided a brief description of AMLEV's design and the operating principles of its self-regulating magneto-dynamic suspension and permanent magnet propulsion motor. The feasibility of self-regulation of both the magnetic suspension and the propulsion motor is proven, thus making it possible to utilize the properties and peculiarities of mechanical, magnetic and electro-dynamic processes to ensure their interaction so as to achieve self-regulation of vehicle flight.

1   Introduction

American magnetic Levitation High-Speed Ground Transportation (AMLEV) is based on the use of permanent magnets and steel cores, producing magnetic forces with maximum efficiency while eliminating dynamic instability. Its Magnetic Suspension and Propulsion Motor are both self-regulating, and its Power System is much simpler, more reliable, and cheaper than those of the other types of Maglev. A detailed description of AMLEV is presented in [1, 2, 3, 4]. AMLEV consists of three components:

1) a magneto-dynamic suspension system – MDS [1, 2, 4];
2) a linear motor based on permanent magnets – PMLM [3, 4];
3) a conventional power system [3, 4].

The sources of magnetic field are Crumax rare-earth permanent magnets and steel cores. AMLEV stator's winding is powered by sinusoidal current of constant frequency.

AMLEV compensates instantly and flawlessly for any external effects by producing interacting mechanical electromagnetic processes.

2 Magneto-dynamic suspension (MDS)

An Amlev vehicle has to fly with the speed of $V \leq 150$ *m/sec* along winding track set by steel cores within a short distance from them, $g<0.01m$. During its flight the vehicles affected by a number of external forces: weight $G \geq 25t$, centrifugal force on the curves (up to 15 t), lateral wind pressure (up to 5 t per vehicle) and so on. A shift of the vehicle by a value of $\delta = g$ leads to a catastrophe. That's why the vehicle has to be supplied with a stable magnetic suspension (MS) that would instantly and faultlessly generate internal stabilizing force F_S that is proportional to the shift value and directed the opposite way. Only a combination of rare-earth magnets and steel cores can generate such big forces.

The purpose of the magnetic suspension is production of stabilizing forces maintaining a vehicle in equilibrium during its motion along a projected trajectory. Equilibrium should be indifferent along the trajectory and stable in all perpendicular directions. Such devices are considered in stability theory.

Magnetic suspension utilizing permanent magnets is a conservative system, i.e. one that preserves its magnetic energy. Two of its parts - the stator and the levitator - are separated in space, interacting with one another through the magnetic field.

Internal forces in a conservative system are derivatives of potential magnetic energy with respect to coordinates of the shift between its parts. In the absence of external forces, the parts of the conservative system tend to assume position with respect to each other in which potential energy of the system is reduced. Therefore, if the levitator together with the vehicle is in a position of stable equilibrium (i.e. all internal forces turn into zero) and is not touching the guideway surface (Lagrange-Dirichlet theorem [5]), it can be stated that the magnetic suspension represents a stable conservative system with its potential energy having a local minimum located off guideway surfaces. In this case, any shift of the vehicle from its equilibrium position under pressure of an external force instantly produces an internal stabilizing force that attracts the vehicle to its equilibrium position, since in the vicinity of the minimum of potential energy its derivatives (i.e., internal forces) along any direction are negative. Hence, to achieve MS self-regulation it is sufficient to ensure stable equilibrium of a flying vehicle along the whole length of its track.

When a vehicle is in stable equilibrium, stabilizing force acting on it is equal to zero. Therefore MS stabilizing force in close vicinity [δ] of a projected trajectory can be expanded in Maclaurins's series and expressed as

$$F_s(\delta) \approx \frac{\partial F_s}{\partial \delta} \times \delta = F_s' \times \delta.$$

Consequently, stabilizing force is determined not by the value of internal forces F, but by the value of its derivatives, that is, by stiffness F_s' of stabilizing force.

Possibility of creating a stable MS was discovered more than two centuries ago and supported by Lagrange-Dirichlet theorem. In our case this theorem states that the position of MS levitator magnets is stable if potential energy of magnetic field of the MS has its local minimum $E_{P\,min}$ located outside of the steel cores surface. However all attempts to create a stable MS using permanent magnets and steel had failed, so in the 70s of the last century they were suspended and

a conclusion was made that potential energy E_P cannot have a local extremum. Our purpose is to show that this conclusion is wrong.

Potential energy in any conservative system is a result of existing rigid constrains that limit movement of the sources of its field. In our case these are constrains between permanent magnets of the levitator and steel cores of the stator. Consequently presence of E_P minimum depends solely on the character and properties of these constrains.

In terms of stability theory, analysis of stability of a conservative system can be simplified by substituting solid bodies composing the system with points. In our case the system has just one solid body - levitator magnets assembly with its equilibrium position denoted by a point Q. Then the extremum E_P looks like regular function of two variables (y, z) . Let us draw a circle in close vicinity $[\delta]$ around the point Q and find out whether the system has extremum. For this purpose we will shift the levitator from the equilibrium position by distance δ in any direction and find an internal magnetic force that is a derivative of E_P with respect to δ. If all forces originating in the point Q are directed along radiuses away from the center we have E_{Pmax} in Q (in this case $Q= Q_{max}$, and the forces F_d are destabilizing). If the internal forces are directed toward the center we have E_{Pmin} in Q (in this case $Q= Q_{min}$, and the forces F_s are stabilizing). Thus a radial pattern of the vectors of internal forces can be indicative of extremums of E_P.

Our purpose is creating an MS in which shift δ of the magnets from a given trajectory (axis OX) would generate stabilizing force F_s only. Let's examine simple constructions of magnetic devices.

1. In the Fig.I a permanent magnet is located symmetrically between the ends of a C-shaped steel core. Forces attracting magnet poles to the ends of the core are equal and oppositely directed, the magnet (dotted line) is in equilibrium. Vertical shift δ_V of the magnet generates stabilizing force

$$-F_s(\delta) \approx \frac{\partial F_s}{\partial \delta} \times \delta \qquad (I)$$

attempting to bring the magnet back to equilibrium. Horizontal shift of the magnet δ_H generates destabilizing force

$$F_d(\delta) \approx \frac{\partial F_d}{\partial \delta} \times \delta \qquad (I')$$

that increases the shift. Extremum E_P is not present here.

2. Fig. II shows two devices of the same kind that are perpendicular to each other and have firmly connected magnets and steel cores. Shift δ of the magnets from their equilibrium along both horizontal and vertical axes would generate oppositely directed forces F_d and $-F_s$. Rigid constrain between the magnets sums the forces into a single resulting force $F_\Sigma = F_d - F_s$, that will be only destabilizing if $F_d > F_s$ or only stabilizing when $F_s > F_d$.

Shift δ_α at any angle α (in the plane of the figure) will generate forces of the same values

$$F_{s\alpha}(\delta) \approx \frac{\partial F_s}{\partial \delta} \times \delta \times f(\alpha) = -F_s \qquad , \qquad (II)$$

$$F_{d\alpha}(\delta) \approx \frac{\partial F_d}{\partial \delta} \times \delta \times f(\alpha) = F_d \qquad (II')$$

where $f(\alpha) = (cos^2\ \alpha + sin^2\ \alpha)^{1/2} = 1$, and resulting force $F_{\Sigma\alpha}$ will also be only destabilizing $F_{\Sigma\alpha} = F_{d\alpha}$ or only stabilizing, $F_{\Sigma\alpha} = F_{s\alpha}$. But conditions (II) and (II') indicate that $E_P(Q)$ has a local extremum, either maximum or minimum. Hence the device presented in Fig.II overturns the conclusion that potential energy E_p cannot have a local extremum. Moreover, this example indicates direction and purpose of our research: in order for MS to be more stable its design has to ensure greatest possible inequality $F_s >> F_d$. Substituting in this

inequality expressions of forces by (I) and (I') we obtain the condition of MS stability: in the point of levitator equilibrium the following inequality has to be ensured:

$$\frac{\partial F_s}{\partial \delta} > \frac{\partial F_d}{\partial \delta}$$

3. Fig. 2 presents cross-sectional view of Amlev MDS unit in which the magnitude of the force F_d is proportional to the difference of magnetic fluxes Ψ in the right and left core tips [1]. Nonlinear dependency of magnetic permeability μ_f of steel on the flux density B in it allows fulfillment of the above inequality. If at equilibrium of the quadruple magnets the cores backs will be evenly saturated along their entire length, then the shift of the quadruple to the right will cause decreasing of the right air gap, the flux in the right back will increase and its magnetic reluctance will grow too compensating for the decrease of the right gap. On the left – vice versa, the gap will increase, the flux will decrease and will in turn decrease reluctance of the left back. Dependency of the flux difference on the magnets shift will decrease and the value of the derivative $\dfrac{\partial F_d}{\partial \delta}$ will drop sharply, thus ensuring the above inequality. During a vertical shift of the quadruple saturation of the backs will have practically no effect on the value of the derivative $\dfrac{\partial F_d}{\partial \delta}$.

Thus saturation of core backs reduces destabilizing force only.

The MDS consists of four identical interconnected magnetic units (Fig.1), each of which, in turn, consists of two components: one movable and the other stationary (Fig.2). The movable component – a levitator – contains four long permanent magnets of rectangular cross-section assembled in a quadrupole with the help of a steel insert. The immovable component – a stator – consists of two laminated steel cores of unlimited length with "C"-shaped cross-sections. Each core has a long back and two thickened unsaturated tips. The core backs are covered by aluminum screens. The cores are located mirror-symmetrically to each other and extended along the entire guideway. A constant air gap is maintained between the thickened tips pertaining to the right and left cores. The quadrupole is inserted into this air gap and can move freely within it in all directions. It is proven in [1] that:

a. a quadrupole located symmetrically between the core tips is in equilibrium (Fig.2);
b. a lateral shift of the quadrupole from symmetrical position invokes destabilizing force F_d tending to increase the shift and to attract the quadrupole to the nearest core tip (Figs. 2a, 2b);
c. a vertical shift of the quadrupole invokes stabilizing force F_s tending to decrease the shift and to bring the quadrupole back to equilibrium. The mode of the unit action is similar to a bow. Tubes of magnetic flux closing through air are resilient. They are permanently coupled with their source – a permanent magnet – and are held by the ends of steel cores. If the magnet shifts up or down, the flux tubes bend and stretch, thus creating a force opposing the shift, which varies proportionate to shifts (Fig.2c).

The unit forms a double-contour magnetic circuit with permanent magnets – the sources of *mmf* (magneto motive force) – and magnetic reluctances, both linear (the distance between the steel insert and core tips) and non-linear (saturated steel core backs), which increases rapidly with the growth of its magnetic flux. If the long levitator's magnets are divided into ν equal components, and each even component is turned by 180°, an alternative magnetic flux (including leakage flux) appears in the stator's cores during vehicle motion. The leakage flux induces eddy currents in the aluminum screen with the magnetic field oriented contrarily to the leakage flux. This means that an electromagnetic barrier is raised, almost completely suppressing the leakage

flux and maintaining core saturation at the required level. By exploiting the saturation of the steel core backs it is possible to reduce the value of destabilizing force by up to 20 times.

The theoretical basis for MDS operation principle, and its design and analytical methods for its calculation are presented in [1, 2, 4]. Despite the relative simplicity of the MDS design, unusual interaction of internal physical processes during vehicle flight complicate understanding of its operation and generate questions not addressed earlier [1, 2]. It is helpful in this regard to understand certain considerations and estimations that led to the creation of the MDS principle.

2.1 Earnshaw and Lagrange-Dirichlet theorems

Numerous earlier attempts to construct a stable magnetic suspension (MS) based on permanent magnets and steel cores were abandoned after inventors erroneously concluded that Earnshaw's theorem proved that such systems were physically impossible. Analyzing the theorem, I concluded that the theorem held true only for objects with constant magnetic permeability, but the permeability of steel suspension components is highly dependant on the intensity of the field. This peculiarity of saturated steel suggested that the creation of a stable MS based on the permanent magnets and steel cores was in fact possible. I applied deductive method to the Lagrange-Dirichlet theorem [5] stating in our case that the position of MS levitator magnets is stable if potential energy E_p of magnetic field produced by permanent magnets has a local minimum E_{pm} outside the cores' surface. Since it is impossible to measure potential energy E_p, it becomes expedient to proceed from the opposite premise: if the MS levitator is in equilibrium, and any slight shift produces a stabilizing force, then the MS is stable. Such an interpretation of Lagrange-Dirichlet theorem made it possible to create a stable MS.

2.2 Application of Lagrange-Dirichlet theorem for creating a stable suspension

The levitator's magnets are fixed rigidly on a Maglev vehicle and together with it form a solid body of cylindrical shape. The solid body summarizes all forces applied to it in one total equivalent force. Considering this peculiarity of a solid body when proving Lagrange-Dirichlet theorem, a real, conservative system comprising bodies of different configurations was substituted by system of mass points. With this approach real distribution of forces and torques acting on each body was not considered but instead was substituted by an equivalent force. Therefore in order to apply Lagrange-Dirichlet theorem for creating a stable suspension of a real body of definite shape, the equivalent force must be expanded into components in such way that they satisfy all necessary equations of static body's equilibrium. Within the context of the Maglev system it is essential to ensure stable equilibrium of two bodies only: an immobile stator and a flying levitator. To attain this effect, it is necessary to position levitator magnets and stator cores in a specific pattern.

2.3 Maximum stability of the flying vehicle

The interaction of levitator magnets and stator steel cores produces stabilizing forces. To impart maximum stability to the flying vehicle, the torques of these forces must be as large as possible. Because the torque of the couple of forces is proportional to the distance between these forces, the magnets on the vehicle must be attached to its bottom and walls close to the edges (between the bottom and walls) along the entire body. Correspondingly, the stator cores must be located along the guideway and be parallel to flying magnets within a small gap (Fig. 1). The stator cores together with two sets of magnets located in series on the vehicle make up two magnetic devices intended to produce stabilizing forces F_s. In this case the vehicle has one degree of freedom directed along Axis OX. All other shifts and turns should produce stabilizing forces and torques.

2.4   Expressing stabilizing force through magnetic forces

The derivative of E_p with respect to levitator shift δ equals to magnetic force

$$F = -\frac{\partial E_p}{\partial \delta} ,$$

pointed in direction of E_p reduction. Therefore, forces of interaction between levitator magnets and the stator cores are the components of force F_s in the vicinity of equilibrium, where $E_p \approx E_{pm}$. It follows from above that:

(a)   A minimum of potential energy of real Maglev vehicle is simultaneously achieved at multitude of points of regular three-dimensioned space.

(b)   The shapes of both MS magnets and cores must be cylindrical with their generatrices parallel to Axis OX.

Let's assume that design of MS ensures local minimum of E_{pm}. This means that when the levitator is in a position corresponding to this minimum (point 0) then according to definition of minimum, the sum of all forces acting on it is zero, that is the levitator is in equilibrium. However each magnet produces a force. Consequently, equilibrium results from counter forces balancing each other. The following conclusions can be drawn:

(a)   The shapes of magnets and positions of steel cores in MS must be mirror- symmetrical;

(b)   The force generated at magnets shift δ from the equilibrium should be stabilizing only, i.e. opposed to the shift.

$$F_s(\delta) = F(0) + \Delta F - (F(0) - \Delta F) = 2\Delta F ,$$

but $$\Delta F \approx \frac{\partial F(0)}{\partial \delta}\delta = \frac{\partial^2 E_{pm}}{\partial \delta^2}\delta .$$

Therefore $$F_s(\delta) \approx \frac{\partial F_s}{\partial \delta}\delta = -2\frac{\partial F(0)}{\partial \delta}\delta = -2\frac{\partial^2 E_{pm}}{\partial \delta^2}\delta \qquad (1)$$

One can see from formula (1) that the value of stabilizing force is proportional to the shift δ and does not depend on the value of magnetic forces $\pm F(0)$ (as it is commonly considered) but does depend on the value of its change ΔF (at the levitator shift δ) which is the greater, the less is the volume of field with energy E_p (comparing to δ). This brings us to a very important conclusion:

2.5   The magnitude of the stabilizing force in AMLEV

The approach of a permanent magnet to a steel core tip induces magnetizing currents (flowing without resistance) on the tip surface in the vicinity of the magnet pole. Their values are of the same order, and their direction coincides with the direction of magnetizing currents in the magnet. Therefore both currents attract each other and thus concentrate the energy of the resulting field in a small volume of the air gap between the pole and core tip. The stabilizing force in AMLEV is created by interaction between these currents. The force of interaction between two parallel contours of currents is proportional to the product of the current values and inversely

proportional to a certain mean distance between the contours. The stiffness of the force is inversely proportional to the square of this distance. Hence, the less is the distance, the greater is the stiffness. This explains why stabilizing force in AMLEV is so large.

2.6 How to create a stabilizing force in magnetic device

If each of magnetic devices described in 2.3 produces stabilizing force with components F_{sy}, and F_{sz} at the shift of levitator-vehicle assembly, then such an MS is stable. To create a stabilizing force in a magnetic device-unit I employed an analogy between magnetic lines of force and a stretched bowstring. In assembling magnets in quadrupoles I placed them into a gap between tips of two C-shaped mirror-symmetrical steel cores (Fig.2). A shift of a magnet along the gap bends and stretches magnetic lines like a bowstring (Fig.2c) thus producing a stabilizing force F_{sz}. However a shift of the magnets across the gap produces an interfering destabilizing force F_d (Fig. 2a, 2b).

2.7 Condition of stability

A pair of such units with rigidly connected reciprocally-perpendicular quadrupoles at their shift will produce either only stabilizing force ($F_s > F_d$) or only destabilizing force ($F_d > F_s$). Two such coupled units may create a stable MS if a condition

$$\frac{\partial F_s}{\partial \delta} > \frac{\partial F_d}{\partial \delta} \qquad (2)$$

is fulfilled.

It has been shown [1] that condition (2) may be fulfilled if flying levitator's magnets saturate the steel core backs.

2.8 Compensation of reluctances of the air gap by saturation of the core back

Each unit is in fact a symmetrical double-contour magnetic circuit. Two permanent magnets (the source of mmf), a C-shaped steel core and two air gaps between core tips and magnetic poles are sequentially connected in each contour. Stabilizing (F_s) and destabilizing (F_d) forces are proportional to the difference of magnetic fluxes penetrating top and bottom segments of the surfaces of all four tips ([1], equations 4, 5).

When the density of the flux B in electrical steel exceeds $2T$, the plot of its specific magnetic reluctance against flux density $\rho(B)$ is an almost straight line (Fig. 3). If there are no leakage fluxes, this peculiarity of saturated steel enables adjusting the sizes of quadrupole magnets, air gaps and steel cores in such a way that at equilibrium the backs of the cores are saturated to a required level $B = (2.04$ to $2.06)$ T [1].

To further explain this statement let me explain deriving formulas (10) and (12) in [1]. By substituting the values $r = \dfrac{e}{\Psi_w^0}$ and $B_f = \dfrac{\Psi_w^0 bN}{\varepsilon\, l_s}$ into equation $r_f = r(\varepsilon - 1) = b(B_f - B_s)$

we derive a quadratic equation in respect to: $b = \dfrac{l_s}{N t_s}$

$$\frac{e}{\Psi_w^0}(\varepsilon - 1) = b\left(\frac{\Psi_w^0 bN}{\varepsilon\, l_s} - B_s\right)$$

which in normal form looks as follows:

$$b^2 N \Psi_w^{\,o} - b \varepsilon l_s B_s - r\varepsilon(\varepsilon - 1)l_s = 0 \qquad\qquad (3)$$

Formula (10) in [1] is a solution of this equation.

Formulas (12) in [1] were derived by solving the following quadratic equations

$$\Psi_{WR(L)}^2 - \Psi_{WR(L)} t_s\left(B_s - \frac{r_{R(L)}}{b}\right) - \frac{e t_s}{b} = 0 \qquad\qquad (4)$$

and their subsequent simple modifications.

When the quadrupole in such a unit shifts, for example, to the right, then magnetic reluctance of the right gap is reduced (while that of the left gap is increased). In this case magnetic flux in the right core and reluctance of the right core back is increased (at the left side everything is vice versa). Thus saturation of the core backs compensates for the reluctances of the air gaps at magnets shifts, thus reducing dependencies $F_d(\delta)$ and their derivative $\dfrac{\partial F_d}{\partial \delta}$ almost by 20 times.

2.9 Electro-magnetic barrier against leakage flux

There are no natural isolators for static magnetic flux at normal environmental temperatures. Meanwhile, saturation in the steel cores should be maintained on a required level. This is impossible to attain if the magnets are immobile. However, when the magnets are in motion, it is possible to convert the magnetic flux in the core backs to alternative and almost completely suppress leakage fluxes through the lateral surfaces of core backs. It has been proved [1] that covering lateral surfaces of the core back with aluminum layer enables alternative magnetic flux to induce eddy currents in aluminum, which in turn creates electromagnetic barrier for leakage flux and thus ensures the required level of saturation in the core backs.

2.10 Elimination of the higher harmonics of magnetic field intensity

Fig. 9 of [1] shows that by removing higher harmonics of magnetic field intensity in core backs one can increase the factor K_{sup} of suppression of flux leakage by about 20%. The non-linear shape of the magnetizing curve $B(H)$ for electrical steel makes it possible to approximate distribution $H_f(x)$ (see [1], Fig.7) to a sinusoidal pattern, retaining at the same time constant size of the air gap g and only slightly altering the profile of cross-section of quadrupole magnets' bases and steel insert between them by the plane XOY (Fig. 4).

2.11 Estimating effect of aluminum screen

Let us estimate effect of aluminum screen upon the level of saturation of the core back. For this we determine maximal possible leakage fluxes from lateral surfaces (uniformly along the entire length l_s) of a saturated back with a screen $\Delta\Psi_s$ and without one $\Delta\Psi$ and compare them to a working flux Ψ_w.

Let's assume that magnetic flux with a density $B_f = 2.05\ T$ flows through the back 1 m wide and 0.01 m thick. From the curve $B(H)$ we find that $\mu_f = 40$. The value of the working flux is $\Psi_w = B_f\, t_s = 2.05 \cdot 10^{-2}\ Wb$

The back length is $2l_s = 0.24$ m. If the back is saturated uniformly the magnetic field intensity in it is

$$H_{f0} = \frac{B_f}{\mu_0\,\mu_f} = 4.1 \cdot 10^4\ A/m$$

Consequently, the value of a normal component of the leakage flux density B_n through the lateral surfaces the back with no screen will not exceed the value of $B_n = \mu_0 H_{f0} = 0.05152\ T$. At vehicle speed V = 150 m/s the aluminum screen will reduce sinusoidal density B_n by a factor of 60, and at speed V = 40 m/s – by a factor of 30:

$$B_{ns(150)} = \frac{B_n}{60} = 8.59 \cdot 10^{-4}\ T, \qquad B_{ns(40)} = \frac{B_n}{30} = 17.18 \cdot 10^{-4}\ T,$$

Hence leakage flux through both lateral surfaces of each half of the back of a screened core at V = 150 m/s will be

$$\Delta\Psi_s = 2l_s \cdot B_{ns(150)} = 0.01\Psi_w \qquad (5)$$

And at V = 40 m/s

$$\Delta\Psi_s = 2l_s \cdot B_{ns(40)} = 0.02\Psi_w \qquad (6)$$

A simple way to reduce the effect of $\Delta\Psi_s$ of such value upon reducing saturation of the back is shown in [1], Fig. 10.

Component $\Delta\Psi$ of the working flux in the core backs under front and rear surfaces of the magnets of the flying quadrupole branches off into adjacent unsaturated sheets (with the width $\nu = 0.3$ mm) of laminated core. The wave of alternating magnetic flux with a frequency f induces eddy currents in the sheets, which oppose flux movement across the sheets. To estimate the value of leakage $\Delta\Psi$ we have to determine the depth of penetrating $\Delta = (\pi f \mu \sigma_F)^{-1/2}$ of the flux wave into unsaturated component of the steel core.

Parameters of electrical steel are as follows: $\sigma_F = 0.3 \cdot 10^7\ Sm/m,\ \mu = \mu_0\,\mu_F,\ \mu_F = 10^4$

The length of the magnet is $l_m = 1.5$ m, so at the speed of the vehicle between 40 m/s and 150 m/s frequency f of the flux will change from 13 to 50 Hz. At the same time the depth Δ will

reduce from 0.8 mm to 0.4 mm. So the leakage $\Delta\Psi$ of the flux on both ends of the magnet will not exceed the component of the working flux Ψ_W under the magnet within 5 sheets and will be

$$\Delta\Psi \leq \Psi_w \frac{15 \cdot 10^{-4}}{1.5} = 10^{-3}\Psi_w = 0.1\%\Psi_w , \quad (7)$$

That is a negligible small value.

2.12   MDS can ensure slower movement of the vehicle

Along with the stable flight of the vehicle at $V > 40$ m/s MDS has to ensure its slower movement, when $V < 40$ m/s. At low speed the electro-magnetic barrier is weaker and the destabilizing force is greater. Thus, to keep the vehicle suspended within the field of the supporting units and prevent its deviation from its set trajectory, the effects of the guiding units must be eliminated and the destabilizing force of supporting ones be compensated.

To achieve this effect, the vehicle has to be equipped with three rows of supporting horizontal rolling wheels protruding at a speed less then 40 m/s from its walls and rolling with low friction along guiding strips on the walls of concrete channel of the stator. At the same time two pullout devices have to remove quadrupoles of guiding units from their cores. After this the vehicle will be suspended in the fields of supporting units. Acting together, these two devices will ensure safety of the vehicle in case of an accident along any point of the guideway and ensure its return to the nearest station. During regular start and braking of the car at and near a station, there are no cores of guiding units and thus there is no need to engage the pullout devices.

MDS is an example of a conservative system consisting of permanent magnets and steel cores covered by aluminum screens. Its potential energy has a local extremum (see [4, Fig.6]). However, when the MDS levitator is at rest, its equilibrium is unstable because the extremum in this case is a maximum. As levitator speed increases, the energy maximum is depressed and then (at speed $V > 25$ *m/s*) transformed into a minimum. At vehicle speed >100 *m/s* the stiffness of the stabilizing force per vehicle length 22 *m* reaches $3 \cdot 10^7$ *N/m* and can be increased even further by increasing levitator's magnets' weight.

3   A self-regulating motor based on permanent magnets and steel cores

The linear motor designed for AMLEV utilizes permanent magnets and steel cores installed on a vehicle rotor and a special form of stator winding. It is called PMLM.

It is essentially different from other LSM employed in the existing Maglev systems.

PMLM consists of an extended stator winding (Fig. 5), which is common for all vehicles, and a permanent magnet rotor (Fig. 6) installed on each vehicle. The winding is divided into different components, each powered by sinusoidal current from a separate step-down transformer. Current frequency in the winding is constant, however the length and cross section of its turns vary from one component to another [3].

The transverse turn segments form a U-shaped propulsion channel, the longitudinal segments (equal to the turn lengths) are gathered in two bars disposed on the external walls of the channel. The transverse bus-bars positioned on the bottom and on the walls of the channel the

currents running forward and back produce a current wave traveling with velocity V proportional to the turn length.

The rotor comprises mirror-symmetrical halves (Fig. 6) of a steel yoke inserted into a longitudinal slit on the vehicle bottom which are capable of moving apart and coming together along the slit and are operated by a synchronizing mechanism. Each half has cells containing permanent magnets capable of moving upward and downward within the cells, being operated by a synchronizing device. All magnets are of rectangular form and have pole shoes. In different halves magnets have opposite polarities.

The cross-section of each yoke half is made of two mirror- symmetrical C- shaped cores with core shoes. The core backs loosely embrace the stator's winding bars.

The steel yoke increases considerably the magnetic flux of the working gap in the PMLM. The PMLM does not produce any destabilizing forces, nor does it increase the stator's winding inductance.

The installation of the bus-bars in specific order (Fig. 7) simultaneously performs three functions:

1)   ensures a constant in time value of the total current (and propulsion force) in both halves of the traveling wave;

2)   eliminates additional *mmf* produced by the currents in the facing bars pertaining to the right- and left hand yoke components;

3)   makes it possible to change the rotor propulsion force by ± 28% on the acceleration and deceleration sections by moving apart and together the rotor's pole magnets synchronously with changing the winding turn lengths that the vehicle is passing by.

The PMLM design makes it possible to vary the Lorentz force proportionally to the rotor speed [5]. To attain this effect, the width of the bars of the winding components and also the power of the feeding transformers are made proportional to the winding turn length while the length of the rotor's magnets and pole pitches varies synchronously in accordance with the turn length of the stator's winding as it is being passed by the rotor. As a result, the rotor's magnet poles coincide with central components of halves of the traveling wave where linear current density (and, consequently, the propulsion force) is greatest.

The forces resisting the vehicle movement increase as its speed grows. By knowing the dependencies of all forces acting on the vehicle on its speed and by applying Newton's Third Law, we can establish the distribution of the winding turn length along the entire track (taking into account curvatures, slopes, acceleration sections etc.) to ensure Lorentz force exceed resistance to the motion everywhere. Such winding with signal indicators distributed along its length switches the synchronizing mechanism and devices by a strict program of self-regulation, ensuring stable PMLM operation and eliminating malfunctions.

Thus, PMLM self-regulation has two components, the chief of which – regulating the speed and amplitude of the running current wave – is provided by analytically calculating the distribution of length and cross-section of winding turns and the power of the feeding transformers at each track segment between two nearest stops. An additional component – the regulation of propulsion force –

is secured by the resilience of magnetic field lines within the rotor's working gap.

To simplify understanding of PMLM and its self-regulating let me lay out consideration that led to its creation.

3.1 Regulation of the vehicle speed

The dependence of the vehicle speed V on frequency f of powering current and stator winding turn length L_w is expressed by simple formula $V = 2 L_w \cdot f$.

Analogous to rotating motors in all the existing Maglev LSM, vehicle speed is regulated by f with L_w constant along the vehicle track. Regulation by f requires the whole energy to be converted twice.

I employed the peculiarity of a linear motor – its unfolded stator winding that makes it possible – to regulate V by L_w, keeping f constant. The vehicle speed can be calculated beforehand along the different segments of the track by solving the equation of the vehicle motion. The equation is obtained by equating the sum of all propulsion and resisting forces acting on the vehicle: that is, expressed in terms of the speed, to zero. Consequently, by knowing the speed distribution we can also determine $L_w(x)$ along the whole track at f constant and embody this solution in the stator design. Thus we avoid conversion of energy and ensure the identical speed of all the AMLEV vehicles throughout the track.

3.2   Regulation of the vehicle propulsion force

The vehicle propulsion force is proportional to the powering current.

In the existing Maglev LSM current is regulated with the help of a monitoring system that achieves control via radio transmission between sensors installed on the vehicle and feeding substations.

In the PMLM, non-uniform distribution of L_w requires changing rotor pole-pitches length during movement in accordance with L_w. The design of unfolded rotor poles makes effect feasible by installing synchronizing devices for regulation of pole length according to the length of stator winding turns that the vehicle passes by at the moment.

Thus vehicle speed and propulsion force of the motor are strictly controlled by stator winding. Resilience of lines of magnetic force in the working gap of the motor provides additional accurate regulation. Magnetic lines of the rotor's magnets in the air gap between its poles resemble stretched strings that are fixed at the pole shoes. The traveling current wave captures the string in the middle and bends them, thus creating a propulsion force that drags the vehicle along like a sled.

3.3   PMLM Design Optimization

[3] shows an example of design optimization for the PMLM rotor with a simple objective function – reducing weight of rotor magnets. In reality it is more expedient to proceed from a more complicated objective function. For example, after setting a required value of propulsion force, one should attempt to minimize expenses for creating the entire AMLEV system, which, in turn, are dependent on several parameters, such as the size and weight of the vehicle itself, rotor magnets and stator winding, frequency f of feeding current etc. To achieve this effect, one has first to define the formulas reflecting relations between the above parameters and use the method

of gradient descent move towards minimal expenses, similar to approach taken done during MDS design [1,2]. For instance, reducing frequency to 15 Hz will increase current wavelength λ_{15} to 10 m, induction B – to 1.4 T, weight of the magnets - by 1.66 times. But at the same time the weight of stator winding will be reduced almost twice and will significantly lower expenses per kilometer of the track.

3.4 Increasing efficiency factor

Propulsion winding of the stator has no steel cores or even regular spiral winds. Total alternating current in longitudinal segments passing through the openings in the steel yoke is equal to zero at any moment. So the yoke does not generate any inductive resistance. Current frequency in the winding is $f \leq 25$ *Hz*, which is a low value. That's why inductive resistance of the propulsion winding is insignificant and ***cos* φ** > 0.95.

3.5 The stability of PMLM, derivation of vehicle motion equation

PMLM like any electrical motor is capable of self-regulation (Fig.8) until the forces resisting the vehicle motion F_{Σ} less than Lorentz force $F_{Lor} = B\,h_g I$.

In order to eliminate PMLM loosing synchronism the Lorentz force must exceed sum resisting forces hindering vehicle movement. The unfolded forms of the LSM stator and rotor provide two means of achieving this effect:

(a) Increasing total current in both halves of traveling wave, automatically keeping the magnet's pole length L_{pl} proportional to the stator's winding turn length L_w.
$L_{pl} = \nu\,L_w$ where parameter $\nu < 1$. In our case $I = \nu\,L_w\,I_o$, where $I_o \approx const$ is a current in the stator's winding bars occurred in the rotor's pole gap per unit pole length;

(b) Restraining the growth of $F_{\Sigma}(x)$ by restriction of the vehicle speed $V(x)$ so that the following condition

$$F_{lor}(x) > F_{\Sigma}(x) \qquad\qquad (8)$$

is fulfilled along the whole track.

The first possibility was completed by working out a simple design of synchronizing devices. To fulfill another possibility I employed dependence of all forces acting on the moving vehicle on speed and applied Laws of mechanics to the vehicle motion. By introducing safety factor **$q > 1$,** I converted the above inequality (8) into equation (see (2) in [3]):

$$F_{lor}\,[V(x)] = C_o\,V(x) = q\,F_{\Sigma}\,[V(x)], \qquad\qquad (9)$$

where $C_o = B \cdot h_g \nu \cdot I_o \cdot (2f)^{-1} = const.$

Expressing all forces acting on the vehicle in terms of its speed $V(x)$ and substituting them in (9) I obtain a regular differential equation. Solving it with consideration of the restrictions on the values of all the accelerations and centrifugal forces I found the distribution of the vehicle speed $V(x)$ that would satisfy the above inequality along the entire track. Then knowing speed distribution it is easy to determine the distribution of the stator winding turn length $L_w(x)$ and the width $w_b(x)$ of the winding bus bars along the all stator segments and embody it in the stator design. Thus, the speed of the traveling current wave $V(x)$ is rigidly fixed at any point of the stator winding. Knowing this, I was then able to determine the distribution of all forces resisting vehicle motion $F_{\Sigma}(x)$. Summarizing these distributions and multiplying them by the safety factor q, I

obtained the desired distribution of Lorentz force $F_{Lor}(x)$. Now I can calculate current I in the traveling wave and in the stator winding phases for each section and eventually voltage and power of all the feeding substations.

The PMLM designed in such a way will be self-regulating and stable.

4   Conclusions

Amlev is not only a new idea, it's a completed project of self-regulating high-speed transportation system, where problems that have been delaying commercial use of other Maglev types, are completely resolved. Flight regulation is performed not by sensors and fast-acting monitoring systems, but the very properties of interrelated physical processes generated by car movement within Amlev system:

- Resilience inherent to the tubes of magnetic flux in the air gap between MDS core tips. Stretching of magnetic lines of force (Faraday tubes) like with rubber threads, creates forces opposing stretching.
- Coinciding of the minimum of potential energy of the field of Amlev permanent magnets with the trajectory of Amlev car flight that is defined by steel cores. Any shift $\boldsymbol{\delta}$ of the car from defined trajectory generates stabilizing force $\mathbf{F_s}$ attempting to eliminate the shift.
- Velocity V(x) of the running current wave of constant frequency in the three-phase winding of PMLM stator is proportional to non-uniform distribution of length $L_w(x)$ of its turns. Any small deviation $\pm\Delta V(x)$ of Amlev car speed from current wave velocity V(x) changes propulsion force F_p of the rotor to eliminate this deviation.
- Lorentz force F_{Lor} is proportional to current value I in PMLM stator winding. For stable performance of PMLM it is necessary that inequality $F_{Lor} > F_p$ is true in every point of set trajectory. This is achieved by corresponding distribution of feeding transformers' power along entire track.

Amlev ensures complete passengers' safety during the flight. Malfunction of any of its parts will result in soft breaking of the flying vehicle by air friction and subsequent stop in a suspended state.

5   References

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3.   Oleg V. Tozoni, "Self-regulating Permanent Magnet Linear Motor", IEEE Transactions on Magnetics., vol. 35, no 4, pp. 2137-2145 July, 1999.

4.   Oleg V. Tozoni, "AMLEV – A Self-regulating Version of Maglev", IEEE Transactions on Magnetics, vol. 37, no 6, November, 2001.

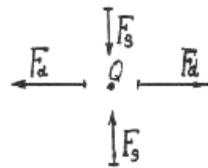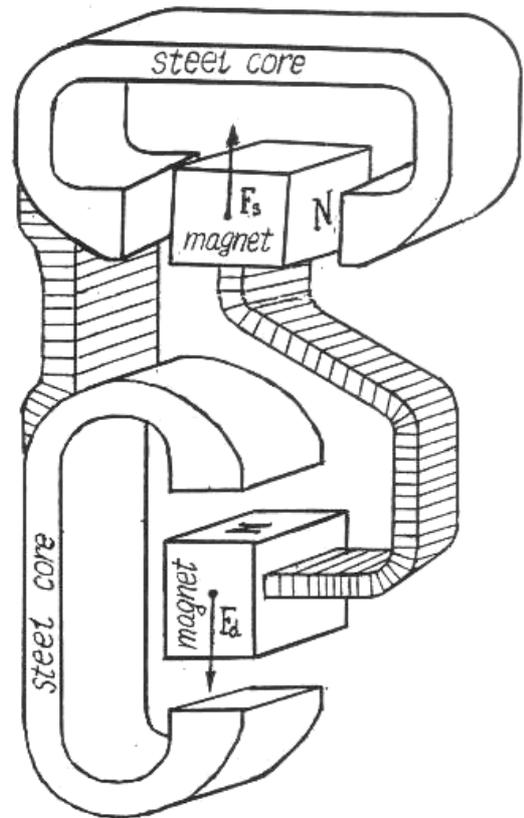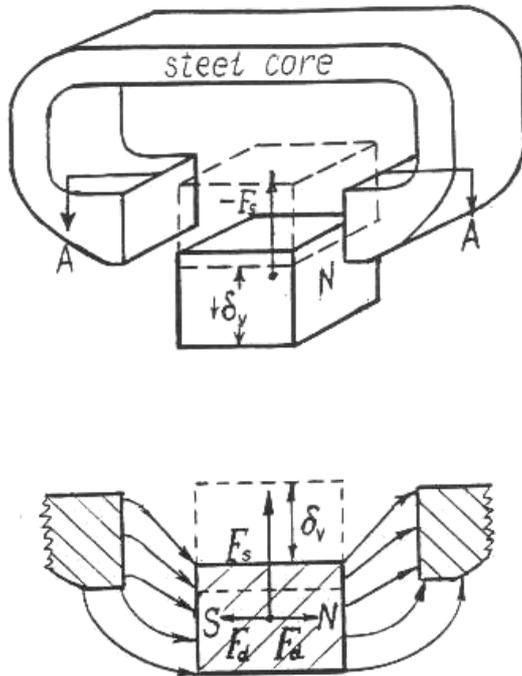5.   A.M. Lyapunov, Lectures in Theoretical Mechanics. Kiev, Ukraine, Naukova Dumka, 1982, pp.376 – 384.

steet core

F_s

A   A

$+\delta_y$ N

δ_v

F_s

S $\underset{F_d}{\longleftarrow}$ $\underset{F_d}{\longrightarrow}$ N

steet core

F_s

magnet   N

steel core

magnet E_d

F_s

F_d Q F_d

F_s

Fig. I
Extremum
is absent

R

E_d E_d

R   R

F_d

R

F_s F_s

R   R

F_s
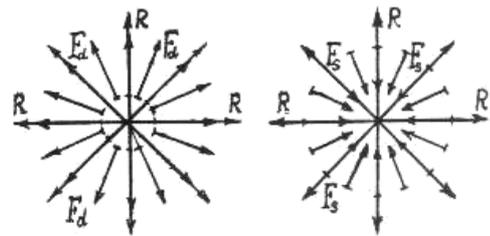
Fig. II
Extremum   Extremum
maximum   minimum
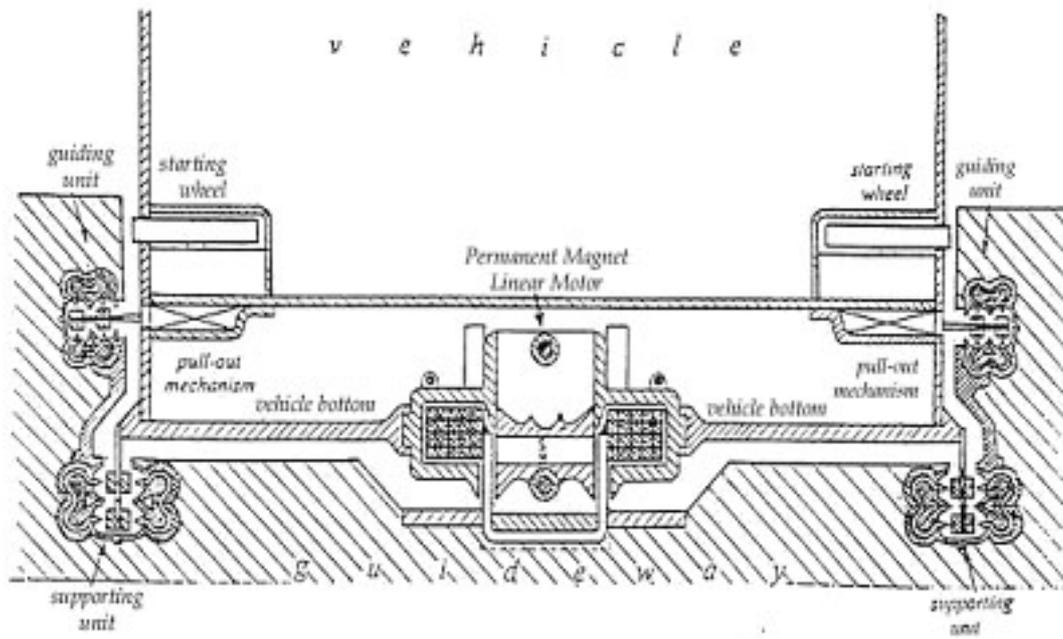
Fig.1 Cross-sectional view of AMLEV vehicle and stator.
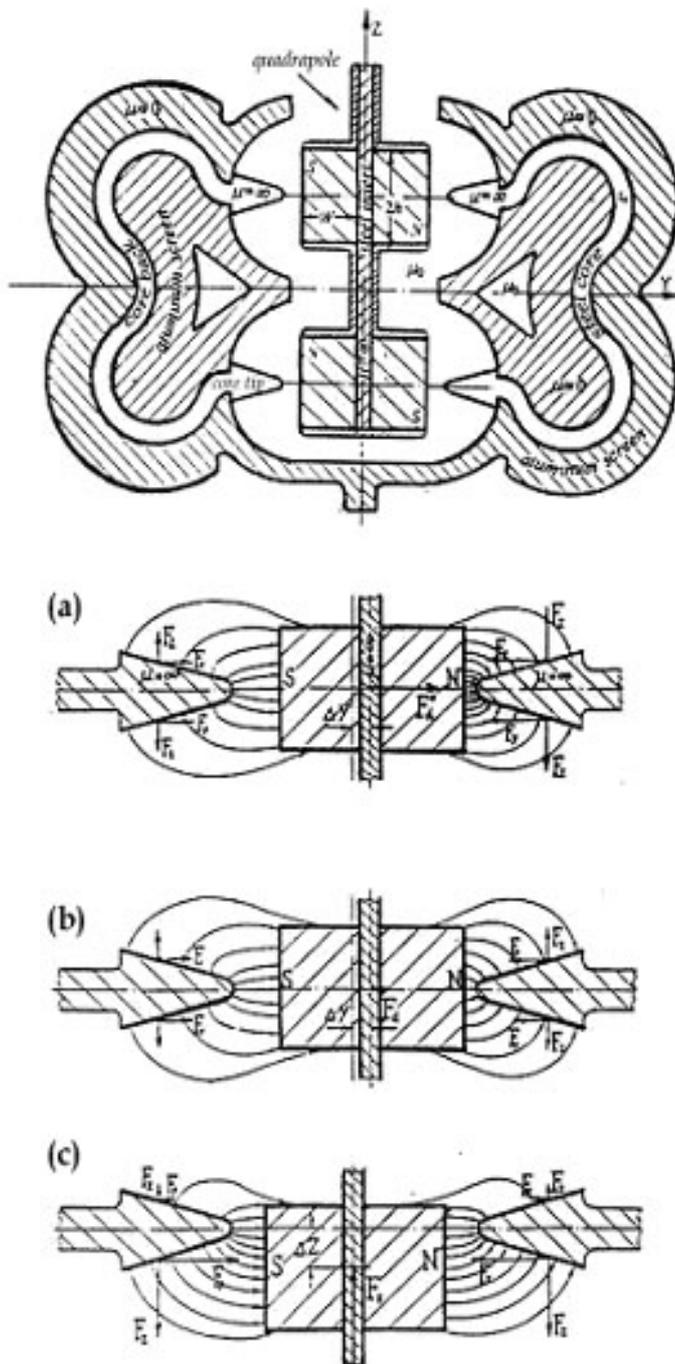
Fig.2 Cross-sectional view of MDS unit and
illustration of lines of force in the unit's air gap:
(a) at unsaturated core back and shift ΔY of magnets;
(b) at saturated core back and shift ΔY of magnets;
(c) at saturated core back and shift ΔZ of magnets.
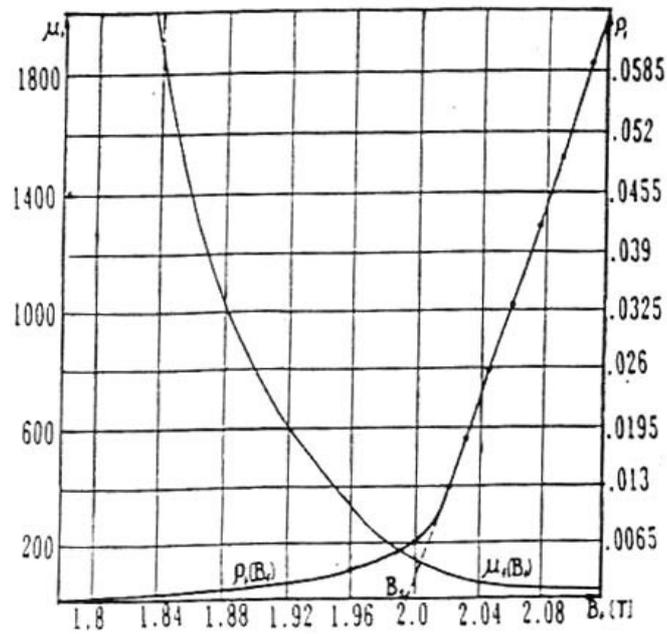
Fig.3 Graphs of relative magnetic permeability of electrical steel and its specific magnetic reluctance as a function of magnetic flux density.
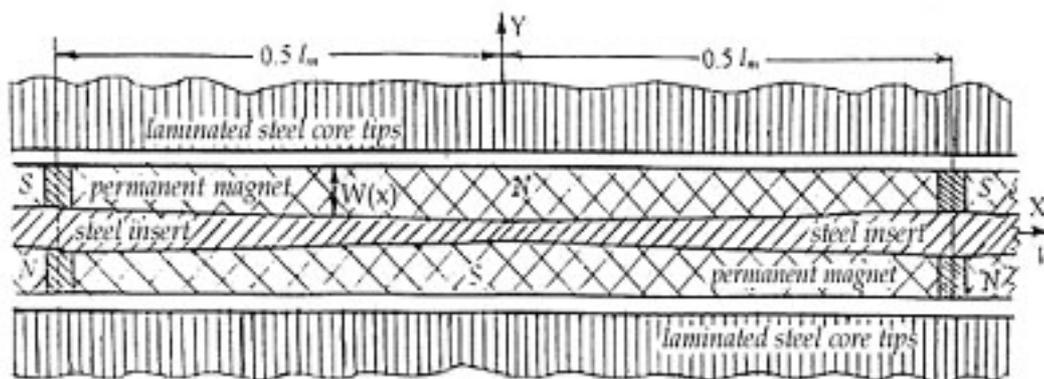
Fig.4 Cross-sectional view of an MDS unit air gap with the profile of quadrupole magnets' bases and steel insert between them altered.
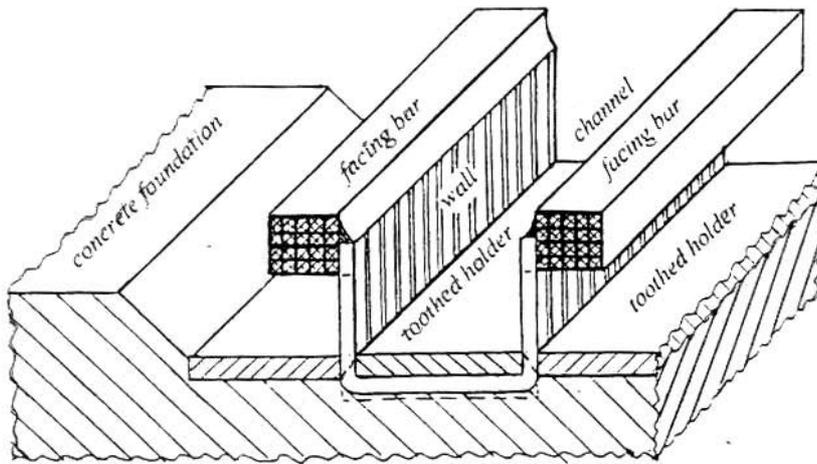
Fig.5 Perspective view of fragment of stator winding section.
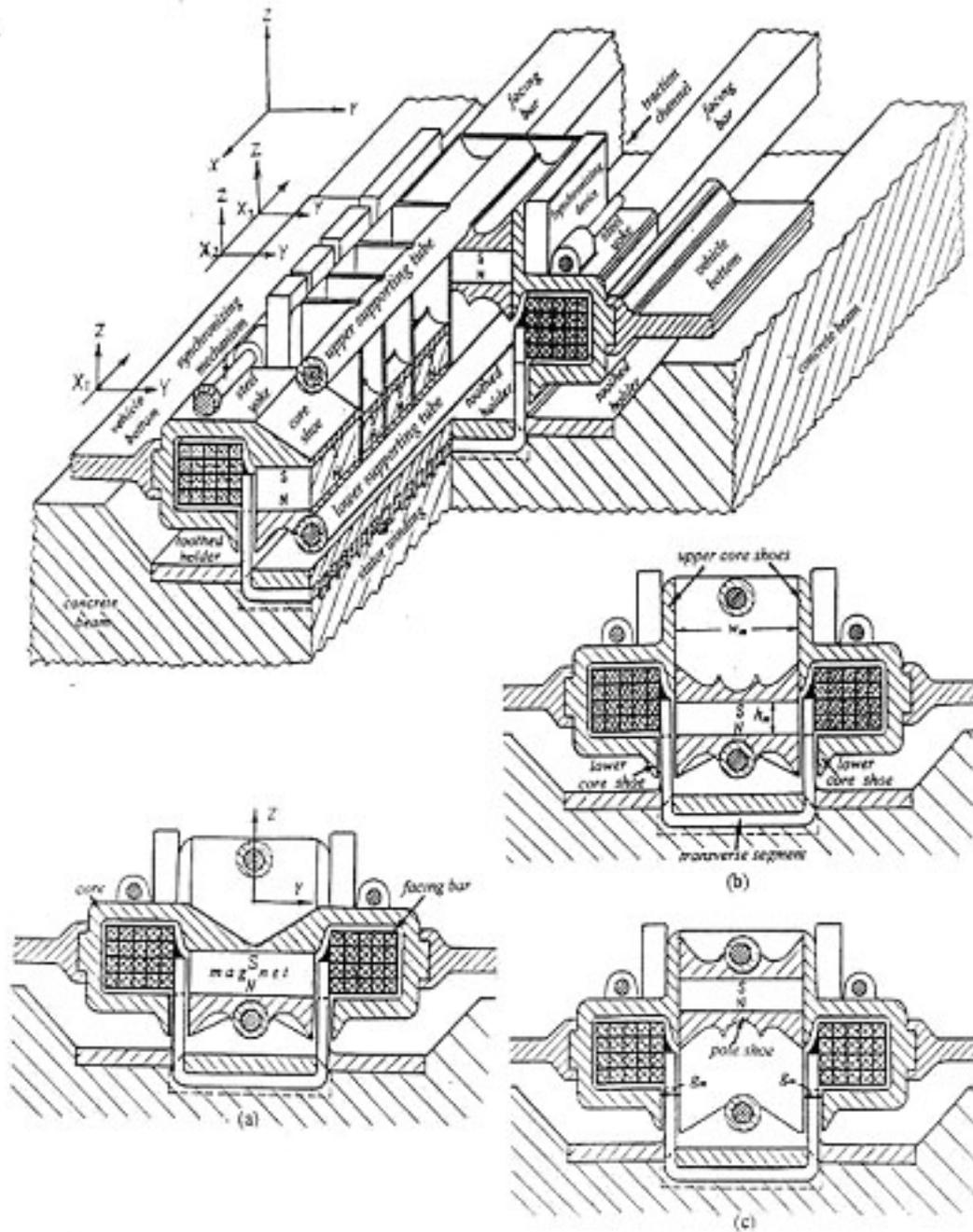
Fig.6 Cutaway view of a half of PMLM and cross-section views of PMLM magnetic units by planes $X_i YZ$ (i = 1,2,3)

    (a) a central unit by plane $X_1 YZ$;

    (b) an operating unit by plane $X_2 YZ$;
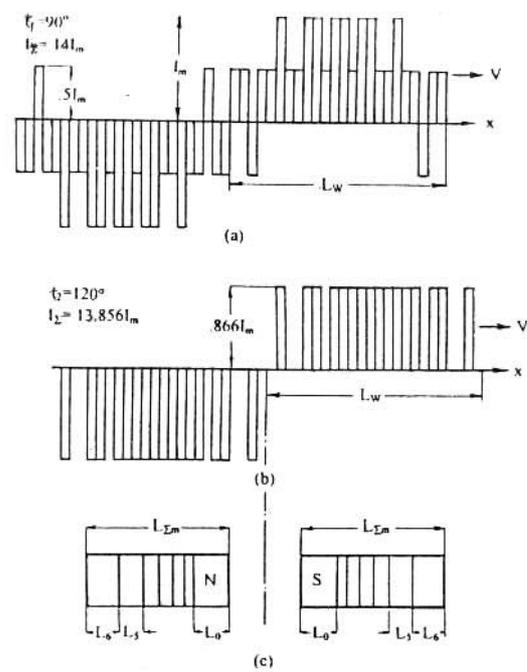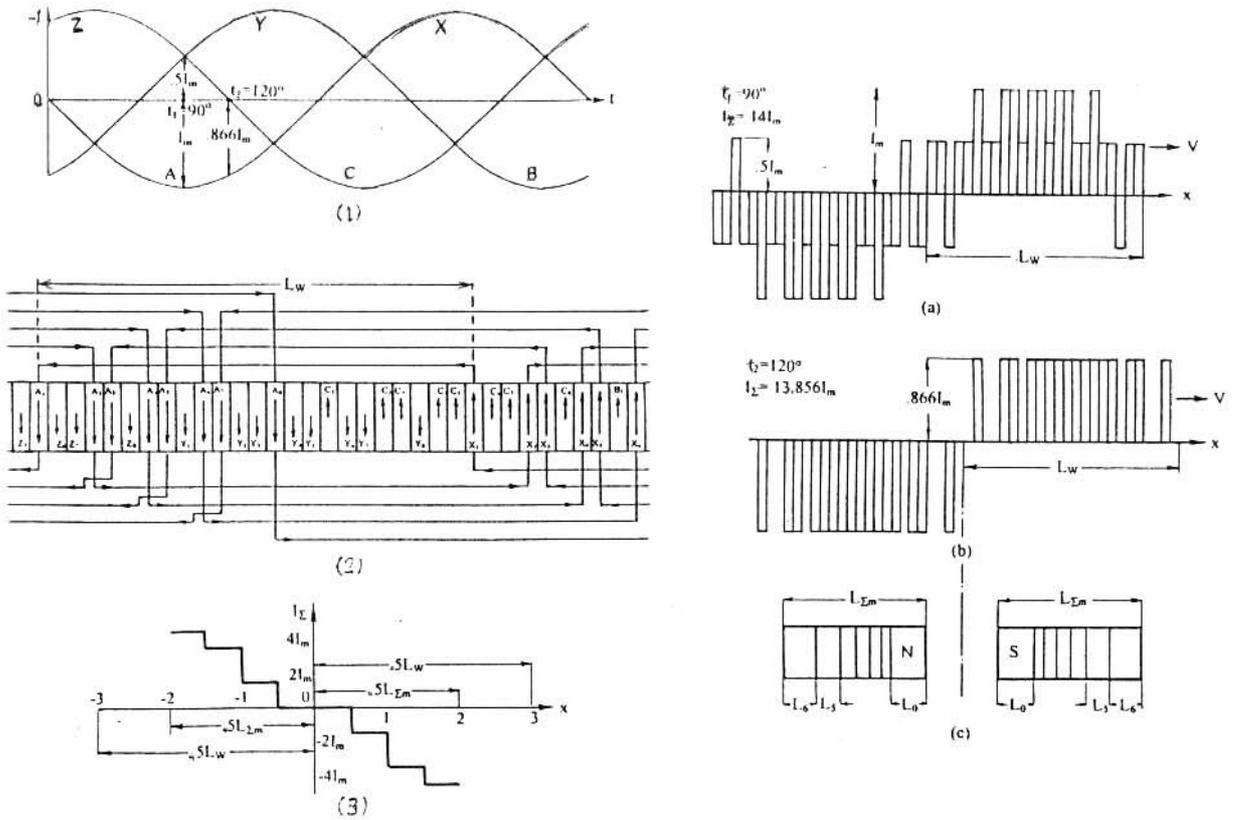
    (c) non-operating unit by plane $X_3 YZ$.

Fig.7 (1) Time distribution of sinusoidal current in phases of stator winding.
(2) Connection of stator's winding turns (phase A). Direction and size of arrows correspond to the current in the transverse segments at the moment $t_1 = 90^0$ shown in Fig. 7(a).
(3) Space distribution of currents in longitudinal segments of facing bars.
 Space distribution of currents in transverse segments of stators winding conductors at two different moments: (a) $t_1 = 90^0$, (b) $t_2 = t_1 + 30^0$
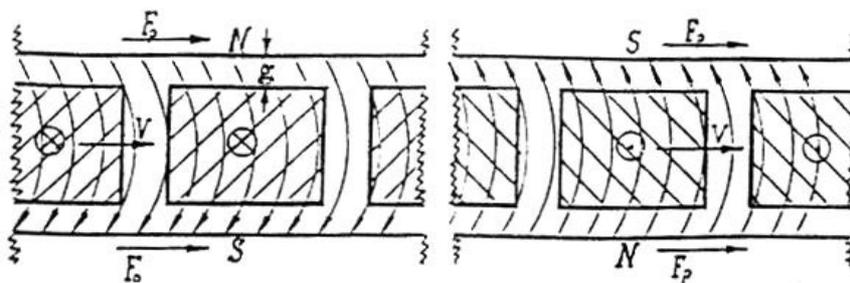(c) Disposition of rotor magnets with respect to a current wave traveling with velocity 150 m/s.

Fig. 8 Cross-section view of air gap between lower core shoes of rotor yoke and the magnets and illustration of lines of force.