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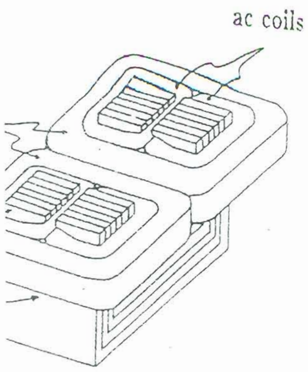

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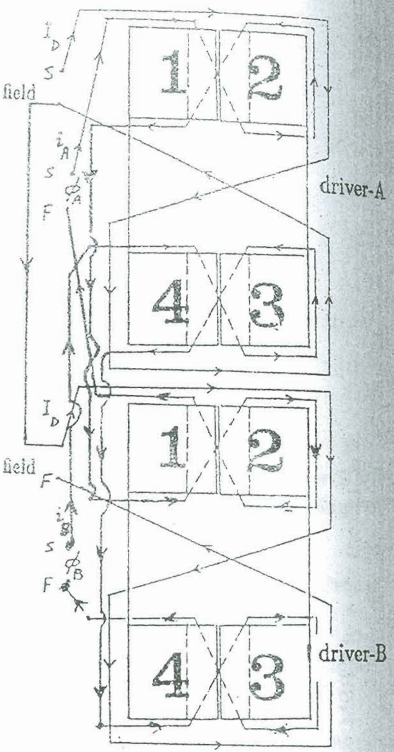

Fig.5 Coil connections for TRSM drivers

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THRUST DERATING DUE TO STABILITY REQUIREMENTS OF THE TRAPIZOIDAL LINEAR SYNCHRONOUS MOTOR-PAIR INTEGRATING LIFT AND THRUST FOR MAGLEV VEHICLES

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ABSTRACT

The Trapizoidal Linear Synchronous Motor Pair, TLSMP, is composed of two magnets one of which is shown in Fig.1. These are attached to the maglev vehicle-boggie as shown in Fig.2, and are reacting against the trapizoidal-shaped rail shown in Fig.3. The coils of each magnet are connected as shown in Fig.4, with dc coils fed from a chopper power amplifier controlling field current to provide lift at constant gap, Z. The feedback loops involved in field control uses signals proportional to gap position and speed as well as field flux. The ac coils are, on the other hand, fed from a two-phase inverter providing armature currents such that the field is distorted among the four sub-poles of each magnet, and hence propulsion is obtained.

It was found necessary to make a twin pair of magnets, for the elemenation of harmonic currents in the field circuits. Maximum thrust force was found when the armature mmf peak value equals to about 1.633 that of field mmf. This maximum thrust force relative to supported weight was found to be $0.354\pi Z/p$, where p is the pole-pitch shown in Fig.3.

The work described in the proposed paper looks upon the stability requirements of TLSMP and proves that the above maximum thrust value corresponds to uncontrollable lift system. To make it controllable, this maximum thrusting force must be severely derated to gain stability.

KEYWORDS

Trapizoidal; linear; synchronous; machine; thrust; derating; maglev; vehicle; suspension; Propulsion.

INTRODUCTION

The Trapizoidal Linear Synchronous Motor Pair, TLSMP, is a machine that utilizes a pair of magnets developed by McLean [1,2] and West [1,3]. One magnet is shown in Fig.1, and the pair is attached to the maglev vehicle boggie as shown in Fig.2. These magnets are reacting against the trapizoidal-shaped rail shown in Fig.3. As the rail moves relative to magnets in the direction indicated in Fig.3, induced emf's will appear at sub-pole coil terminals due to the field excitation. Al-Kasimi [4,5,6] suggested the TLSMP connections shown in Fig.4 for pulsation-free integrated-lift-propulsion using a two-phase inverter supply for armature. The field coils are fed from a chopper power amplifier controlling the excitation current to provide lift at constant gap, Z. The feed-back loops involved in the field control uses signals that are proportional to gap-position, gap-speed and field-flux.

Both West [3] and Al-Kasimi [6] found that a twin pair of magnets is necessary for the elimination of harmonic currents in the field circuits. Their machines provide maximum thrusts when the sub-polar armature mmf peak values equal to 1.414 and 1.633 that of field, respectively. These maximum thrusts relative to the supported weight was found [3,6] as: 1 and 0.354 respectively of $\pi\, Z/p$, where p is the pole-pitch shown in Fig.3.

Al-Kasimi [7] showed that for the machine developed by West to be actively suspended, then lift-control requirements derate the maximum thrust by r, the perturbation ratio.

This paper reviews the theory of TLSMP developed by Al-Kasimi [6] and then looks at its stability requirements. It then proves that the above maximum thrust value corresponds, likewise, to an uncontrollable lift system. To make it controllable, the maximum thrusting force must be derated for stability.

NOTATIONS

The symbols used in this paper are listed below:

α_{hs}	horziontal steady acceleration relative to gravity
α_{hsx}	maximum horziontal steady acceleration relative to gravity
A	sub-pole surface area
A_i	energized area of sub-pole i
B_i	flux density over sub-pole i
E_X	open circuit induced voltage at phase X coil terminals
ϕ_k	flux due to all sub-polar mmfs that leaves sub-pole k
F_h	horizontal thrust force
F_v	vertical lift force
I_D	current flowing in the field
i_X	current flowing in phase-X ac
μ_0	permeability of air
M_D	net dc mmf excitation of field
$\overline{M}_D$	optimum M_D values for maxin
m_X	ac mmf of phase X armature
m	peak values of ac mmf excitati
$\overline{m}$	optimum m values for maximu
m_j	resultant mmf excitations arou
N	number of turns of ac coil aro
N_D	number of turns of dc coil aro
p	pole pitch
r	perturbation level of m_1 relati
θ	phase angles of ac excitations
$\overline{\theta}$	optimum phase angles at maxi
T	time period to complete one c
t	time starting zero when rail c
u	speed of rail relative to magne
ω	angular frequency of ac suppl
W	weight of supported boggie
Z	energized air gap

ASSUMPTIONS

For simplicity, the following assumptio

1. All sub-poles have the same su them fed with sinusoidal ac c
2. Width of slot in the main pol of dc coils around them are co
3. Fringing, leakages, steel and drag forces are ignored.
4. Air gap, Z, is homogeneous ov at rail-surface above it and at motion.
5. The energized area per pole i belongs to one of the two adja assumed to vary sinusoidally
6. The motor does no rotation a track; which is assumed rigid.
7. The motor force is composed o ity line and along direction of in the third direction is exerte
8. Flux linkage for any ac coil zero when its sub-pole is fully its sub-pole is fully coupled to

REVIEW ANALYSIS OF TLSM

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s that leaves sub-pole k

i_X	current flowing in phase-X ac coils
μ_0	permeability of air
M_D	net dc mmf excitation of field winding per pole
$\overline{M}_D$	optimum M_D values for maximum thrust
m_X	ac mmf of phase X armature winding per sub-pole
m	peak values of ac mmf excitation of any phase per sub-pole
$\overline{m}$	optimum m values for maximum thrust
m_j	resultant mmf excitations around sub-pole j
N	number of turns of ac coil around any sub-pole
N_D	number of turns of dc coil around any pole
p	pole pitch
r	perturbation level of m_1 relative to operational level of M_D
θ	phase angles of ac excitations
$\overline{\theta}$	optimum phase angles at maximum thrust conditions
T	time period to complete one cycle
t	time starting zero when rail completely links sub-poles 1 and 3
u	speed of rail relative to magnet
ω	angular frequency of ac supply
W	weight of supported boggie
Z	energized air gap

ASSUMPTIONS

For simplicity, the following assumptions were made in the analysis to come.

1. All sub-poles have the same surface area, A, with identical ac coils around them fed with sinusoidal ac current phase-locked to rail.
2. Width of slot in the main poles is negligible, and field mmf excitations of dc coils around them are constants.
3. Fringing, leakages, steel and copper losses, windage, friction and other drag forces are ignored.
4. Air gap, Z, is homogeneous over the sub-poles, and faces equal areas both at rail-surface above it and at magnet-pole-surface below it throughout motion.
5. The energized area per pole is composed of two portions. Each portion belongs to one of the two adjacent sub-poles within the main pole and is assumed to vary sinusoidally between zero and A.
6. The motor does no rotation and it has constant speed, u, relative to the track; which is assumed rigid.
7. The motor force is composed of two components only, namely, along gravity line and along direction of motion. Although some force component in the third direction is exerted, it will be ignored.
8. Flux linkage for any ac coil varies sinusoidally between a minimum of zero when its sub-pole is fully uncoupled to rail and a maximum when its sub-pole is fully coupled to rail.

REVIEW ANALYSIS OF TLSMP PERFORMANCE

When the rail of TLSMP moves in the direction indicated in Fig.3, Al-Kasimi

[4,5,6] found that the flux linkages of ac coils per magnet vary in-phase for adjacent sub-poles and so can be series-connected forming one phase. This phase is in quadrature to the other phase of the opposing sub-poles. The period and angular frequency of these variations are given respectively by: $T = 4p/u$ and $\omega = \pi\, u/2p$.

This illustrates the connections shown in Fig.4, per motor. Note that in each motor, phase-A leads phase-B by a quarter of a cycle; and that the dc coils are connected so as to build constructive flux components. Hence, with:

$$M_D = N_D\, I_D\,,$$

$$m_A(t) = N\, i_A(t) = m\, cos(\omega\, t + \theta)\ \& \qquad m_B(t) = N\, i_B(t) = m\, sin(\omega\, t + \theta);$$

and assuming positive sense when forcing flux to leave the sub-poles of motor-A, then:

$$m_1(t) = -M_D - m_A(t)\,, \qquad m_2(t) = -M_D + m_A(t)\,,$$
$$m_3(t) = +M_D + m_B(t)\ \& \qquad m_4(t) = +M_D - m_B(t)\,.$$

The energized areas of motor-A are approximated to:

$$A_1(t) = (A/2)\,[1 + cos(\omega\, t + \pi/4)\,, \qquad A_2(t) = (A/2)\,[1 - cos(\omega\, t + \pi/4)]\,,$$
$$A_3(t) = (A/2)\,[1 + cos(\omega\, t - \pi/4)]\ \& \qquad A_4(t) = (A/2)\,[1 - cos(\omega\, t - \pi/4)]\,.$$

The fluxes of motor-A are given [5,6], using superposition, as:

$$\begin{aligned}
\phi_1(t) &= -\mu_0\, A_1\, [2\, M_D + 2\, m_A + m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,,\\
\phi_2(t) &= -\mu_0\, A_2\, [2\, M_D - 2\, m_A + m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,,\\
\phi_3(t) &= +\mu_0\, A_3\, [2\, M_D + 2\, m_B - m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\ \&\\
\phi_4(t) &= +\mu_0\, A_4\, [2\, M_D - 2\, m_B - m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,.
\end{aligned}$$

From the above equations, the sub-polar flux densities are found for motor-A as:

$$\begin{aligned}
B_1(t) = \phi_1(t)/A_1(t) &= -\mu_0\, [2\, M_D + 2\, m_A + m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,,\\
B_2(t) = \phi_2(t)/A_2(t) &= -\mu_0\, [2\, M_D - 2\, m_A + m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,,\\
B_3(t) = \phi_3(t)/A_3(t) &= +\mu_0\, [2\, M_D + 2\, m_B - m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\ \&\\
B_4(t) = \phi_4(t)/A_4(t) &= +\mu_0\, [2\, M_D - 2\, m_B - m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,.
\end{aligned}$$

The TLSM-A lift force, F_{v_A}, is given [5,6] by:

$$F_{v_A}(t) = \mu_0\, A\, [8\, M_D^2 + 3\, m^2 + 8\, M_D\, m\, cos(\theta - \pi/4) + m^2\, sin(4\omega\, t + 2\,\theta)]/8Z^2\,. \tag{1}$$

Hence, the lift force, F_{v_A}, of TLSM-A is pulsating at four times the synchronous frequency. This pulsating component of motor-A is neutralized [6] by that of motor-B due to the connections shown in Fig.4. Hence, the TLSMP lift force, F_v, of the twin pair has only steady component that lifts the boggie weight, W, actively by field control. This force is given by:

$$F_v(t) = F_{v_A}(t) + F_{v_B}(t) = W = \mu_0\, A\, (16\, M_D^2 + 6\, m^2 + 8\sqrt{2}\, M_D\, m\, cos\theta)/8Z^2\,. \tag{2}$$

The open cicuit induced voltages at ac ter
to be:

$$E_A(t) = -\mu_0\, \omega\, A\, M_D\, N$$
$$E_B(t) = -\mu_0\, \omega\, A\, M_D\, N$$

The TLSM-A thrust force, F_{h_A}, can be ob

$$F_{h_A} = (E_A\, i_A + E_B\, i_B)/u = \mu_0\, \pi$$

Likewise, the TLSM-B thrust force, F_{h_B},

$$F_{h_B} = \mu_0\, \pi\, A\, M_D\, m\, si$$

Hence, the TLSMP thrust force, F_h, of th

$$F_h = F_{h_A} + F_{h_B} = \mu_0\, \pi\, A$$

The steady thrusting acceleration, α_{hs}, rel
as:

$$\alpha_{hs}(\theta, m) = \mu_0\, \pi\, A\, M_D(\theta,$$

where $M_D(\theta, m)$ is an implicit function of

The maximum, α_{hsx}, of $\alpha_{hs}(\theta, m)$ occur
as:

$$\overline{\theta} = \pm[\pi - cos^{-1}$$
$$\overline{m} = Z\, \sqrt{W/(\mu_0}$$
$$\alpha_{hsx} = 0.354\, (\pi\, Z/$$

STABILITY OF TLSMP LIFT SYS

The TLSMP lift system is controlled usi
are:

1. the gap, Z, that can be measured us
motor poles,

2. the gap speed, $Z^{\bullet}$, that can be me
certain frequency band, and:

3. the pole flux linkage, λ, that can be
magnet poles.

Since the equations of the TLSMP lift
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whereby Linear Control Theory is utiliz
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$$m_B(t) = N\, i_B(t) = m\, sin(\omega\, t + \theta)\,;$$

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$$m_2(t) = -M_D + m_A(t)\,,$$
$$m_4(t) = +M_D - m_B(t)\,.$$

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$$A_2(t) = (A/2)\,[1 - cos(\omega\, t + \pi/4)]\,,$$
$$A_4(t) = (A/2)\,[1 - cos(\omega\, t - \pi/4)]\,.$$

sing superposition, as:

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$$+ m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,,$$
$$- m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\ \&$$
$$- m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,.$$

ar flux densities are found for motor-A as:

$$+ 2\, m_A + m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,,$$
$$- 2\, m_A + m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,,$$
$$+ 2\, m_B - m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\ \&$$
$$- 2\, m_B - m\, sin(2\,\omega\, t + \theta - \pi/4)]/2Z\,.$$

[5,6] by:

$$cos(\theta - \pi/4) + m^2\, sin(4\omega\, t + 2\,\theta)]/8Z^2\,. \quad (1)$$

is pulsating at four times the synchronous nt of motor-A is neutralized [6] by that of wn in Fig.4. Hence, the TLSMP lift force, component that lifts the boggie weight, W, s given by:

$$4\,(16\, M_D^2 + 6\, m^2 + 8\sqrt{2}\, M_D\, m\, cos\theta)/8Z^2\,. \quad (2)$$

The open cicuit induced voltages at ac terminals of motor-A in Fig.4 can be found to be.

$$E_A(t) = -\mu_0\, \omega\, A\, M_D\, N\, sin(\omega\, t + \pi/4)/Z\ \&$$
$$E_B(t) = -\mu_0\, \omega\, A\, M_D\, N\, sin(\omega\, t - \pi/4)/Z\,.$$

The TLSM-A thrust force, F_{h_A}, can be obtained using the energy principle as:

$$F_{h_A} = (E_A\, i_A + E_B\, i_B)/u = \mu_0\, \pi\, A\, M_D\, m\, sin(\theta - \pi/4)/(2p\, Z). \qquad (3)$$

Likewise, the TLSM-B thrust force, F_{h_B}, can be found as:

$$F_{h_B} = \mu_0\, \pi\, A\, M_D\, m\, sin(\theta + \pi/4)/(2p\, Z).$$

Hence, the TLSMP thrust force, F_h, of the twin pair is:

$$F_h = F_{h_A} + F_{h_B} = \mu_0\, \pi\, A\, M_D\, m\, sin\theta/(\sqrt{2}\, p\, Z).$$

The steady thrusting acceleration, α_{hs}, relative to gravity could, hence, be obtained as:

$$\alpha_{hs}(\theta, m) = \mu_0\, \pi\, A\, M_D(\theta, m)\, m\, sin\theta/(\sqrt{2}\, p\, W\, Z); \qquad (4)$$

where $M_D(\theta, m)$ is an implicit function of θ and m given in eq. (2).

The maximum, α_{hsx}, of $\alpha_{hs}(\theta, m)$ occures at $\overline{\theta}$, $\overline{M}_D$ and $\overline{m}$. These are found [6] as:

$$\begin{aligned} \overline{\theta} &= \pm[\pi - cos^{-1}\sqrt{(1/3)}]\,, \\ \overline{m} &= Z\,\sqrt{W/(\mu_0\, A)} = 1.633\, \overline{M}_D\ \& \qquad (5) \\ \alpha_{hsx} &= 0.354\,(\pi\, Z/p)\,. \end{aligned}$$

STABILITY OF TLSMP LIFT SYSTEM

The TLSMP lift system is controlled using three feed-back signals. These signals are:

1. the gap, Z, that can be measured using the capacitance between the rail and motor poles,
2. the gap speed, Z^{*}, that can be measured using differentiation of Z over a certain frequency band, and:
3. the pole flux linkage, λ, that can be measured using a search coil around the magnet poles.

Since the equations of the TLSMP lift system are nonlinear with inherited extreme instability; linearization techniques are applied to obtain a linearized model, whereby Linear Control Theory is utilized to design a controller using the above feed-back signals. The controller is composed simply of a circuit that adds up all three signals after appropriate scaling so that the resulting system complies with the pre-determined characteristics.

The TLSMP lift-system being considered for linearization is trusted to have each of its variables perturbing about a non-zero operational level. Moreover, the magnitude of perturbation must be much smaller than the operational level. If either of these two conditions is violated, the linearized model is no longer representative to the actual system. This will consequently endanger stability.

The most critical variable in this respect was found to be the sub-polar mmf, typically given as:

$$m_1(t) = -M_D - m_A(t).$$

This suggests that the perturbation in $m_1(t)$ is equal to $m_A(t)$ plus the perturbation of M_D. The ratio r of the perturbation of $m_1(t)$ to the operating level of M_D is found as:

$$r = m/M_D;$$

which at maximum thrusting condition indicated in eq. (5) evaluates to:

$$r = 1.633\,.$$

This violates both conditions trusted to the lift system. To correct for that, $\overline{m}$ must be derated to match reasonable level for r. Hence, substituting in eq. (4):

$$\alpha_{hs}(r,\theta) = \mu_0\, \pi\, A\, r\, M_D^2(r,\theta)\, sin\theta/(\sqrt{2}\, p\, W\, Z)\,.$$

But $M_D(r,\theta)$ relates to W using eq. (2) as:

$$M_D^2(r,\theta) = \frac{4\,W\,Z^2}{\mu_0\, A\,(8 + 3\,r^2 + 4\sqrt{2}\,r\,cos\theta)}\,.$$

Hence:

$$\alpha_{hs}(r,\theta) = (\pi\, Z\,/p)\,.\,\frac{2\sqrt{2}\,r\,sin\theta}{(8 + 3\,r^2 + 4\sqrt{2}\,r\,cos\theta)}\,.$$

This is maximum at $\theta_m(r)$ given by:

$$\theta_m(r) = cos^{-1}[\frac{-4\sqrt{2}\,r}{8 + 3\,r^2}]\,.$$

Hence, derated maximum thrust, $\alpha_{hsx}(r)$ relative to weight is:

$$\alpha_{hsx}(r) = (\pi\, Z\,/p)\,.\,\frac{2\sqrt{2}\,r}{\sqrt{64 + 16\,r^2 + 9\,r^4}}\,.$$

For the linearized lift model to represent the actual TLSMP lift system, the value of r must be fairly small. Hence:

$$\alpha_{hsx}(r) = 0.354\,r\,(\pi\, Z/p)\,.$$

This shows that the maximum thrust relative to weight is derated by factor r from its value at passive support due to active lift of TLSMP weight. Tollerable

perturbation level depends on the severity of
and could reach as low as 10 % of the oper
derating of α_{hsx} from its value when TLSMI

CONCLUSION

This paper shows that the representablity
a controller for stable active suspension of
maximum thrust of TLSMP that can be achi
wheels. Suspending TLSMP actively using
the maximum thrust from its value when su
equals the acceptable level of perturbation
the operational level of field excitation. Th

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n of $m_1(t)$ to the operating level of M_D

M_D;

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33.

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$$,\theta)\, sin\theta/(\sqrt{2}\,p\,W\,Z) .$$

s:

$$\frac{4\,W\,Z^2}{3\,r^2 + 4\sqrt{2}\,r\,cos\theta)} .$$

$$\frac{2\sqrt{2}\,r\,sin\theta}{+ 3\,r^2 + 4\sqrt{2}\,r\,cos\theta)} .$$

$$^{1}[\frac{-4\sqrt{2}\,r}{8 + 3\,r^2}] .$$

relative to weight is:

$$\frac{2\sqrt{2}\,r}{\sqrt{64 + 16\,r^2 + 9\,r^4}} .$$

the actual TLSMP lift system, the value

$$54\,r\,(\pi\,Z/p) .$$

elative to weight is derated by factor r
active lift of TLSMP weight. Tollerable

perturbation level depends on the severity of nonlinearity of TLSMP relationships, and could reach as low as 10 % of the operational level. This results in a 10 % derating of α_{hsx} from its value when TLSMP is passively supported.

CONCLUSION

This paper shows that the representablity of the linearized model used to design a controller for stable active suspension of TLSMP system, requires derating the maximum thrust of TLSMP that can be achieved when passively supported, say by wheels. Suspending TLSMP actively using field control has the price of derating the maximum thrust from its value when supported otherwise. The derating factor equals the acceptable level of perturbation of sub-polar mmf excitation relative to the operational level of field excitation. This can be as bad as 10 % .

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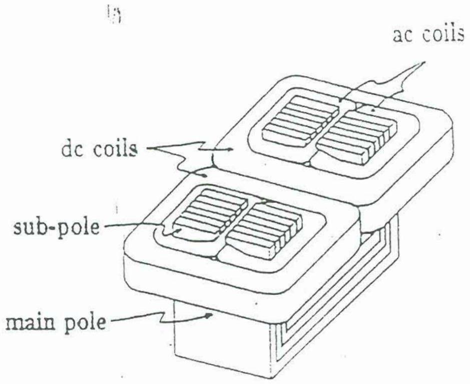


Fig.1 Magnet

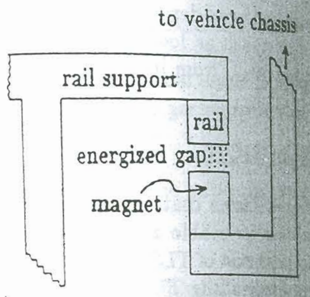
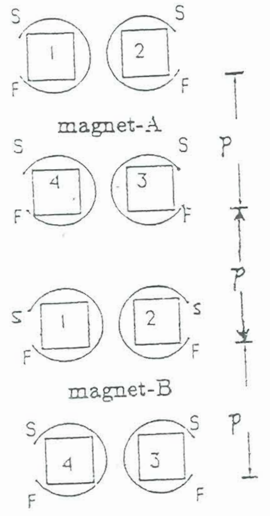
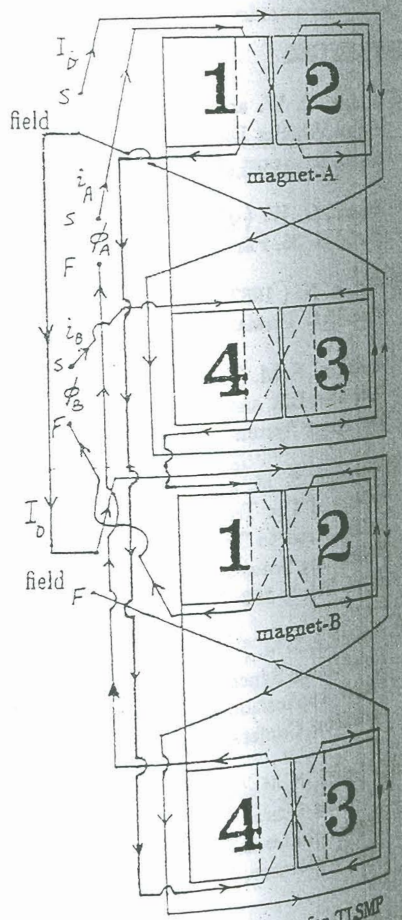


Fig.2 Boggie support





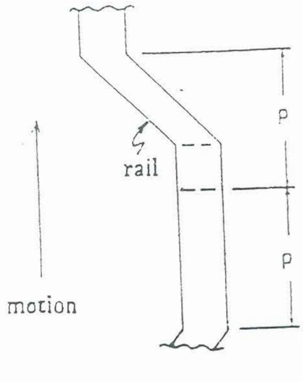


Fig.3 Rail of TLSMP

Fig.4 Coil connections for TLSMP

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THE ACCELERATION CHARACTERIST
LINEAR SYNCHRONOUS MOTORS
PAIR VERSION FOR MAG

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ABSTRACT

The Zigzag Linear Synchronous Motor, ZLS
bined lift and thrust for maglev vehicles.
supported by magnetic attraction between
chassis and a pair of iron tracks. The mag
a two-pole machine in which each pole is sp
is surrounded by a coil fed by an inverter s
among the four sub-poles. The rail of the Z
relative to the sub-poles to minimize reluct

The ZLSM machine is unable to start itse
problem is solved by putting another ZLSM
pair will start the other.

The ZLSM version was modified by changing
one, and hence obtaining a Trapizoidal Lin
though this motor is self-starting, it was four
of a cycle apart would improve some of its a

This paper describes in theory the acceleratio
machine that could be used for maglev transp
It also compares the merits of a twin-pair to a
pair of ZLSM machines.