Effect of Propelling Velocity on the Restoring Force in Induction type Coil Guns

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Abstract -While the projectile in the induction type coil guns is in motion, there exists an induced current in the sleeve coils of the projectile.   The motion includes not only the z-axial movement but transversal movement. The projectile in coil guns, which is not supported physically, gets a force in the transversal axis to have a motion in this axis.   As a result of this motion, sleeve effects are exhibited to the projectile.   This paper presents the analysis of the secondary effect especially due to the propelling velocity of the projectile.

1. INTRODUCTION

Induction type linear electromagnetic launchers (LIL) have array of multi-turns circular coils in the barrel and conductive sleeve in the projectile.   The drive coils in the barrel are solidly fixed while the projectile is traveling inside the barrel with extra-high velocity.[1][2]   The projectile, which is not supported by any physical means except air, is oscillating and balloting in the barrel while it is propelled.   The force acting on the transversal axis of the projectile is called restoring force.[3][4] Since the projectile is moving in the strong magnetic field produced by the drive coil currents, there exist motional induced currents.   It is obvious that not only the transversal velocity but propelling velocity affect on the sleeve current, and as a result, the restoring force is affected by the propelling velocity besides transversal motion.   As shown in Fig. 1, sleeve, which is a finite and continuous conductor, is virtually discretized in multi-section of coils.[5]
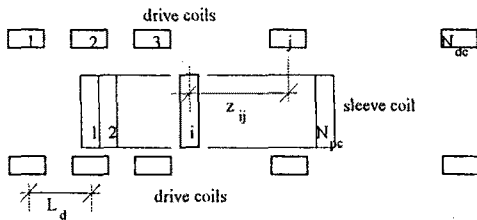

Fig. 1. Multi-coils sleeve and Multi-coils drive

Dynamic motion of the projectile can be analyzed as a result of the combined motion of individual sleeve coils. Thus, investigating the phenomena in single couple of the drive and sleeve coils is a fundamental tool for the analysis of the dynamics in coil guns.

2. EFFECTS OF THE MOTION - INDUCED CURRENTS

2-1. In case that the sleeve coil is located on the left side of the drive coil.

When the sleeve coil is in motion, there exists a sleeve effect due to this motion.   Consider the four points on the sleeve coil as shown on Fig. 2.
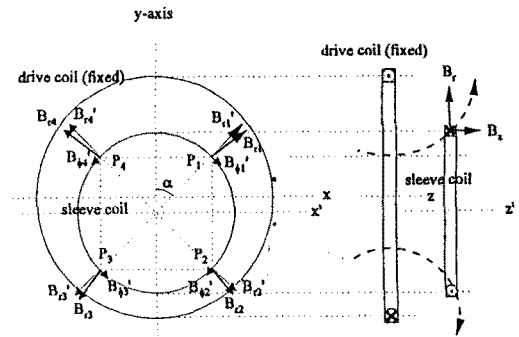

Fig. 2. magnetic flux map at the sleeve coil

The vectors of the magnetic flux density at each point are,

at P_1 : $\quad \vec{B}_{p1} = \vec{B}_{r1}' + \vec{B}_{\phi1}' + \vec{B}_{z1}'$
$$= B_{r1} \cdot \vec{a}_r' - B_{\phi1} \cdot \vec{a}_\phi' + B_{z1} \cdot \vec{a}_z' \qquad (1a)$$

at P_2 : $\quad \vec{B}_{p2} = \vec{B}_{r2}' + \vec{B}_{\phi2}' + \vec{B}_{z2}'$
$$= B_{r2} \cdot \vec{a}_r' - B_{\phi2} \cdot \vec{a}_\phi' + B_{z2} \cdot \vec{a}_z' . \qquad (1b)$$

at P_3 : $\quad \vec{B}_{p3} = \vec{B}_{r3}' + \vec{B}_{\phi3}' + \vec{B}_{z3}'$
$$= B_{r2} \cdot \vec{a}_r' + B_{\phi2} \cdot \vec{a}_\phi' + B_{z2} \cdot \vec{a}_z' \qquad (1c)$$

at P_4 : $\tilde{B}_{p4} = \tilde{B}_{r4}' + \tilde{B}_{\phi4}' + \tilde{B}_{z4}'$

$\qquad = B_{r1} \cdot \tilde{a}_r' + B_{\phi1} \cdot \tilde{a}_\phi' + B_{z1} \cdot \tilde{a}_z'$ $\qquad$ (1d)

where, $B_{r1} < B_{r2}$ and $B_{z1} < B_{z2}$

The velocity vector of the sleeve coil assuming the coil is not spinning or rotating about the center of the coil is shown in Fig. 3 and it can be denoted as,

at P_1 : $\tilde{v}_{p1} = v_{r1} \cdot \tilde{a}_r' + v_{\phi1} \cdot \tilde{a}_\phi' + v_z \cdot \tilde{a}_z'$ $\qquad$ (2a)

at P_2 : $\tilde{v}_{p2} = -v_{r2} \cdot \tilde{a}_r' + v_{\phi2} \cdot \tilde{a}_\phi' + v_z \cdot \tilde{a}_z'$ $\qquad$ (2b)

at P_3 : $\tilde{v}_{p3} = -v_{r1} \cdot \tilde{a}_r' - v_{\phi1} \cdot \tilde{a}_\phi' + v_z \cdot \tilde{a}_z'$ $\qquad$ (2c)

at P_4 : $\tilde{v}_{p4} = v_{r2} \cdot \tilde{a}_r' - v_{\phi2} \cdot \tilde{a}_\phi' + v_z \cdot \tilde{a}_z'$ $\qquad$ (2d)

where,

$\qquad v_{r1} = v_{\phi2} = v_{ym} \cos \alpha$ $\qquad$ (2e)

$\qquad v_{r2} = v_{\phi1} = v_{ym} \sin \alpha$ $\qquad$ (2f)

$\qquad v_z = -(v_s - v_{zm}) = -s v_s$

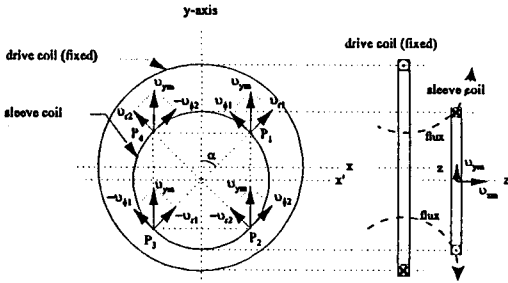when, s = slip $\quad v_s$ = synchro velocity. $\qquad$ (2g)

Fig. 3. velocity vector in the sleeve coil in motion

Motional $e.m.f.$ can be obtained from the fundamental relationship $\tilde{e} = \tilde{v} \times \tilde{B}$. When the conductivity of the sleeve coils is σ, motion-induced current at the point is $\tilde{J} = \sigma \tilde{e}$. Hence, from Eqs.1 and 2, the motion-induced current at the point is calculated such that,

at P_1 : $\tilde{J}_1 = \sigma(\tilde{v}_{p1} \times \tilde{B}_{p1}) = \sigma \begin{bmatrix} \tilde{a}_r & \tilde{a}_\phi & \tilde{a}_z \\ v_{r1} & v_{\phi1} & v_z \\ B_{r1} & -B_{\phi1} & B_{z1} \end{bmatrix}$ $\qquad$ (3a)

$= \sigma[(v_{\phi1}B_{z1} + v_z B_{\phi1}) \cdot \tilde{a}_r + (v_z B_{r1} - v_{r1}B_{z1}) \cdot \tilde{a}_\phi - (v_{r1}B_{\phi1} + v_{\phi1}B_{r1})] \cdot \tilde{a}_z$

at P_2 : $\tilde{J}_2 = \sigma(\tilde{v}_{p2} \times \tilde{B}_{p2}) = \sigma \begin{bmatrix} \tilde{a}_r & \tilde{a}_\phi & \tilde{a}_z \\ -v_{r2} & v_{\phi2} & v_z \\ B_{r2} & -B_{\phi2} & B_{z2} \end{bmatrix}$ $\qquad$ (3b)

$= \sigma[(v_{\phi1}B_{z2} + v_z B_{\phi2}) \cdot \tilde{a}_r + (v_{r2}B_{z2} + v_z B_{r2}) \cdot \tilde{a}_\phi - (v_{r2}B_{\phi2} - v_{\phi2}B_{r1})] \cdot \tilde{a}_z$

at P_3 : $\tilde{J}_3 = \sigma(\tilde{v}_{p3} \times \tilde{B}_{p3}) = \sigma \begin{bmatrix} \tilde{a}_r & \tilde{a}_\phi & \tilde{a}_z \\ -v_{r1} & -v_{\phi1} & v_z \\ B_{r2} & B_{\phi2} & B_{z2} \end{bmatrix}$ $\qquad$ (3c)

$= \sigma[-(v_{\phi1}B_{z2} + v_z B_{\phi2}) \cdot \tilde{a}_r + (v_z B_{r2} + v_{r1}B_{z2}) \cdot \tilde{a}_\phi - (v_{r1}B_{\phi2} - v_{\phi1}B_{r2})] \cdot \tilde{a}_z$

at P_4 : $\tilde{J}_4 = \sigma(\tilde{v}_{p4} \times \tilde{B}_{p4}) = \sigma \begin{bmatrix} \tilde{a}_r & \tilde{a}_\phi & \tilde{a}_z \\ v_{r2} & -v_{\phi2} & v_z \\ B_{r1} & B_{\phi1} & B_{z1} \end{bmatrix}$ $\qquad$ (3d)

$= \sigma[-(v_{\phi2}B_{z1} + v_z B_{\phi1}) \cdot \tilde{a}_r + (v_z B_{r1} - v_{r2}B_{z1}) \cdot \tilde{a}_\phi - (v_{r2}B_{\phi1} + v_{\phi2}B_{r1})] \cdot \tilde{a}_z$

Since the sleeve coil is considered as a filamentary, only the tangential component of the current vector is considered. However, if a single conductor of the sleeve coil has considerably large cross-sectional area, the radial and axial components of the current vector can not be neglected and calculation may be more complicated. From the fundamental equation $d\tilde{f} = I d\tilde{\ell} \times \tilde{B} = a_s \tilde{J} R_s d\alpha \times \tilde{B}$, the force due to the motion-induced current, can be obtained as,

$d\tilde{f}_{r1} = \sigma a_s R_s (v_z B_{r1}B_{z1} - v_{r1}B_{z1}^2) d\alpha \cdot \tilde{a}_r \ (N)$ $\qquad$ (4a)

$d\tilde{f}_{r2} = \sigma a_s R_s (v_{r2}B_{z2}^2 + v_z B_{r2}B_{z2}) d\alpha \cdot \tilde{a}_r \ (N)$ $\qquad$ (4b)

$d\tilde{f}_{r3} = \sigma a_s R_s (v_{r1}B_{z2}^2 + v_z B_{r2}B_{z2}) d\alpha \cdot \tilde{a}_r \ (N)$ $\qquad$ (4c)

$d\tilde{f}_{r4} = \sigma a_s R_s (v_z B_{r1}B_{z1} - v_{r2}B_{z1}^2) d\alpha \cdot \tilde{a}_r \ (N)$ $\qquad$ (4d)

Since the restoring forces at each point are the y-component of the radial forces, the net restoring force for entire sleeve coil due to the motion-induced current becomes,

$F_s = \int_0^{\pi/2} \sum_{i=1}^{4} df_{si}(\alpha) \quad (N)$

$\quad = \int_0^{\pi/2} \sum_{i=1}^{4} \cos \alpha \ df_{ri}(\alpha) \quad (N)$

$\quad = -\sigma a_s R_s \int_0^{\pi/2} [2 v_z (B_{r2}(\alpha)B_{z2}(\alpha) - B_{r1}(\alpha)B_{z1}(\alpha)) +$

$\qquad (v_{r1} + v_{r2})(B_{z1}^2(\alpha) + B_{z2}^2(\alpha))] \cos \alpha \ d\alpha \quad (N) \ (5)$

Since three terms, $(B_{r2}(\alpha)B_{z2}(\alpha) - B_{r1}(\alpha)B_{z1}(\alpha))$, $(\upsilon_{r1} + \upsilon_{r2})$ and $(B_{z1}^2(\alpha) + B_{z2}^2(\alpha))$, in the parentheses have positive values, and the force due to the motion-induced current is acting in the negative y-direction. Thus, it is anti-restoring force.

2-2. In case that the sleeve coil is located on the left side of the drive coil.

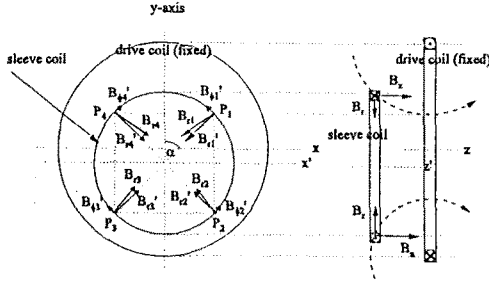Consider the case as shown in Fig. 4.

Fig. 4. The sleeve coil is located on the left side of the drive coil

The vector of the flux density at the four points on the sleeve coil is such as,

at P$_1$: $\quad \tilde{B}_{p1} = -B_{r1} \cdot \tilde{a}_r' + B_{\phi1} \cdot \tilde{a}_\phi' + B_{z1} \cdot \tilde{a}_z'$ (6a)

at P$_2$: $\quad \tilde{B}_{p2} = -B_{r2} \cdot \tilde{a}_r' + B_{\phi2} \cdot \tilde{a}_\phi' + B_{z2} \cdot \tilde{a}_z'$ (6b)

at P$_3$: $\quad \tilde{B}_{p3} = -B_{r2} \cdot \tilde{a}_r' - B_{\phi2} \cdot \tilde{a}_\phi' + B_{z2} \cdot \tilde{a}_z'$ (6c)

at P$_4$: $\quad \tilde{B}_{p4} = -B_{r1} \cdot \tilde{a}_r' - B_{\phi1} \cdot \tilde{a}_\phi' + B_{z1} \cdot \tilde{a}_z'$ (6d)

where, $B_{r1} < B_{r2}$ and $B_{z1} < B_{z2}$

The velocity vector remains same as Eq. 2. Therefore, the restoring force equation for this case can be written by changing the sign of B_r and B_ϕ in Eq.5 as shown in Eq. 7.

$$F_s = -\sigma a_s R_s \int_0^{\pi/4} [-2\upsilon_z (B_{r2}(\alpha)B_{z2}(\alpha) - B_{r1}(\alpha)B_{z1}(\alpha)) +$$
$$(\upsilon_{r1} + \upsilon_{r2})(B_{z1}^2(\alpha) + B_{z2}^2(\alpha))] \cos\alpha \, d\alpha \quad (N) \quad (7)$$

3. CONCLUDING REMARKS

From Eq. 5 and 7, one can notice that the restoring force is affected by the propelling velocity. As shown in Eq.5,

in case that the sleeve coil is located on the right side of the drive coil, the effect due to the propelling velocity does an anti-restoring force. However, as shown in Eq.7, the effect of the propelling velocity is a positively directed force while the effect due to the transverse velocity remains the same direction.

Reminding the definition of υ_z as shown in Eq. (2g), the effect of propelling velocity to the restoring force reduced as the propelling velocity get bigger. However, since the magnetic flux density difference at the top and bottom of the sleeve coil is small, the effect of the motion-induced currents is not a dominant one and it can be considered a second order effect.

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