Passive Electrodynamic Magnetic Thrust Bearing Especially Designed for Constant Speed Applications

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***Abstract* - Two years ago we presented a magnetic thrust bearing consisting of two stationary sets of coils located between two rotating planar repulsive Halbach arrays. We will present here a small modification of these bearings by purely passive elements, which increase the restoring stiffness by a factor of up to ten. This modification is particularly suitable for constant speed applications.**

***Index Terms* – Passive magnetic bearings, Halbach arrays, electrodynamic bearings, rotating machinery, constant speed.**

I. INTRODUCTION

A. *State of the art of passive low-loss electro-dynamic bearings*

The described passive electrodynamic thrust bearing is composed of a stationary set of coils located between two rotating planar repulsive Halbach arrays. Generally, the coil set links the magnetic field in the air gap between Halbach arrays. The coils are connected in series (with an appropriate polarity) and then short-circuited. In the centered position no voltage is induced within the coils, thus no losses are present in this case. Only during axial excursions restoring forces are created.

In general, for proper operation of an electrodynamic magnetic bearing a certain phase shift between the induced voltage and coil current have to be present; usually greater than 45 degrees, ideally close to 90 degrees. In case that this angle is small, a braking torque will prevail over restoring forces, which is not desired. At higher rotational speeds the coil reactance preponderates over the coil ohmic resistance. Although the phase angle between voltage and current approaches the desired value of 90 degrees, the increased impedance causes an asymptotic limitation of the coil current and thus restoring forces. When the speed is further increased, the current remains almost constant.

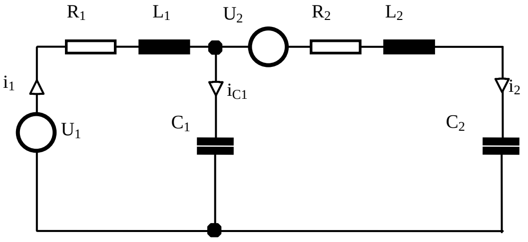

Fig. 1: General layout of two coupled LCR circuits.

The phase angle depends on the rotational speed and the inductance-to-resistance ratio, i.e. on the coil's time constant. This time constant is governed by the coil geometry and therefore, due to a limited space available, bounded in a rather narrow range. The detailed description of the passive electrodynamic bearing construction can be found in [1].

II. DESCRIPTION

A. *Proposed new device and its operating principle*

In order to decrease the coil reactance and thus to increase the current, a condenser may be connected in series with the coils, thus compensating the positive reactance with a negative one. The maximum current

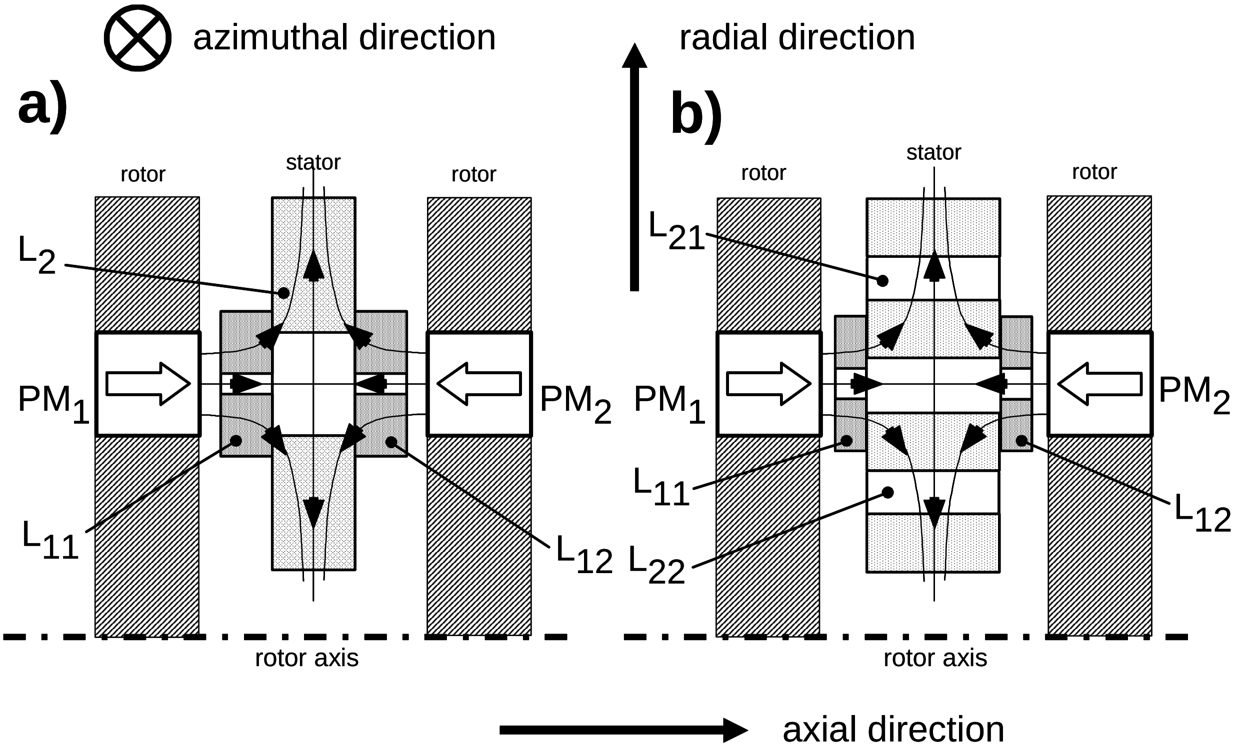

Fig. 2 One unit of a multipolar planar Halbach array in a repulsive mode (cross-section). Spatial orientation is given by arrows and the shape of the magnetic field is shown. **a)** In both coil sets L_1 and L_2 an alternating voltage may be induced (generator / actuator). **b)** Only in the coil set L_1 a voltage may be induced (generator); not in the set L_2 (actuator).

will be achieved near the resonance, however, the phase angle will be shifted close to zero, which is not desirable.

By means of introducing a second coil set into the system, two coupled LCR circuits may arise (Fig. 1) and thus, due to appropriately chosen condenser's values, proper phase shift can be achieved. The coil's reactance is suppressed and along with this the phase angles can be moved into the desired range. By means of this method (in comparison with a simple electrodynamic bearing) restoring forces can be dramatically increased (by a factor of about ten); however, with an in the title mentioned requirement of a constant rotating speed. The width of the speed range for proper operation depends on the circuit figure of merit (*Q*-factor: reactance-to-resistance ratio). At other speeds the restoring forces are progressively reduced and eventually touch-down bearings have to come into operation.

B. *Possible coil configurations*

There are at least three possibilities of coil configurations:

Configuration 1) During an axial excursion in both coil sets an alternating voltage is induced (the voltages are in phase). Note, that coils of the set L_1 are split in two (L_{11} and L_{12}), as shown in Fig. 2a. Both coil sets produce restoring forces.

Configuration 2) During axial excursion an alternating voltage is only induced in the coil set L_1, see Fig. 2b. Note, that both coil sets are split in two in this case (L_{11}, L_{12} and L_{21}, L_{22}). Depending on geometry, the restoring forces are created mainly in the set L_2.

Configuration 3) Only the coil set L_1 is located within the bearing air gap (not shown). The other set L_2 is situated outside the bearing magnetic field and does not contribute to the creation of restoring forces. This set consists solely of one coil; in order to increase the coil inductance and reduce its resistance (and losses) a ferrite core may be used. Thus an arbitrary coil's time constant can be achieved. All restoring forces are due to the set L_1 in this case.

Note that the coils denoted L_1 and L_2 (together with its resistances R_1 and R_2) in the Fig. 1 represent the whole set of a plurality of coil units uniformly distributed along the stator circumference (e.g. eight or more units) and then connected in series. In the Fig. 2 two cross-sections of these units are depicted. As you see, one unit may be composed of three or more coils (some of them denoted by a double subscript).

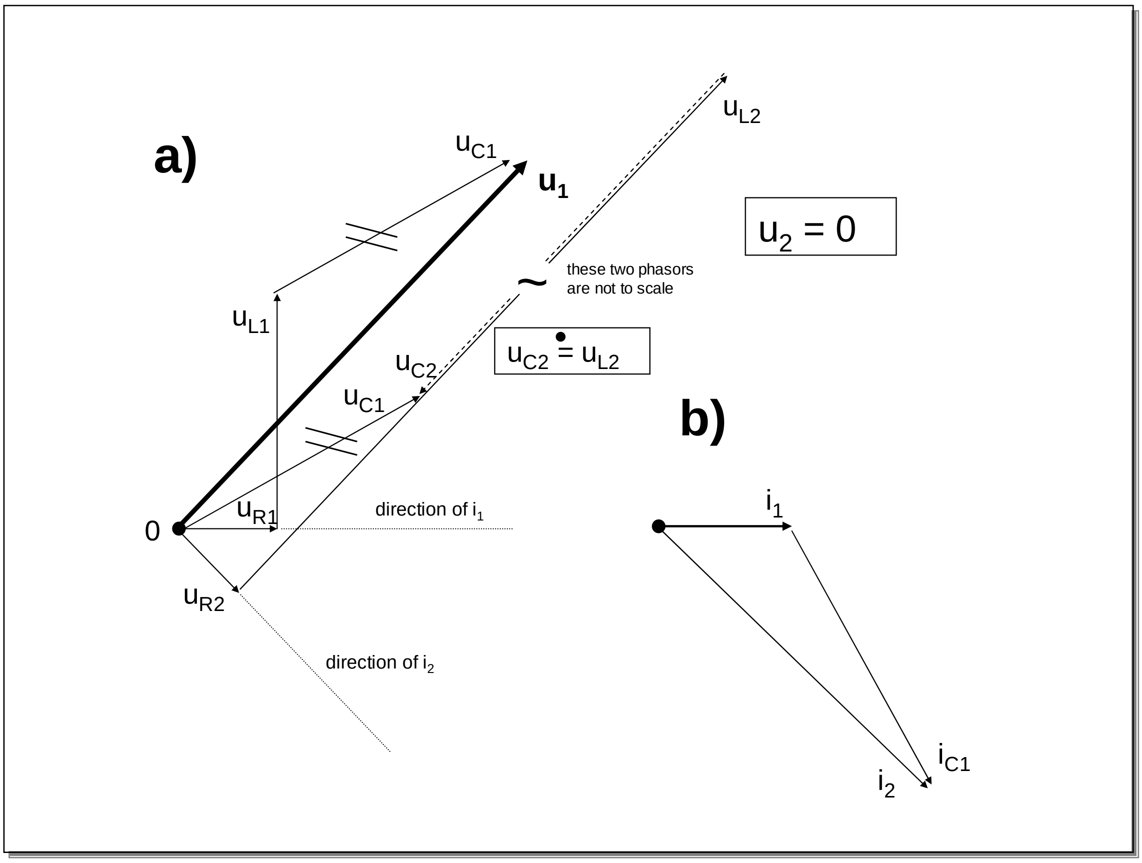

Fig. 3: Phasor diagram of a special case, where $\varphi_1 = 45°$ and $\varphi_2 = 90°$. **a)** Voltage phasor diagram with reference voltage $u_1 = 1$ V (bold line) and $u_2 = 0$. Note that magnitudes and directions of reactance phasors u_{L2} (full line) and u_{C2} (dashed line) are almost equal. These two phasors are not depicted to scale; their magnitudes are 5.458 V and 4.916 V, respectively. **b)** Current phasor diagram.

C. *Evaluation of condenser values*

Although properties of the coupled LCR circuit are easily analytically computable, we have used instead a simple Monte Carlo programme (if coil parameters are given, then for desired phase angles both condenser values C1 and C2 can be obtained). Then with another programme a phasor diagram is generated and afterwards, in order to check for the phase angles, a “PSpice Transient Analysis” is executed.

D. *Construction notes*

According to experience, it is not recommended to use wires with a diameter greater than 0.3 mm. As the coils are located within a strong alternating magnetic field, eddy currents induced in the bulk of the wire will get rather excessive (even at the rotor centered position!). If larger wire cross-sections are needed, a HF-litz has to be used.

In order to conceive the coil system, a ratio of coil inductances L_2/L_1 should be chosen (somewhere between 3 and 20). As the inductance value of the second coil is higher than that of the first one, even a small current in it will produce an appreciable magnetic flux. Therefore, a proper adjusting of the phase angle φ_2 between the current in the second coil i_2 and the induced voltage u_1 in the first one will be more influential than the phase angle φ_1 of the first coil. The angle should be somewhere between 45 and 135 degrees.

As soon as the geometry of coil sets is determined, the coil’s inductance can easily be calculated with known approximate formulae for air-coils. As there is some weak inductive coupling among the coils, the calculated value of the coil set’s inductance should be slightly corrected to a higher value. By estimation of the coil’s resistance a copper filling factor between 50 and 60 percent has to be taken into account. Then the coil’s time constant and the individual circuit’s figure of merit Q will follow (the influence of condensers onto the circuit’s quality may be neglected).

The coil's figure of merit should be kept rather low (say, between 3 and 20). For higher circuit's qualities the band-width will get too narrow (i.e. the range of rotational speeds for proper operation will correspondingly shrink). For a given geometry and desired coil's time constant, the circuit's quality cannot be freely designed. But there exists a possibility how to influence the circuit's qualities: external resistors can be connected parallel to one or both coil sets. Therefore, in this case, the coils are incompletely short-circuited and the original principle of passive electrodynamic magnetic bearing will be partially restored (see [1]). There are still no additional losses due to these resistors, provided the rotor remains at the centered position.

As stated before, the desired value of the phase angle (φ_1 and φ_2) is 90 degrees, but it is impossible to achieve this value in both coils simultaneously (as reactive currents cannot transfer any energy!). Therefore, some compromise has to be chosen.

E. *Some further improvements*

When the second phase angle φ_2 is greater than 90 degrees, then the first phase angle φ_1 can be greater than 45° and can even approach a value close to 90°. Thus, proper resonance can be attained, i.e. the positive coil reactance will be completely compensated by the condenser's negative one.

An example of a phasor diagram with $\varphi_1 = 45°$ and $\varphi_2 = 90°$ is shown in the Fig. 3.

An evaluation of success can be done by means of an improvement factor i_2/i_0, i.e. by a ratio of the resulting current i_2 and a current i_0, where i_0 is the current in that case, where the condensers are absent and the coils are short-circuited.

III. RESULTS

A. *Basic data*

For the sake of a numerical example we present the following case:

$u_1 = 1$ V (in a real case this voltage will be much higher than 1 V)

$u_2 = 0$; f = 500 Hz; $L_2/L_1 = 5$; $\varphi_1 = 45°$; $\varphi_2 = 90°$; $Q_1 = 4$ and $Q_2 = 20$.

Coil inductances: $L_1 = 10$ mH; $L_2 = 50$ mH
Coil resistances: R1 = R2 = 7.86 Ω
Coil reactances: $X_{L1} = 31.42\ \Omega$; $\mathbf{X_{L2} = 157.1\ \Omega}$

B. *Calculated condenser values*

Condensers: $C_1 = 13.55\ \mu F$; $C_2 = 2.25\ \mu F$
Condenser reactances: $X_{C1} = -23.49\ \Omega$;
$\mathbf{X_{C2} = -141.5\ \Omega}$

Note that the second reactance absolute values X_{L2} and X_{C2} are approximately equal.

Currents: $i_1 = 16.46$ mA ; $i_{C1} = 25.85$ mA ;
$i_2 = 34.76$ mA

Note further that the second current i_2 is greater than the first current i_1 .

Short-circuit current (when both condensers are absent):
$i_0 = 5.287$ mA

Short-circuit flux (when both condensers are absent):
$\Phi_0 = (L_1 + L_2) * i_0 = 0.317$ mWb

Improvement factor: $i_2/i_0 = 6.59$

Coil magnetic fluxes: $\Phi_1 = L_1 * i_1 = 0.165$ mWb
$\Phi_2 = L_2 * i_2 = 1.738$ mWb

Flux improvement factor: $\Phi_2 / \Phi_1 = 10.56$

IV. CONCLUDING NOTES

A. *Attainable improvements*

This example was chosen for the sake of simplicity, because the second current i_2 is fairly higher than the first current i_1 and the circuit evaluation is straightforward. For other parameters more suitable results can be achieved. But be cautious; there are cases, where the above defined improvement factor is not very predicative and not only comes the second coil into operation. Therefore, some combination of both coil influences has to be taken into account. The circuit's performance depends on the shape of coil sets, space available for them and also on the ratio of their number of turns.

Improvement factors greater than 10 are readily attainable compared to the setup without condensers.

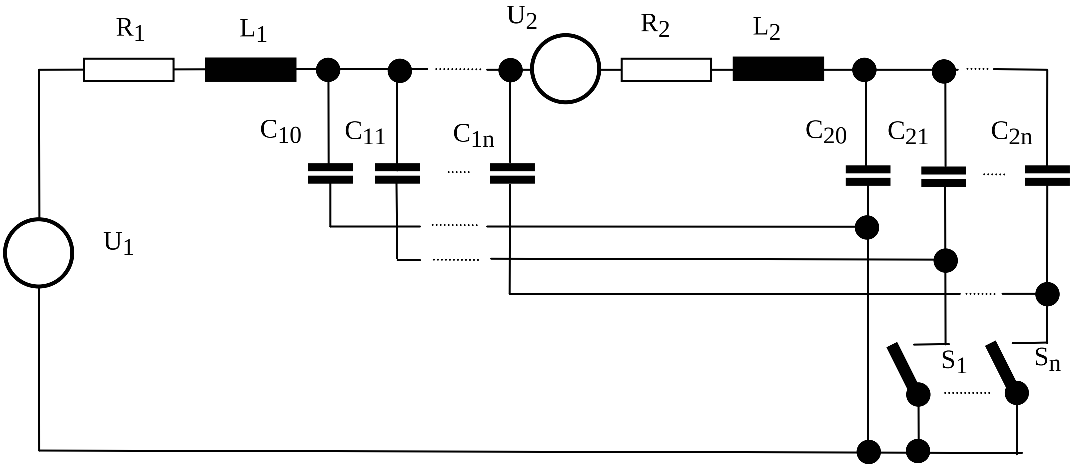

Fig. 4 Multi-frequency version with CMOS switches.

There are many applications of magnetic bearing, where only a constant speed is required, e.g. in turbomolecular pumps, compressors, beam choppers, etc.

B. *Multi-frequency circuit*

As an information about the rotational speed is easily attainable (e.g. with an optical sensor), it is evident that by means of sequentially changing condenser values by switching proper operation at an arbitrary speed can be attained (Fig. 4).

The number of switches depends on the LCR circuit's qualities. For a smooth operation within a wide frequency range a relatively large number of switches will be needed. Some trade-off between costs and high effectiveness has to be taken. Although such extended circuit contains some (active) semiconductors, no feedback is needed, only feed-forward is present. Therefore, stability problems cannot happen.

REFERENCES

[1] J. Sandtner, H. Bleuler: "Electrodynamic Passive Magnetic Bearing with Planar Halbach Arrays", *Proc. of 9th International Symposium on Magnetic Bearings ISMB9*, Lexington, Kentucky, USA, Aug. 3-6, (2004), Paper #5