Lab session 5 – H9x34A
An electrodynamic levitation device

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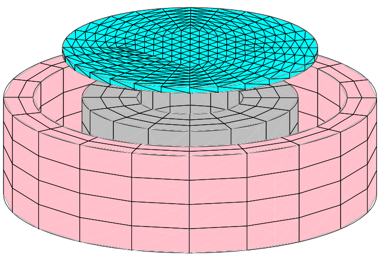
The objective of this lab session is analysing by means of a finite element model an electrodynamic levitation device, namely the **model A** of TEAM workshop problem 28[1]. It concerns a cylindrical aluminium plate ($\sigma = 3.40\ 10^7$ S/m, radius = 65 mm, thickness = 3 mm, mass = 0.107 kg) located above two coaxial coils carrying imposed sinusoidal currents of amplitude 20 A and frequency 50 Hz (see Figure 1 left). The inner and outer coils have $w_1 = 960$ and $w_2 = 576$ turns, respectively. The dimensions of the device are shown in Figure 1 right. Although the specific wire gauge, etc., is not specified in the original problem definition, it is assumed that the coil is wound out of 18 AWG copper wire.

The levitation height z refers to the distance between the lower circular end of the cylindrical plate and the upper sides of the coils ($z = 0$).



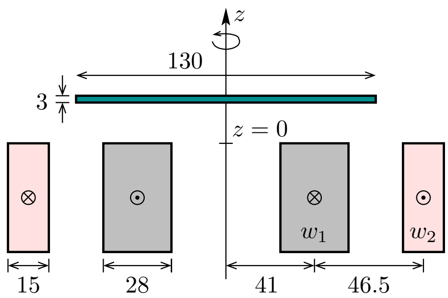


Figure 1: Levitation device model: cylindrical plate above two coaxial coils. Dimensions in mm

At $t = 0$ the plate rests above the coils at a distance of $z = 3.8$ mm. For $t \geq 0$, sinusoidal currents flow in the coils in opposite directions.

The coils generate a time-varying magnetic field that induces eddy currents in the conducting plate Ω_c, which results in a vertical impulsive force $\underline{F}_{mag}$ on it. After some damped oscillations the plate reaches a stationary levitation height of $z = 11.3$ mm (measured). Due to the symmetry of the problem, we assume that the movement is purely translational.

1 Furnished file and data to complete

You have to constract the geometry from scratch thinking about the computations you are asked to perform, e.g. the force computation via the Maxwell stress tensor needs an airlayer around the moving plate. Take advantage of the axisymmetry.

You get a `pro` file to complete taking into account your own geometry [2]. Concretely, you have to define/assign:

- The domains and the associated "physical" regions.

[1] Testing electromagnetic analysis methods (TEAM), `http://www.compumag.org/jsite/team.html`

[2] Advice: use a common data file for the `geo` and `pro` files.

- The piecewise functions linked to the material characteristics (e.g. permittivity, reluctivity).
- The constraints for the magnetic vector potential `MVP_2D`.
- The constraints for the source `Current_2D`. You need a time dependent function for the time-domain computation.
- Estimate the total resistance of the windings of the two feeding coils with the given data `Resistance[]`.
- Any other missing data.

2 To include in the report

Besides the `geo` and the `pro` files you have created and modified, you should perform steady-state and time-harmonic computation. For these two cases,

Steady-state computation with the levitating plate at stationary height $z = 11.3\,\text{mm}$:

- Post-processing map of the MVP (z-component), real and imaginary parts.
- Post-processing map of the magnetic inductance, real and imaginary parts.
- Post-processing map of the electric current density (z-component), real and imaginary parts.
- Expected electromagnetic force.
- Force computation via Lorentz law and/or Maxwell stress tensor in post-processing of the FE computation.
- Sensibility of the force computation with the mesh.

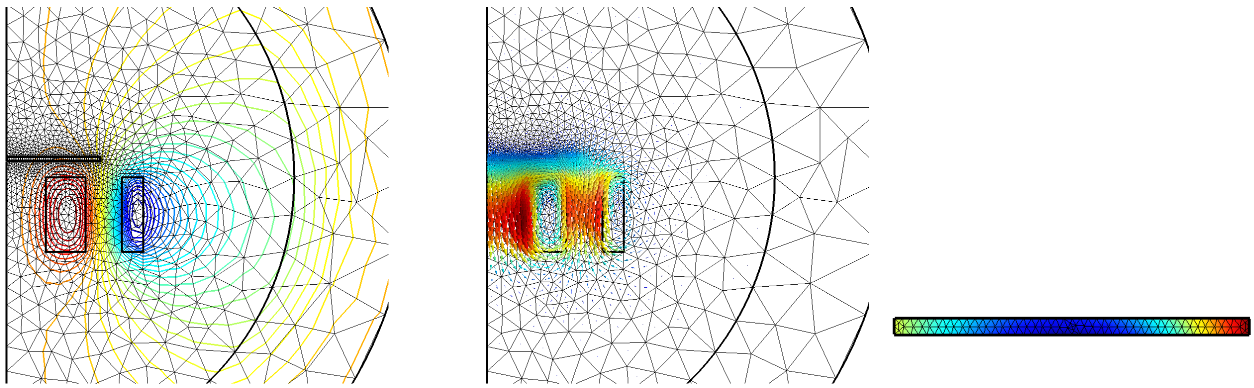


Figure 2: Examples of maps, from left to right: the MVP, the magnetic induction and electric current density (real parts)

Time-harmonic computation with the levitating plate at an initial position of $z = 3.8\,\text{mm}$:

- Time-stepping simulation till equilibrium. How long does it take to get there?
- For a fixed mesh (fine enough), sensibility of the result with regard to the chosen time step.
- For a fixed time step, sensibility of the result with regard to the mesh refinement. (You do not need to reach equilibrium.)
- Comparison of the obtained results with the measurement data furnished in the TEAM problem 28 description furnished as annexe.

Note that in this case, at every time step the plate moves and the mesh have to be updated for the following computation. This is done automatically in the software using the variable `step`. The sequence of computations is as follows: 1) solve magnetodynamic formulation; 2) compute magnetic force; 3) compute new position; 4) remesh; 5) project results of previous time step on new mesh for being able of computating the time derivative $\partial_t a$ (eddy currents).

You can find the theory about force computation in slides 17-32 of file `07Postprocessing.pdf` and about coupled problems in slides 49-57 of file `08Circuits_Movement_CoupledProblems.pdf`. It maybe also useful to have a look at the example of coupled formulations given in the introductory set of slides for GetDP, i.e. `intro_getdp_2014-15.pdf` (page 33).

Description of TEAM Workshop Problem 28: An Electrodynamic Levitation Device

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***Abstract*— This paper presents a new TEAM workshop problem taking into account moving bodies. An electrodynamic levitation device which consists of a conducting plate over two exciting coils shall be examined. The aim is to determine the dynamic characteristics of the levitating plate. A coupled solution of the electromagnetic and the mechanical problem is necessary for that.**

I. Introduction

The modelling of electromechanical devices, i.e. the solution of transient coupled electromechanical problems taking into account moving bodies is gaining significance. For this reason it is necessary to define a benchmark which allows to compare different approaches regarding their advantages and disadvantages for the solution of such problems. Typical difficulties are the treatment of motion, strategies for remeshing, force calculation, weak versus strong electromechanical coupling, efficient time stepping schemes, etc.

Up to now only TEAM workshop problem 9 and TEAM workshop problem 17 deal with moving bodies. In problem 9 a moving body with given constant velocity is considered. The problem is axisymmetric and infinitely extended in the direction of the velocity. Therefore it is stationary and lacks the feature of electromechanical coupling. For problem 17 no measured data are available. Only the description of the underlying experiment is given and therefore the treatment of the problem is difficult. In contrast, the new TEAM workshop problem 28 is a transient problem with electromechanical coupling and measured data being available.

It is intended to split the new problem into different packages with increasing level of difficulty. In this paper, **Model A** is presented. Model A is an axisymmetric problem without significant eddy current reaction to the exciting coils. In the future, two additional packages will be provided. **Model B** will be very similar to Model A, but the levitating plate will have an eccentric bore which disturbs the axisymmetry and requires a full 3D modelling. **Model C** will have a different geometry and operating frequency. The exciting coils will be voltage driven and the reaction due to the motion has to be taken into account. This is an important feature because many actuators are voltage driven and show a typical current drop due to the motion of the armature.

II. Description of Model A

One of the earliest papers on levitation by fields at power frequencies is that due to Belford, Peer and Tonks [1]. Electrodynamic levitation is based on the induction of eddy currents in conducting materials. These eddy currents can be induced by a time varying magnetic field. This is the case for the device shown in Fig. 1. A cylindrical aluminium plate ($\sigma = 3.40 \cdot 10^7$ 1/Ωm, $m = 0.107$ kg) is located above two cylindrical coils. All three parts are aligned coaxially. The inner coil has $w_1 = 960$ and the outer coil $w_2 = 576$ turns. The dimensions of the device are shown in Fig. 2. The levitation height z refers to the distance between the lower edge of the plate and the upper edge of the current carrying area ($z = 0$). For $t \leq 0$ the plate rests above the coils at a distance of $z =$ 3.8 mm due to the thickness of the winding form.

Fig. 1. TEAM Workshop problem 28: An electrodynamic levitation device

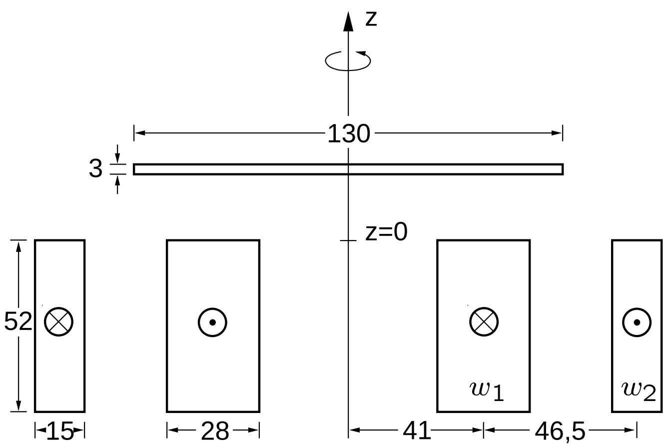

Fig. 2. Dimensions (in mm) of the electrodynamic levitation device

Both coils are connected in series, but with different sense of winding. The device is operated directly between two outer conductors of the three-phase supply network. With the help of an electronic switch, the instant of switching on is synchronized onto the driving supply voltage in a way that there is no electrical transient. For $t \geq 0$, sinusoidal currents $i(t)$ flow in the coils in opposite directions,

$$i(t) = \hat{\imath} \sin(2\pi f_0 t), \qquad \hat{\imath} = 20\,\mathrm{A}, \quad f_0 = 50\,\mathrm{Hz}. \qquad (1)$$

Due to the induced eddy currents a repulsive force is exerted on the plate. After some damped oscillations, the plate attains a stationary levitation height of $z = 11.3$ mm. A possible reaction of the induced eddy currents can be neglected. For this reason, the current in (1) can be regarded as impressed.

III. Measurement of the levitation height

The levitation height is measured by means of laser triangulation. The principle is shown in Fig. 3. A laser beam emitted by a laser diode is directed near the center of the plate. The reflected beam is detected by a position sensing semiconductor detector (PSD). A displacement Δz of the plate yields a displacement Δs of the reflected beam. With this principle, a high resolution limited only by amplifier noise can be achieved.

In practice, however, there are some undesired effects which complicate the measurements. The first problem is that the device can never be perfectly axisymmetric. Any radial displacement of the plate, nonhomogeneous winding of the coils and other similar effects disturb the symmetry. This causes additional oscillations of the plate around a radial axis. Luckily the experiments showed that these oscillations have only a minor effect on the measured results. Fig. 4 shows the measured levitation height of four different measurements and gives an idea about the reproducibility. The difference of the respective results is acceptable. The average values of these measured data are given in Table I on the next page and should be used for the comparison with numerical results.

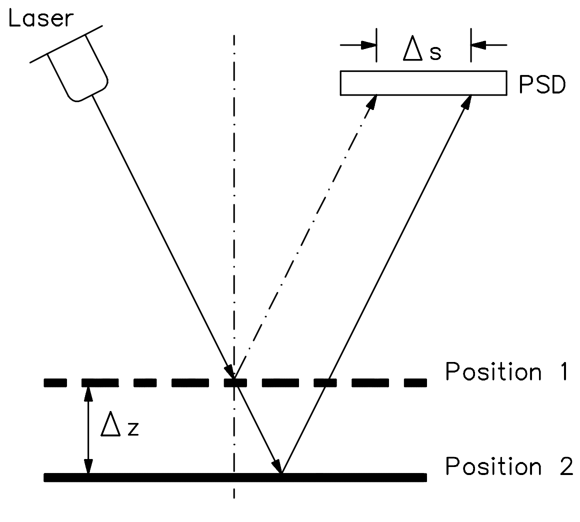

Fig. 3. Measurement of the levitation height by means of laser triangulation

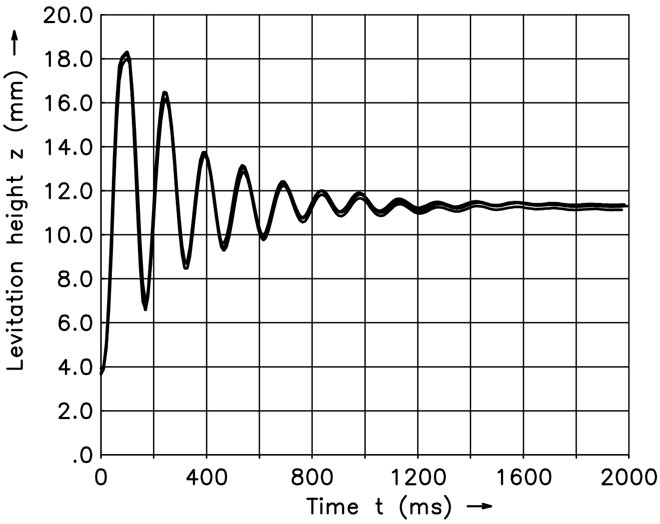

Fig. 4. Measured levitation height of four different measurements.

It is important to make sure that the plate and the coils have ambient temperature when the measurement starts. Due to the ohmic losses the temperature of the device raises significantly during operation. This would increase the resistance and cause inaccurate results.

Another difficulty is related to the exact modelling of the coils. For numerical purposes the coils are represented by domains which carry a homogeneous azimuthal current density. The cross section of these domains is given by the rectangular cross section of the winding space. The coils are made of copper wire with 1.2 mm diameter and contain insulating layers. The real current density is neither strictly homogeneous nor sharply bounded by a rectangle. These effects may influence the plate during its initial lift-off phase. It is difficult to estimate the influence of this effect.

IV. Comparison of Measured and Computed Results

For the sake of completeness we include a comparison between the measured data according to Table I and computed results in this description, see Fig. 5. The computed results have been obtained with the help of the BEM-FEM code described in [2], [3]. The discrepancy of the maximum levitation height during the first half period might be traced back to the modelling of the coils as explained in the previous section.

V. Concluding Remarks

This description of TEAM problem 28 superseeds the preliminary description [4]. The results in Table I can be supplied on request by e-mail (hans.karl@ite.uni-stuttgart.de). It is hoped eventually to have the entire

Table I: Measured results of the levitation height

t (s)	z(mm)	t (s)	z(mm)	t (s)	z(mm)	t(s)	z(mm)	t (s)	z(mm)	t(s)	z(mm)
0.0	3.7	287.4	11.9	574.9	11.6	862.3	11.7	1149.8	11.5	1437.2	11.4
9.9	4.0	297.4	10.4	584.8	11.0	872.3	11.4	1159.7	11.4	1447.2	11.4
19.8	4.9	307.3	9.3	594.7	10.4	882.2	11.2	1169.6	11.3	1457.1	11.4
29.7	6.9	317.2	8.7	604.6	10.0	892.1	11.1	1179.5	11.2	1467.0	11.3
39.6	9.7	327.1	8.7	614.5	9.9	902.0	11.0	1189.4	11.1	1476.9	11.3
49.6	12.8	337.0	9.2	624.5	10.0	911.9	11.0	1199.4	11.1	1486.8	11.3
59.5	15.6	346.9	10.2	634.4	10.3	921.8	11.1	1209.3	11.1	1496.7	11.3
69.4	17.4	356.8	11.4	644.3	10.8	931.7	11.2	1219.2	11.1	1506.6	11.3
79.3	18.0	366.7	12.4	654.2	11.3	941.6	11.4	1229.1	11.2	1516.5	11.3
89.2	18.1	376.7	13.2	664.1	11.7	951.6	11.6	1239.0	11.2	1526.4	11.3
99.1	18.2	386.6	13.6	674.0	12.1	961.5	11.7	1248.9	11.3	1536.4	11.3
109.0	17.8	396.5	13.7	683.9	12.3	971.4	11.8	1258.8	11.4	1546.3	11.4
118.9	16.4	406.4	13.3	693.8	12.3	981.3	11.8	1268.7	11.4	1556.2	11.4
128.9	14.1	416.3	12.7	703.8	12.2	991.2	11.8	1278.6	11.4	1566.1	11.4
138.8	11.5	426.2	11.8	713.7	12.0	1001.1	11.7	1288.6	11.4	1576.0	11.4
148.7	9.0	436.1	10.9	723.6	11.6	1011.0	11.5	1298.5	11.3	1585.9	11.4
158.6	7.2	446.0	10.1	733.5	11.3	1020.9	11.4	1308.4	11.3	1595.8	11.4
168.5	6.7	456.0	9.6	743.4	11.0	1030.8	11.2	1318.3	11.3	1605.7	11.4
178.4	7.3	465.9	9.4	753.3	10.8	1040.8	11.1	1328.2	11.2	1615.7	11.4
188.3	8.8	475.8	9.6	763.2	10.7	1050.7	11.0	1338.1	11.2	1625.6	11.3
198.2	10.7	485.7	10.1	773.1	10.8	1060.6	11.0	1348.0	11.2	1635.5	11.3
208.2	12.6	495.6	10.8	783.0	10.9	1070.5	11.0	1357.9	11.2	1645.4	11.3
218.1	14.3	505.5	11.6	793.0	11.2	1080.4	11.1	1367.9	11.2	1655.3	11.3
228.0	15.6	515.4	12.2	802.9	11.5	1090.3	11.2	1377.8	11.3	1665.2	11.3
237.9	16.2	525.3	12.7	812.8	11.7	1100.2	11.3	1387.7	11.3	1675.1	11.3
247.8	16.3	535.2	13.0	822.7	11.9	1110.1	11.4	1397.6	11.4	1685.0	11.3
257.7	15.8	545.2	12.9	832.6	12.0	1120.1	11.5	1407.5	11.4	1694.9	11.3
267.6	14.8	555.1	12.7	842.5	11.9	1130.0	11.5	1417.4	11.4	1704.9	11.3
277.5	13.5	565.0	12.2	852.4	11.8	1139.9	11.5	1427.3	11.4	1714.8	11.4

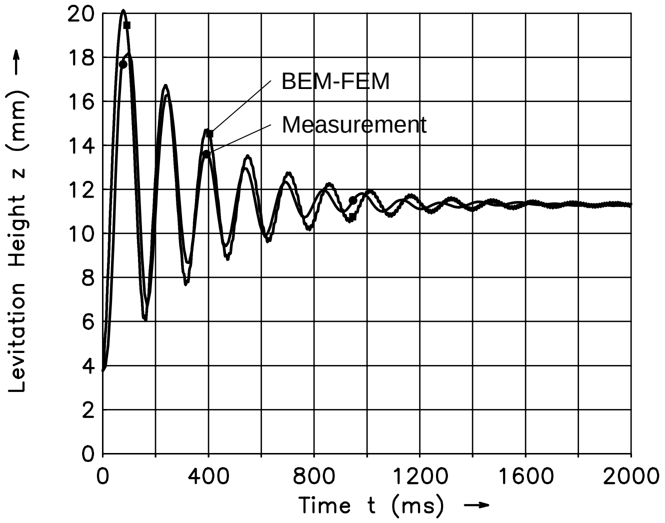

Fig. 5. Comparison between the measured (Table I) and the computed (BEM-FEM) levitation height

description available on a WWW TEAM page.

References

[1] B.D. Bedford, L.H. Peer, and L. Tonks, "The electromagnetic levitator," *Gen. Elect. Rev.*, vol. 42, no. 6, pp. 246–247, 1939.

[2] S. Kurz, J. Fetzer, and G. Lehner, "Threedimensional transient BEM-FEM coupled analysis of electrodynamic levitation problems," *IEEE Transactions on Magnetics*, vol. 32, no. 3, pp. 1062–1065, May 1996.

[3] S. Kurz, J. Fetzer, G. Lehner, and W.M. Rucker, "A novel formulation for 3D eddy current problems with moving bodies using a Lagrangian description and BEM-FEM coupling," Submitted to the COMPUMAG 1997.

[4] H. Karl, J. Fetzer, S. Kurz, G. Lehner, and W.M. Rucker, "Preliminary proposal for a new TEAM workshop problem: An electrodynamic levitation device," in *Proc. of the TEAM Workshop*, Graz, Austria, Sept. 1996, pp. 41–42.