Magic Unit Checks for Physics and Extended Field Theory based on interdisciplinary Electrodynamics with Applications in Mechatronics and Automation

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1. Introduction

What is the problem? The often recognised problem in mechatronics is a lack of experience in applying electrodynamic knowledge. Therefore a compact introduction in an extended Maxwell's field theory with interdisciplinary applications shall introduce a valuable key for all "Mechatronicists". All the described industrial developments were primarily based on electrodynamics, using innovative ideas, Maxwell's equations and both software and computer-aided simulation. However the focus of this publication is primarily on the advantage and necessity of electrodynamics inside mechatronics.
FIRST, the mighty capabilities of Unit Checks for deriving all central equations and formulas in physics are surprising and magic. These mostly unknown Unit Check methods will demonstrate the commonly unused fast derivation of famous and complex equations in physics from mechanics, electrodynamics up to quantum mechanics, Einstein's relativity formulas etc.
SECOND, the known Maxwell's equations in rest were extended and re-formulated for arbitrarily moving objects. Additionally, the sketched derivation of a unified equation for relativistic quantum electrodynamics based on Faraday and Einstein - including Maxwell's equations as a subset - will show further interdisciplinary applications in classic, quantum and relativistic physics.
THIRD, the structure identity of the complete eddy current equations in electrodynamics with respect to other disciplines in physics (i.e. hydrodynamics, thermodynamics, elastomechanics etc) opens a door for both quick analytical approximation and interdisciplinary development or optimisation of new mechatronic systems. Actual computer-based and analytical applications in the broad field of motor car production, robot gripper design, anti-vibration systems and complex hard disc drives will show the high efficiency and central position of extended Maxwell's equations in electrodynamics for automation and mechatronics.

This publication about interdisciplinary electrodynamics is based on research and development by Prof Stanek at University of Applied Sciences Koblenz (Germany), in addition to his guest lectures at Swiss German University SGU (BSDCity / Jakarta Indonesia) and Technical University Opole (Poland), his contributions at the REM conference Research and Education in Mechatronics (Stanek & Grueneberg, 2003), his own publications and his books about field theories and industrial mechatronics (Cassing & Stanek, 2002; Stanek et al., 2001), his results of an advised Master Thesis at SGU about robotics (Andries, 2003), his research and developments for motor car production (Stanek et al, 1984) and his own web sites about extended Electromagnetic Field Theory using Heaviside's streamlined re-design of Maxwell's equations and extensions (Stanek, 2010).

2. Electrodynamics as a central part in mechatronics

The fact that electrodynamics is a central part in mechatronics will be shown by different views of Maxwell's equations and interdisciplinary evaluations.

2.1 Electrodynamics based on Maxwell's equations

One of the most famous formulations in physics is the set of Maxwell's equations. Later, some basic equations will be shown or re-formulated and then extended.

2.1.1 Basic Maxwell's equations and constitutive relations

A compact overview of basic Maxwell's equations in differential and integral formulation with (nonlinear) constitutive relations is presented in this section.
Eq. (1) in Fig. 1 is Ampere-Maxwell's Law and eq. (2) Faraday-Lorentz' Law, both of which are called field equations. Eq. (3) is electric Gauss' Law and eq. (4) magnetic Gauss' Law, both are called source equations for Maxwell's field theory. **B** is magnetic flux density in **Vs/m²**, **H** is the magnetic field strength in **A/m**, **D** is displacement or electric flux density in **As/m²,** E is the electric field strength in **V/m, J** is the electric current density in **A/m², ρ** is the electric volume charge density in **As/m³,** Q is electric charge in **As**, and ∇ is the Nabla-Operator for vector analytical operations. For all bodies in rest, the dot (•) over **D** and **B** means partial derivatives of these characteristics with respect to time (here $d/dt=\partial/\partial t$). Simple mnemonics are shown in Fig.1.

Maxwell's equations in differential form

The basic set of Maxwell's equations (1) - (4) can be written in differential form:

$$\nabla \times \mathbf{H} = \mathbf{J} + \dot{\mathbf{D}} \quad (1)$$

$$\nabla \times \mathbf{E} = -\dot{\mathbf{B}} \quad (2)$$

$$\nabla \cdot \mathbf{D} = \rho \quad (3)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (4)$$

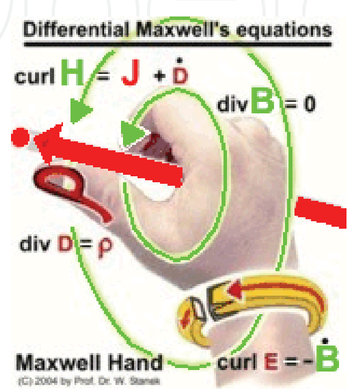

Fig. 1. Set of Maxwell's equations with equivalent mnemonics "Maxwell's Hand" (Stanek, 2002+2010)

Maxwell's equations in integral form

Using the known vector analysis laws by Stokes and Gauss we get from eq. (1) - (4):

$$\oint \mathbf{H}\, d\mathbf{l} = \iint \mathbf{J}\, d\mathbf{s} + \iint d\mathbf{D}/dt \cdot d\mathbf{s} \quad (1a) \qquad \oint \mathbf{E}\, d\mathbf{l} = -\iint d\mathbf{B}/dt \cdot d\mathbf{s} \quad (2a)$$

$$\oiint \mathbf{D}\, d\mathbf{s} = \iiint \rho\, dv = Q \quad (3a) \qquad \oiint \mathbf{B}\, d\mathbf{s} = 0 \quad (4a)$$

Because of primarily using the superior magnetic vector potential **A** shown in later equations, we introduce letter **s (=surface) for area**, **l is the length** and ν **(=nu) is the volume**. If we don't consider moving bodies, the terms d/dt are partial derivatives ∂/∂t.

Constitutive relations

The constitutive relations between the **classical field terms D, E, B, H and J**, also including both polarisations and external current sources, are defined by eq. (5) - (7):

$$\mathbf{D} = [\varepsilon]\, \mathbf{E} + \mathbf{P} \quad (5) \qquad \mathbf{B} = [\mu]\, \mathrm{H} + \mathbf{B}_p \quad (6) \qquad \mathbf{J} = [\gamma]\, \mathrm{E} + \mathbf{J}_e \quad (7)$$

Eq. (6) with details: $\mathbf{B} = \mu\, \mathbf{H} + \mathbf{B}_p = \mu_0\, \mathbf{H} + \mu_0\, \mathbf{M}_e + \mu_0\, \mathbf{M}_p = \mu_0\, (\mathbf{H} + \mathbf{M}_e) + \mu_0\, \mathbf{M}_p$ (6a)

In eq. (6a) $\mathbf{B}_p$ is the magnetic polarisation and $\mathbf{M}_p$ is the magnetisation in permanent magnets, $\mathbf{M}_e$ is the magnetisation in magnetic iron caused by an external field (index "e"), considering magnetic iron without permanent magnets $\mathbf{B}_p = 0$, without iron $\mathbf{M}_e = 0$, too (Oberretl, 2008). The material property $\mu = \mu_0 \cdot \mu_r$ is the permeability in ferromagnetic materials, $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$ is the permittivity in dielectric materials and γ is the electrical conductivity. **P** is the electric polarisation, $\mathbf{J}_e$ are all possible external current sources. In most industrial applications magnetic material properties, primarily permeability, show non-linear characteristics, ref. Fig. 2. [$\mu_0 = 4\pi \cdot 10^{-7}$ Vs/Am = $1/(c^2 \cdot \varepsilon_0)$]

2.1.2 Extended Maxwell's equations considering moving bodies

The following four re-formulated Maxwell equations (1b) - (4b) can be used for all advanced calculations and computations in electrodynamics (with fields and waves), including constitutive relations [ref. to eq. (5)-(7)] and arbitrary movements of bodies (or particles) with **speed v**. The basis of these extensions is the relativity relation $\boxed{(\mathbf{v} \cdot \nabla)\, \mathbf{A} = d\mathbf{A}/dt - \partial \mathbf{A}/\partial t}$ (ref. to Einstein's Relativity Theory (Einstein, 1905), Helmholtz' theorems for moving objects (Cassing & Stanek, 2002; Stanek, 2010), and Sommerfeld's electrodynamics (Sommerfeld, 1988)), where **A** may be any vector, scalar or tensor. Furthermore these equations are the central basis for understanding interdisciplinary physics, especially structure identical formulations in i.e. hydrodynamics, diffusion, thermodynamics etc compared with directly derivable eddy current equations. Material properties of [μ], [ε] **and** [γ] in brackets shall be a reminder that they are often non-linear and additionally tensors.

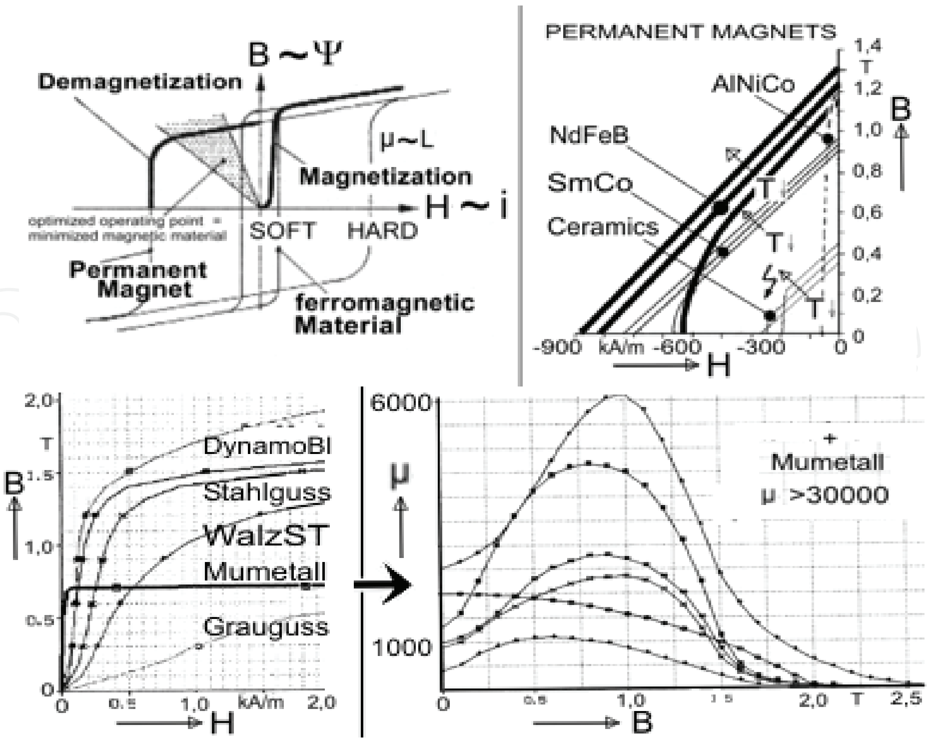

Fig. 2 Constitutive relations of permanent magnets + ferromagnetic materials (Cassing & Stanek, 2002; Stanek & Grueneberg, 2003)

1. extended Maxwell's equation **Ampere-Maxwell's Law**	$\nabla \times \mathbf{H}' = +\left(\frac{\partial}{\partial t} + (\mathbf{v} \cdot \nabla)\right) \cdot \mathbf{D} + \mathbf{J}$	(1b)
2. extended Maxwell's equation **Faraday-Lorentz' Law**	$\nabla \times \mathbf{E}' = -\left(\frac{\partial}{\partial t} + (\mathbf{v} \cdot \nabla)\right) \cdot \mathbf{B}$	(2b)
3. extended Maxwell's equation **electric Gauss' Law**	$\nabla \cdot \mathbf{D}' = \rho'$	(3b)
4. extended Maxwell's equation **magnetic Gauss' Law**	$\nabla \cdot \mathbf{B}' = 0'$	(4b)
→ **using B, H, D, E** etc *area* based vector analysis (8a)	$(\mathbf{v} \cdot \nabla) \cdot \mathbf{B} = -curl\ (\mathbf{v} \times \mathbf{B}) + \mathbf{v} \cdot div\ \mathbf{B} - \mathbf{B} \cdot div\ \mathbf{v} + (\mathbf{B} \cdot grad) \cdot \mathbf{v}$	(8a)
→ using **A** (with **B** = curl **A**) *line* based vector analysis (8b)	$(\mathbf{v} \cdot \nabla) \cdot \mathbf{A} = -\mathbf{v} \times curl\,\mathbf{A} + grad(\mathbf{v} \cdot \mathbf{A}) - (\mathbf{A} \cdot grad) \cdot \mathbf{v} - \mathbf{A} \times curl\,\mathbf{v}$	(8b)

Fig 3. Extended Maxwell's equations for moving bodies and basics in vector analysis (Cassing & Stanek, 2002; Stanek, 2010)

The transformation equations in *general* formulation are:

E' **=** E **+** v **x** B **+ ...** ***further terms*** H' **=** H **-** v **x** D **+ ...** ***further terms* -> refer to eq.** (8)

The additional field entities i.e. v x B and v x D - caused by moving bodies - are only 1 of 4 possible terms. The transformation equations in *simplified* formulation are therefore

$$\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B} \quad \text{(2c)} \qquad \text{and} \qquad \mathbf{H}' = \mathbf{H} - \mathbf{v} \times \mathbf{D} \quad \text{(1c)}$$

and well known as basic Lorentz' Transformation. Using only this special transformation the transformed current caused by moved body (i.e. conductor) is

$$\mathbf{J}' = \mathbf{J} - \mathbf{v}\,\rho. \quad \text{(1e)}$$

The following three examples shall deepen the background about influences of transformations:

1. EXAMPLE for evaluation with magnetic flux density terms. The derivation of Faraday-Lorentz' Law using equation (8a): Assuming special conditions/restrictions (in literature often not mentioned) i.e. incompressible materials div $\mathbf{v}$ = 0, space independent constant movements ($\mathbf{B}$ grad) $\mathbf{v}$ = 0 and in magnetic fields directly from magnetic Gauss' law always div $\mathbf{B}$ = 0 the remaining term on the right side in eq. (8a) yields rot ($\mathbf{B} \times \mathbf{v}$) = - rot ($\mathbf{v} \times \mathbf{B}$) = - curl ($\mathbf{v} \times \mathbf{B}$). Inserting this result in Faraday's Law we can simply derive the extended 2. Maxwell's equation for moving bodies:
differential Faraday - Lorentz' – Law

$$\text{curl } \mathbf{E}' = - \text{d}\,\mathbf{B} \,/\, \text{dt} = - \partial\,\mathbf{B} \,/\, \partial\,\text{t} + \text{curl } (\mathbf{v} \times \mathbf{B}) \quad \text{(2d)}$$

Using equation (8b) with the same conditions mentioned above, we get eq. (2d) with $\nabla \times \mathbf{A}$ = Nabla x $\mathbf{A}$ = curl $\mathbf{A}$ = $\mathbf{B}$. The first term on the right side of this equation (2d) was proved by Faraday, the second one by Lorentz. NOTE: using this vector analytical formulation we get the Lorentz-Term $\mathbf{E} = \mathbf{v} \times \mathbf{B}$ automatically! The famous Lorentz law is therefore a (very important) vector identity, but not really a separate physical law.

2. EXAMPLE for evaluation with electric flux density terms. The derivation of Ampere-Maxwell's Law using equation (8a): Assuming special conditions/restrictions as in the Example 1 (i.e. incompressible materials div $\mathbf{v}$ = 0, space independent constant movements ($\mathbf{D}$ grad) $\mathbf{v}$ = 0 and in electric fields directly from electric Gauss' law div $\mathbf{D} = \nabla \bullet \mathbf{D}$ the remaining term on the right side in eq. (8a) yields for the cross product rot ($\mathbf{D} \times \mathbf{v}$) = - rot ($\mathbf{v} \times \mathbf{D}$) = - curl ($\mathbf{v} \times \mathbf{D}$) and in opposite to the Faraday-Lorentz' Law in eq. (2d) for the Ampere-Maxwell's Law in equation (1d) an additional term. Considering simplified conditions like non-relativistic, linear and constant Movements yields eq. (3). But generally $\mathbf{v} \bullet \text{div } \mathbf{D}' = \mathbf{v} \bullet \rho'$ is valid, ref. to eq. (3b) (Sommerfeld, 1988; Stanek, 2010).
Inserting these results in Ampere-Maxwell's Law eq. (1a) we can derive the extended eq. (1b). Maxwell's equation for moved bodies or particles with the following expressions:

$$\text{curl } \mathbf{H}' = \mathbf{J} + \text{d}\,\mathbf{D} \,/\, \text{dt} = \mathbf{J} + \partial\,\mathbf{D} \,/\, \partial\,\text{t} + \mathbf{v} \bullet \rho - \text{curl } (\mathbf{v} \times \mathbf{D}) \quad \text{(1d)}$$

The first term on the right side of this equation (1d) was proved by Ampere, the third term by Rowland, the second term by Hertz (suggested and introduced by Maxwell), and the fourth term by Roentgen. NOTE: using this vector analytical formulation we get the "dualism" of the Lorentz-Term $\mathbf{H} = - \mathbf{v} \times \mathbf{D}$ automatically! The Rowland and Roentgen terms are therefore (important) vector identities, but not really separate physical laws.

3. EXAMPLE for proof of extended eq. (1b) and eq. (2b) Maxwell's equations using the famous HELMHOLTZ' formula. Helmholtz derived for any arbitrary vector flux $\mathbf{X}$ in physics (i.e. hydrodynamics) through a moved ($\mathbf{v}$) and simultaneously deformable area element in his curl laws - as a subset of (8a) –which yields the following formula:

$$d\mathbf{X} / dt = \partial \mathbf{X} / \partial t + \text{curl}\,(\mathbf{X} \times \mathbf{v}) + \mathbf{v}\,\text{div}\,\mathbf{X} \quad (*)$$

Inserting this Helmholtz' formula (*) in the Maxwell equations (1a) and (2a) – with the prerequisite of the same above mentioned conditions and **X** = **B** alternatively **X** = **D** - we immediately get the extended Maxwell's equations (1b) and (2b) in the 1. and 2. example! NOTE: using (*) the extended Maxwell's equations are derivable without any knowledge in vector analysis. The Helmholtz' formula is ingenious and the basis for Lorentz, Minkowski and Einstein, too. Helmholtz derived his formula visualising - like a "mnemonics artist" - moved and deformable geometric elements. Nevertheless Helmholtz' formula $d\mathbf{X} / dt$ neglects the LAST term, here $(\mathbf{X}\,\nabla)\,\mathbf{v}$ inside $(\mathbf{v}\,\nabla)\,\mathbf{X}$ (i.e. additional rotations), refer to (8a) and (8b) !

2.1.3 Extended Maxwell's equations in 4-dimensional formulation

Another compact expression of Maxwell's equations (i.e. in vacuum without materials and no movable bodies) can be derived, using 4-dimensional expressions (Sommerfeld, 1988; Cassing & Stanek, 2002):

1. space-time operator $\Box\,(x, y, z, i \cdot c \cdot t)$ with d'Alembert $\Box \equiv \Delta - 1/c^2 \cdot \partial^2/\partial t^2 = \sum_{i=1}^{4} \partial^2/\partial x_i^2$
2. **A**-φ-Potential $\boldsymbol{\Omega}\,(A_x, A_y, A_z, i \cdot \varphi / c)$ with $c = 1/\sqrt{(\varepsilon_0 \cdot \mu_0)}$, $i = \sqrt{(-1)}$ and
3. current densities $\Gamma\,(J_x, J_y, J_z, i \cdot \rho \cdot c)$ respectively $\mathbf{J}' = \mathbf{v} \cdot \rho$ with condensed results:

$$\text{a)}\ \Box\,\boldsymbol{\Omega} = -\mu_0 \cdot \Gamma\,, \quad \text{b)}\ \nabla \cdot \boldsymbol{\Omega} = 0\,, \quad \text{c)}\ \nabla \cdot \Gamma = 0\,, \quad \text{d)}\ \mathbf{F} = \mu_0 \cdot \mathbf{G} = \nabla \times \boldsymbol{\Omega} \tag{9}$$

where **F** $(\mathbf{B}, -i \cdot \mathbf{E}/c)$ and **G** $(\mathbf{H}, -i \cdot c\mathbf{D})$ define the electromagnetic Maxwell field tensors.

2.1.4 Extended Maxwell's equations in quantum electrodynamics

Quantum electrodynamics is a complex interdisciplinary field, but is not normally used daily by practical mechatronics engineers. On the other side many phenomena (duality of wave and particle, tunnel diode, special superconductivity up to quantum computers etc) are important and must be handled with a background of this superior theory based on the integration of electrodynamics, quantum mechanics and (for relativistic processes) relativity theory (Cassing & Stanek, 2002). As a compromise only the resulting extended Maxwell equations in quantum electrodynamics will be shown in (1f) - (4f).

$$\nabla \times \mathbf{H} = \mathbf{J} + \dot{\mathbf{D}} - \kappa^2 \cdot \mathbf{A} / \mu_0 \tag{1f}$$

$$\nabla \times \mathbf{E} = -\dot{\mathbf{B}} \tag{2f}$$

$$\nabla \cdot \mathbf{D} = \rho - \kappa^2 \cdot \varphi \cdot \varepsilon_0 \tag{3f}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{4f}$$

These extended Maxwell's equations, which are called Proca's equations, additionally describe special phenomena in quantum electrodynamics (Lehner, 1994; Cassing&Stanek, 2002). These further quantum terms consist of classical magnetic vector potential **A**, electrical scalar potential φ, the special term $\kappa^2 = (m_0 \cdot c / \hbar)^2$ and material properties in vacuum (namely permeability μ_0 and permittivity ε_0).

The term κ^2 is famous in quantum mechanics, because κ is Compton's frequency divided by the speed of light c or Einstein's energy in view of quantum mechanics. The mass in rest is 0, the universal Planck's constant in quantum mechanics is $\hbar$ (= h / 2π ≈ $1 \cdot 10^{-34}$ J s).

2.2. Interdisciplinary evaluation of Maxwell's equations

From Maxwell's equations we can directly derive all central relations for electromagnetic waves and fields, eddy current equations, structure identities inside electrodynamics and with other physical disciplines as well. Ref. to all possible derivations in chap. 2.2.4.

2.2.1 Electromagnetic field and wave equations

Electrodynamics as one compact equation including polarisations and movable bodies is given by:

$$curl\frac{1}{\mu}curl\mathbf{A} = \mathbf{J}_e + curl\frac{1}{\mu}\mathbf{M}_p + \frac{\partial \mathbf{P}}{\partial t} + \mathbf{v}\cdot\rho + \left(\gamma + \varepsilon\frac{\partial}{\partial t}\right)\cdot\left[-grad\varphi - \frac{\partial \mathbf{A}}{\partial t} + \mathbf{v}\times curl\mathbf{A}\right] \qquad (10)$$

Choice of gauges in electrodynamics is important for evaluation of fields and waves, because potentials **A** and φ are not unique (Ψ scalar magnetic potential), eq.(10).

$$\mathbf{A} = \mathbf{A}^* - \nabla\psi \;, \quad \varphi = \varphi^* + \partial\psi / \partial t \qquad (10a+b)$$

$$\Delta\mathbf{A} - \mu\varepsilon\frac{\partial^2\mathbf{A}}{\partial t^2} - \mu\gamma\frac{\partial \mathbf{A}}{\partial t} = \nabla\cdot\left[\nabla\mathbf{A} + \mu\varepsilon\frac{\partial\varphi}{\partial t} + \mu\gamma\varphi\right] \qquad (11)$$

The most used gauges are the complete Lorentz gauge […]=0, eq. (11) and reduced Lorentz gauge $\nabla\mathbf{A} = -\mu\varepsilon\cdot\partial\varphi/\partial t$ for waves, and Coulomb gauge $\nabla\mathbf{A}=0$ for eddy current and static applications. Wave equations from eq. (11) using eq. (3) and polarisations:

$$\Delta\mathbf{A} - \frac{1}{c^2}\frac{\partial^2\mathbf{A}}{\partial t^2} = -\mu_0\left(\mathbf{J} + \nabla\times\mathbf{M_p} + \frac{\partial \mathbf{P}}{\partial t}\right) \qquad (12a)$$

$$\Delta\phi_S - \frac{1}{c^2}\frac{\partial^2\varphi_S}{\partial t^2} = -\frac{1}{\varepsilon_0}\left(\rho - \nabla\cdot\mathbf{P}\right) \qquad (12b)$$

Wave equations derived from concentrated field elements in electric circuits with resistance R, conductance G, capacitance C, inductance L (mutual inductance M) yield the same result for voltage V and current I, instead of **A** or φ, as shown in eq.(11) respectively eq.(12a,b).

2.2.2 Eddy current equation in electrodynamics

With (ε ∂/∂t) = 0, eq.(10) leads to interdisciplinary usage of eddy current equation(13).

$$curl\;\frac{1}{\mu}curl\;\;\mathbf{A} = \mathbf{J} - \gamma\cdot grad\;\;\varphi + curl\;\;\frac{1}{\mu}\mathbf{M}_p - \gamma\cdot\frac{\partial\mathbf{A}}{\partial t} + \gamma\cdot\mathbf{v}\times curl\;\;\mathbf{A} \qquad (13)$$

The current density J includes all further electrical excitations shown in eq. (10).

2.2.3 Static equations inside electrodynamics with identical structure

From Maxwell's equations we get formulations with identical structure for magnetic fields in magnetostatics, electric fields in electrostatics and electric current flow. In Fig. 4 six identical fields are sketched for different areas inside electrodynamics. The field map for only electrostatics automatically yields the results for the other shown disciplines, refer to eq.(19a, 20a). The field maps were evaluated for the centre of the applications shown, while neglecting the leakage fluxes i.e. of capacitor and current sheets.
"Trial and Error" field mapping proved by field numerical computations with FEM program MagnetoCAD is shown in Fig.4. Field mapping rules in Fig. 4a considered field lines and equipotential lines as perpendicular, equidistantly arranged and sketched by means of curvilinear squares.

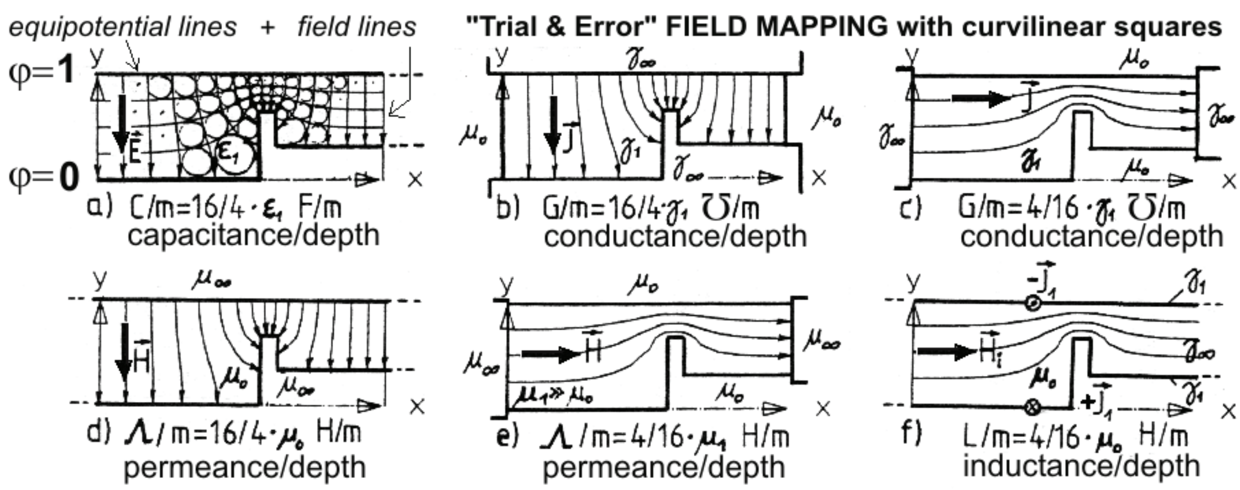

Fig. 4. Application of one field map to six interdisciplinary cases inside electrodynamics (Stanek, 2002)

2.2.4 All possible Mind Map derivations from variations of "Maxwell's Hand"

All central derivations from Maxwell's equations with respect to all important phenomena inside electrodynamics are developed by the author and visualised as a new Mind Map with 10 memorable Memo Maps. These maps are based on variations of Maxwell's "Right Hand Rule" and Brain Power Rules (Stanek et al, 2006). Starting from differential equations we can formulate all central equations governing electrodynamics and interdisciplinary physics. These Memo Maps are valuable mnemonics for necessary derivations, useful backgrounds and compact results. Memorising these pictures is easy for us to bear all derivations in mind concerning the variety of extended Maxwell's equations.
The Mind Map can be found on a special web site prepared by the author (Stanek, 2010) as given in Fig. 5. Most of all these formulas and equations can be derived using the powerful unit check method shown in the next chapter 2.2.5.

Fig. 5. Mind Map for central derivations from Maxwell's equations (Stanek, 2010)

2.2.5 The mighty method in physics: Deriving equations by unit checks

Following questions (Q1 … Q20) and answers (A x.y) will demonstrate and train this useful method using both sides of our brain to understand, to derive, to learn and to recall most of the important formulas in physics without any effort.

***Q1)** What will happen with an electric Charge Q placed in an electric field **E**?*
The scalar Q in As and vector **E** in V/m build the product Q · **E** . (A1.1)
Equivalent unit equation: As · V/m = Ws/m = Nm/m = N = Newton → Force $\mathbf{F}_{el}$ (A1.2)
The result is Coulomb's law, an electric force $\mathbf{F}_{el} = Q \cdot \mathbf{E}$ (A1.3)

***Q2)** What is equivalent to a space-depending electric potential φ defined by gradient "grad"?*
This term can be written as a product of Nabla operator and electric potential $\nabla\varphi$ (A2.1)
Equivalent unit equation: 1/m · V = V/m electric field strength **E** (A2.2)
Regarding signs for "grad" in mathematics and **E** in physics the result is: $\mathbf{E} = -\,\mathrm{grad}\,\varphi$ (A2.3)

***Q3)** What will happen in a magnetic field **B** moving a particle / body with a uniform speed **v**?*
Both vectors **v** in m/s and **B** in Vs/m² build a cross product $\mathbf{v} \times \mathbf{B}$. (A3.1)
Equivalent unit equation: m/s x Vs/m² = V/m → electric field strength **E** (A3.2)
The result is the additionally induced *electric* Lorentz' field strength $\mathbf{E}_L = \mathbf{v} \times \mathbf{B}$ (A3.3)

***Q4)** What will happen in an electric field **D** moving a particle / body with a uniform speed **v**?*
Both vectors **v** in m/s and **D** in As/m² build a cross product **v** x **D** → (ref. to Q18 !) (A4.1)
Equivalent unit equation: m/s x As/m² = A/m → magnetic field strength **H** (A4.2)
The result is the additional *magnetic* Lorentz' field strength $\mathbf{H} = \mathbf{v} \times \mathbf{D} = -\,\mathbf{D} \times \mathbf{v}$ (A4.3)
Applying "∇" operator on **H** the result is Roentgen's current $\mathbf{J}_{Roe} = \nabla \times (\mathbf{D} \times \mathbf{v}) = \mathrm{curl}\,(\mathbf{D} \times \mathbf{v})$ (A4.4)

***Q5)** What is equivalent to an electric charge density ρ moved with the speed **v**?*
The scalar ρ in As/m³ and vector **v** in m/s build the product $\rho \cdot \mathbf{v}$. (A5.1)
Equivalent unit equation: As/m³ · m/s = A/m² additional electric current density $\mathbf{J}_{Row}$ (A5.2)
The result is Rowland's current density $\mathbf{J}_{Row} = \rho \cdot \mathbf{v}$. (A5.3)

***Q6)** How much is the force on a current carrying conductor or moved ρ in a magnetic field **B**?*
The physical entities ρ, **v** and **B** build the cross product $\rho \cdot \mathbf{v} \times \mathbf{B}$. (A6.1)
Equivalent unit equation: As/m³ · m/s x Vs/m² = Ws/m⁴ = Nm/m⁴ = N/m³ → force density **f** (A6.2)
The result is Lorentz' force density caused by electric currents $\mathbf{f}_L = \mathbf{J} \times \mathbf{B}$ (A6.3)

***Q7)** What will happen when a magnetic flux density **B** is time-changing through a loop?*
The action $\partial\mathbf{B} / \partial t$ causes a reaction in a loop which must be a negatively signed vector, too. (A7.1)
Equivalent unit equation: 1/s · Vs/m² = 1/m · V/m → ∇ applied on electric field strength **E** (A7.2)
The result is Faraday's law or Maxwell's second (field) equation $-\,\partial\mathbf{B} / \partial t = \nabla \times \mathbf{E} = \mathrm{curl}\,\mathbf{E}$ (A7.3)

***Q8)** Which physical entity will be produced by an electric current density **J**?*
All currents will produce a magnetic field strength **H** easily derived by following unit check:
Equivalent unit equation: A/m² = 1/m · A/m → ∇ applied on magnetic field strength **H** (A8.1)
The result is basic Ampère's law or Maxwell's first (field) equation $\mathbf{J} = \nabla \times \mathbf{H} = \mathrm{curl}\,\mathbf{H}$ (A8.2)

***Q9)** Which source divergence "div" of a physical entity produces electric charge density ρ?*
This relation can be written as a product of Nabla operator and electric potential $\nabla \cdot$ "?" $= \rho$ (A9.1)
Equivalent unit equation: 1/m · '?' = As/m³ or '?' = As/m² electric flux density **D** (A9.2)
The result is electric Gauss' law or Maxwell's third (source) equation $\nabla \cdot \mathbf{D} = \mathrm{div}\,\mathbf{D} = \rho$ (A9.3)

***Q10)** Which magnetic source divergence "div" of a physical entity is always zero?*
This relation can be written as a product of Nabla operator and electric potential $\nabla \cdot$ "?" $= 0$ (A10.1)
Equivalent unit equation: 1/m · '?' = Vs/m³ (fictive monopole) → magnetic flux density **B** (A10.2)
The result is magnetic Gauss' law or Maxwell's fourth (source) equation $\nabla \cdot \mathbf{B} = \mathrm{div}\,\mathbf{B} = 0$ (A10.3)

Q11) Which time-changing physical entity* X *will produce a current density* J *in air (vacuum)?

This relation can be written as $\partial \mathbf{X} / \partial t = \mathbf{J}$, where **X** is the searched unknown. (A11.1)

Equivalent unit equation: $1/s \cdot$ '?' $= A/m^2$ or '?' $= As/m^2$ → electric flux density **D** (A11.2)

The result is Maxwell's displacement current $\mathbf{J}_D = \partial \mathbf{X} / \partial t$ (= 2nd part of 1. Maxwell's equation) (A11.3)

***Q12) What is equivalent to the source "div" of a moved charge density* ρ *with the speed* v?**

Applying Helmholtz' law div (curl **H**) = 0 on eq. (A8.2) with (A11.2) or from $\nabla \cdot (\rho \cdot \mathbf{v}) =$ "?" (A12.1)

Equivalent unit equation: $1/m \cdot (As/m^3 \cdot m/s) = A/m^2 = 1/s \cdot As/m^3$ → $\partial / \partial t \cdot$ charge density ρ (A12.2)

The result is Maxwell's continuity law in electrodynamics $\nabla \cdot (\rho \cdot \mathbf{v}) = \nabla \cdot \mathbf{J} = -\partial \rho / \partial t$ (A12.3)

***Q13) What is equivalent to the source "div" of a moved mass density* ρ_M *with the speed* v?**

From $\nabla \cdot (\rho_M \cdot \mathbf{v}) =$ "?" unit equation: $1/m \cdot (kg/m^3 \cdot m/s) = 1/s \cdot kg/m^3$ → $\partial / \partial t \cdot$ mass density ρ_M (A13.1)

The result is Newton's continuity law in mechanics $\nabla \cdot (\rho_M \cdot \mathbf{v}) = \nabla \cdot \mathbf{J} = -\partial \rho_M / \partial t$ (A13.2)

Q14) What is equivalent to the mechanical (im)pulse density* $\mathbf{p}_M = \rho_M \cdot \mathbf{v}$ *in electrodynamics?

Equivalent unit equation: $kg/m^3 \cdot m/s = kg \cdot m/s^2 \cdot s/m^3 = Ns/m^3 = Ws/m^3 \cdot s/m = As/m3 \cdot Vs/m$ (A14.1)

The unit Vs/m defines the magnetic vector potential **A** with its subset $\mathbf{B} = \text{curl}\, \mathbf{A} = \nabla \times \mathbf{A}$. (A14.2)

Moving like Maxwell's hand for $\mathbf{J} = \text{curl}\, \mathbf{H}$ we see that 2-D fields can be calculated by 1-D ! (A14.3)

The result is the equivalence of $\mathbf{p}_M = \rho_M \cdot \mathbf{v}$ in mechanics and $\mathbf{p}_{EM} = \rho \cdot \mathbf{A}$ in electrodynamics (A14.4)

***Q15) What is the relation between (im)pulse density* $\mathbf{p}_M$ *or* $\mathbf{p}_{EM}$ *and force density* f?**

Equivalent unit equation from (A14.1): $Ns/m^3 \cdot$ '?' $= N/m^3$ or '?' $= 1 / s$ → time operator d/dt (A15.1)

a) The result in mechanics is Newton's force law $\mathbf{f}_M = d(\rho_M \cdot \mathbf{v}) / dt = \mathbf{v} \cdot \partial \rho_M / \partial t + \rho_M \cdot \partial \mathbf{v} / \partial t$ (A15.2)

b1) Result in electrodynamics is Lorentz' force law $-\mathbf{f}_{EM} = d(\rho \cdot \mathbf{A}) / dt = \mathbf{A} \cdot \partial\rho / \partial t + \rho \cdot \partial \mathbf{A} / \partial t$ (A15.3)

With re-formulated unit equation for last term: $Vs/m \cdot As/m^3 / s = As/m^3 \cdot 1/m \cdot V$ → $\rho \cdot \nabla\varphi$ (A15.4)

b2) Result in electrodynamics is Lorentz' force law $\mathbf{f}_{EM} = d(\rho \cdot \mathbf{A}) / dt = -\rho \cdot \nabla\varphi - \rho \cdot \partial \mathbf{A} / \partial t$ (A15.5)

***Q16) What is the relation between interdisciplinary force* F *and (potential) energy* W?**

From N = '?' $\cdot$ Nm or '?' = 1 / m → space operator ∇, with **P** = pulse, W = energy, follows: (A16.1)

d'Alembert's force $\mathbf{F} = -\nabla W = -dW / d\mathbf{r} = -dW / dt \cdot dt / d\mathbf{r} = d\mathbf{P} / dt$ → $d(\mathbf{P} \cdot \mathbf{v} + W_{pot}) / dt = 0$ (A16.2)

Integration yields the non-relativistic energy law in classic physics: $W_{total} = W_{kin} + W_{pot} = \text{const}$ (A16.3)

***Q17)** a) What is the relation between energy W of an electromagnetic wave and frequency* ν

Equivalent unit equation: Ws = '?' $\cdot$ 1/s or '?' = Ws $\cdot$ s → Planck's constant h (or $\hbar$) (A17.1)

Result is Planck's energy relation: $W = h \cdot \nu$ or $W = \hbar \cdot \omega$ or complex → $\underline{W} = \mathbf{i} \cdot \hbar \cdot \partial / \partial t$ (A17.2)

b) What is the relation between pulse **P** of an electromagnetic wave and its wave length $\boldsymbol{\lambda}$?

Equivalent unit equation: Ns = Nm s $\cdot$ 1/m = Ws $\cdot$ s $\cdot$ 1/m with wave vector **k** yields both the (A17.3)

→ de Broglie's pulse: $\mathbf{P} = h / \boldsymbol{\lambda}$ or $\mathbf{P} = \hbar \cdot \mathbf{k}$ or complex with $\mathbf{i} = \sqrt{(-1)}$ → $\underline{\mathbf{P}} = -\mathbf{i} \cdot \hbar \cdot \nabla$ (A17.4)

→ de Broglie's wave equation: $\Psi(\mathbf{r}, t) = \Psi_0 \cdot \exp[\, \mathbf{i} \cdot (\omega \cdot t - \mathbf{k} \cdot \mathbf{r}) \,] = \Psi_0 \cdot \exp[\, \mathbf{i} / \hbar \cdot (W \cdot t - \mathbf{P} \cdot \mathbf{k}) \,]$ (A17.5)

c) Can we derive the relation for the uncertainty principle in quantum mechanics where neither energy W & time t nor pulse **P** & place **r** can be exactly determined at the same time?	
From (A17.2) & (A17.4) we get Planck's constant $h = W / \nu = \mathbf{P} \cdot \boldsymbol{\lambda}$, where $\nu \sim 1/t$ & $\boldsymbol{\lambda} \sim \mathbf{r}$.	(A17.6)
and directly in "small Δ - view" → Heisenberg's uncertainty relation $h \approx \Delta\mathbf{P} \cdot \Delta\mathbf{r} \approx \Delta W \cdot \Delta t$	(A17.7)
d) Inserting (A17.2) & (A17.4) in (A16.3) with mass M and kinetic energy $W_{kin} = M \cdot \mathbf{v}^2 / 2$	(A17.8)
→ non-relativistic Schrödinger's equation: $\hbar^2 / (2 \cdot M) + W_{pot} = \mathbf{i} \cdot \hbar \cdot \partial / \partial t$ [applied on $\Psi(r, t)$]	(A17.9)
Q18) *How can we easily derive a formula for arbitrarily formed current loops?*	
Considering the electric Gauss' law we quickly derive $d\mathbf{D} = dQ / (4\pi r^2) \cdot \mathbf{e}_r$, producing a	(A18.1)
magnetic field $d\mathbf{H}$ by moved charges $\mathbf{v} \cdot dQ$ in units: m/s · As = A · m → $\mathbf{v}_{dl} \cdot dQ = I \cdot \mathbf{dl}$	(A18.2)
With unit equation: m/s · As/m² = A/m the transformation from $d\mathbf{D}$ to $d\mathbf{H}$ is $\mathbf{v}_{dl} \times d\mathbf{D}$ (= A4.3)	(A18.3)
The result is Biot-Savart's law: $d\mathbf{H} = \mathbf{v}_{dl} \times d\mathbf{D} = \mathbf{v}_{dl} \cdot dQ / (4\pi \mathbf{r}^2) \times \mathbf{e}_r = I / 4\pi \cdot (\mathbf{dl} \times \mathbf{e}_r) / \mathbf{r}^2$	(A18.4)
Q19) *What is the difference between total derivative "d / dt" and partial derivative "∂ / ∂t" ?*	
i.e. $d\,\mathbf{B}(t, r) / dt = \partial\mathbf{B} / \partial t + \partial\mathbf{B} / \partial\mathbf{r} \cdot \partial\mathbf{r} / \partial t = \partial\mathbf{B} / \partial t + \partial\mathbf{B} / \partial\mathbf{r} \cdot \mathbf{v} = \partial\mathbf{B} / \partial t + (\mathbf{v}\,\nabla)\,\mathbf{B}$	(A19.1)
Basis for viewing point of moved systems → Einstein's special relativity theory (ref. Q20)	(A19.2)
Vector gradient $(\mathbf{v}\,\nabla)\,\mathbf{B} = d\,\mathbf{B} / dt - \partial\mathbf{B} / \partial t$ implies additional fields in Lorentz' transformation	(A19.3)
Applying unit checks i.e. $\mathbf{B} = f$ (temperature T) yields → additional fields $\partial\mathbf{B} / \partial T \cdot \partial T / \partial t$ etc	(A19.4)
Most simple transformation from i.e. Faraday's law: $-\,d\,\mathbf{B}\,(\mathbf{v}) / dt = \text{curl}\,\mathbf{E}' = \text{curl}\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$	(A19.5)
Q20) *Which unit re-design leads from classic physics to Einstein's etc most famous formulas?*	
Newton's force law in mechanics $\mathbf{f}_M = d(\rho_M \cdot \mathbf{v}) / dt$ (ref. Q15a) → $\mathbf{F}_M = d(M \cdot \mathbf{v}) / dt$ (M is mass)	(A20.1)
Equivalent unit equation: 1/s · kg · m/s = kg·m/s² = N = Nm / m = Ws / m → Ws = kg · m²/s²	(A20.2)
The result is Einstein's equation: $\underline{E = M \cdot c^2}$ equivalence of energy E and mass M, where	(A20.3)
the velocity unit m²/s² means the square of the speed of light $c = 1 / \sqrt{(\mu_0 \cdot \varepsilon_0)} = \text{const.}$	(A20.4)
Viewing (ζ) moved body (Δt', v), time in rest Δt → Pythagoras yields: $\underline{(c \cdot \Delta t')^2 = (v \cdot \Delta t')^2 + (c \cdot \Delta t)^2}$	(A20.5)
or Einstein's time dilatation: $\Delta t' = \Delta t / \sqrt{[1 - (v/c)^2]}$. Extending (A20.5) by unit checks to the	(A20.6)
relativistic energy equation: $E^2 = W_{tot}^2 = W_{kin}^2 + W_{pot}^2$, with pulse $\mathbf{P} = M \cdot \mathbf{v}$ & mass in rest M_0	(A20.7)
$(M \cdot c^2)^2 = (P \cdot c)^2 + (M_0 \cdot c^2)^2$ or Lorentz-Einstein's mass equation: $M = M_0 / \sqrt{[1 - (v/c)^2]}$	(A20.8)
Complex notation of (A20.8) using (A17.2) & (A17.4) leads to Klein-Gordon's equation or	
→ relativistic Schrödinger's equation: $\square = \nabla^2 - 1/c^2 \cdot \partial^2/\partial t^2 = (M_0 \cdot c / \hbar)^2$ ("space-time operator")	(A20.9)

2.2.6 Electrodynamics compared with other physical disciplines

Central physical disciplines are compared with electrodynamics, neglecting Maxwell's $d\mathbf{D}/dt$ – term in eq. (14) - (16), (18a), (19a), (20a) and considering it in eq. (17) - (20).

Analogous expressions can be derived for diffusion equation in chemistry, Newton's mechanics, optics and acoustics etc. In eq. (14) the curl M_p-term is re-formulated as grad M_i - Σ term of M_p-components in i = x, y. Eq. (15) is also central for applications in aerodynamics. All these field equations (14) - (16) in Cartesian 2-dimensional coordinates will show identical structure, refer to Fig. 7. The central equation in non-linear elastodynamics is given by eq. (17), where μ_m and λ_m are Lamé characteristics for material elasticity, σ for non-linear tensions, u for mechanical displacement and f for external forces. Assuming linearity (divσ=0) and incompressible media (div u=0), elastodynamics is based on *wave equations* (18) - (20) with identical structure.

Electrodynamics Maxwell etc	$curl\,(1/\mu)\,curl\,\mathbf{A}$	$=\mathbf{J}-grad\,[\gamma\cdot\varphi\pm(1/\mu_i)\cdot M_i]$	$-\gamma\cdot\frac{\partial\mathbf{A}}{\partial t}+$	$\gamma\cdot\mathbf{v}\times curl\,\mathbf{A}$	(14)
Hydrodynamics Navier-Stokes etc	$curl\,\eta\,curl\,\mathbf{v}$	$=\mathbf{f}-grad\,[p+\rho_m\cdot\mathbf{v}^2/2]$	$-\rho_m\cdot\frac{\partial\mathbf{v}}{\partial t}+$	$\rho_m\cdot\mathbf{v}\times curl\,\mathbf{v}$	(15)
Thermodynamics Fourier-Helmholtz	$div\,\lambda\,grad\,T$	$=Q-grad\,q_s$	$-c_p\rho_m\cdot\frac{\partial T}{\partial t}+$	$c_p\rho_m\cdot\mathbf{v}\cdot grad\,T$	(16)
Elastodynamics Newton-Euler,	$\mu_m\cdot\Delta\mathbf{u}-\rho_m\cdot\partial^2\mathbf{u}/\partial t^2=-\mathbf{f}-(\mu_m+\lambda_m)\cdot grad\,div\,\mathbf{u}-div\,\boldsymbol{\sigma}$				(17)
Lagrange etc	$\Delta\mathbf{u}-(\rho_m/\mu_m)\cdot\partial^2\mathbf{u}/\partial t^2=-1/\mu_m\cdot\mathbf{f}$	(18)	Elastostatics	$\Delta\mathbf{u}=-1/\mu_m\cdot\mathbf{f}$	(18a)
Electrodynamics Maxwell, Ampere, Faraday,Gauss etc	$\Delta\mathbf{A}-(1/c^2)\cdot\partial^2\mathbf{A}/\partial t^2=-\ \mu_0\cdot\mathbf{J}$	(19)	Magnetostatics	$\Delta\mathbf{A}=-\ \mu_0\cdot\mathbf{J}$	(19a)
	$\Delta\varphi-(1/c^2)\cdot\partial^2\varphi/\partial t^2=-1/\varepsilon_0\cdot\rho$	(20)	Electrostatics	$\Delta\varphi=-1/\varepsilon_0\cdot\rho$	(20a)

Fig. 6. Interdisciplinary vector analytical structure identities in physics (Cassing & Stanek, 2002; Bronstein, 1995)

2.2.7 Electrodynamics directly integrated with other physical disciplines

Magnetohydrodynamics: Hydrodynamics + Electrodynamics + Thermodynamics

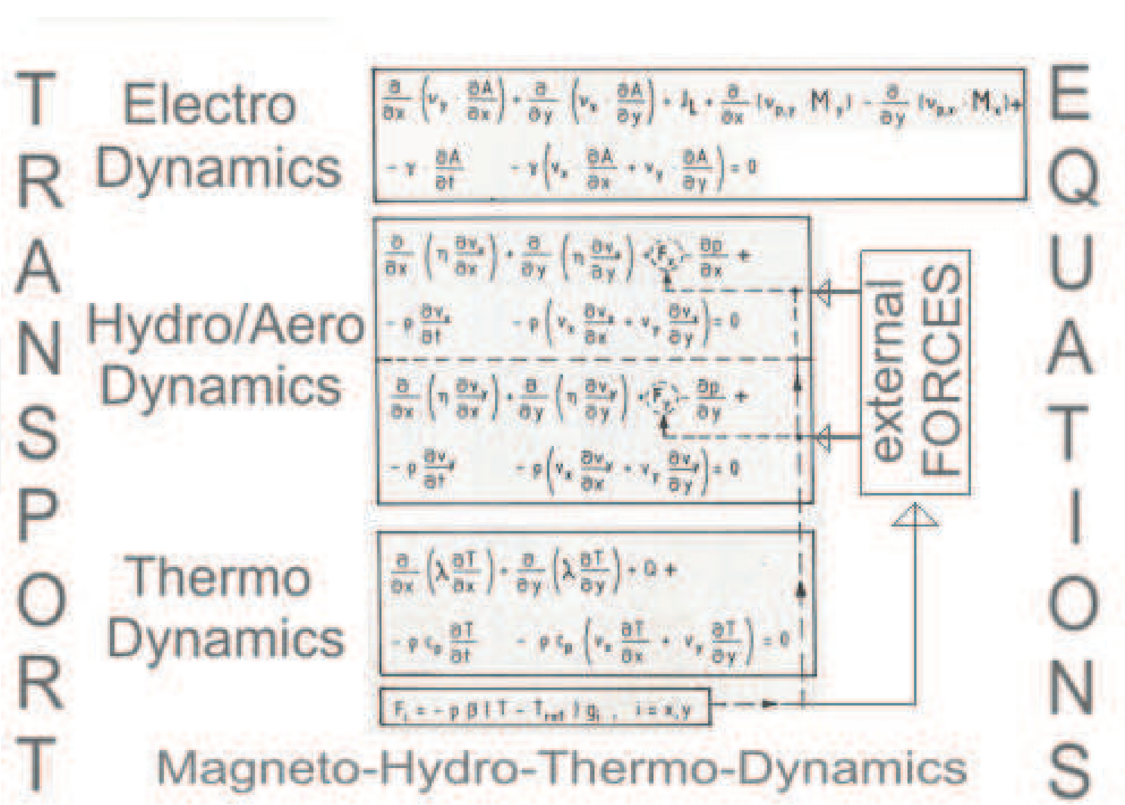

Fig. 7. Interdisciplinary structure identities of different and hybrid physical disciplines (Stanek, 2002).

Ferrohydrodynamic Bernoulli-Rosensweig equation based on magnetic fluids

The Bernoulli equation can be deduced from Navier-Stokes equations and extended with a magnetic polarisation $\mathbf{M}_p$ to handle i.e. industrial separation of diamonds:

$$p + \rho_m \cdot \mathbf{v}^2 / 2 + \rho_m \cdot g \cdot h + \rho_m \cdot \int (\partial \mathbf{v} / \partial t)\, d\mathbf{l} - \int \mathbf{M}_p \cdot d\mathbf{H} = const \tag{21}$$

Eq. (21) describes i.e. lifting of "stones" in magnetic fluids by magnetic fields (Stanek, 2002).

Magnetostriction and Electrostriction: Elastomechanics + Electrodynamics + Entropy

The deformation force densities $\mathbf{f}_{MS}$ (or $\mathbf{f}_{ES}$) of ferromagnetic (or dielectric) materials with density $\tau=1/\nu$ caused by magnetic (or electric) fields **H** (or **E**) can be derived by means of entropy. The converse effect applying mechanical pressure p to certain non-conducting crystals producing electric charges is piezoelectricity. All effects may depend on temperature T, too. In Fig. 8 interdisciplinary derivations are shown.

<table>
<tr><td colspan="4">Maxwell → Poynting E x H → energy thermodynamics → "unavailable for work" entropy dS = dQ/T
Internal system energy dW_i = f [specific volume ν(p), T, H (or E)] = transported heat dQ + total work dW_w</td><td>(22)
(23)</td></tr>
<tr><td>entropy dS_{MS} with $dW_i=f(\nu,H,T)$ for magnetostriction</td><td colspan="3">$dW_{w,MS} + p \cdot dV = H \cdot d(\mu \cdot H) = \mu \cdot H\, dH + H^2 \cdot [(\partial \mu / \partial \nu)\, d\nu + (\partial \mu / \partial T)\, dT]$
$dS_{MS} = dQ/T = \frac{1}{T}(\frac{\partial W_i}{\partial \nu} + \frac{p}{\nu} - H^2 \frac{\partial \mu}{\partial \nu})\, d\nu + \frac{1}{T}(\frac{\partial W_i}{\partial H} - \mu \cdot H)\, dH + \frac{1}{T}(\frac{\partial W_i}{\partial T} - H^2 \frac{\partial \mu}{\partial T})\, dT..$
from eq. (22) - (25) → force density $\mathbf{f}_{MS}$ = - grad p(ν,H,T), neglecting T : eq. (26) - (27)</td><td>(24)
(25)</td></tr>
<tr><td>Magnetostriction force density</td><td>$\mathbf{f}_{MS} = \frac{1}{2} grad\left(H^2 \cdot \tau \cdot \frac{\partial \mu}{\partial \tau}\right)$</td><td>(26)</td><td>Electrostriction force density $\mathbf{f}_{ES} = \frac{1}{2} grad\left(E^2 \cdot \tau \cdot \frac{\partial \varepsilon}{\partial \tau}\right)$</td><td>(27)</td></tr>
</table>

Fig 8. Interdisciplinary entropy equations for magnetostriction + electrostriction (Simonyi, 1993; Stanek, 2002).

3. Interdisciplinary industrial applications in mechatronics

Four developments in the huge field of motor car production, magnetic gripper design in robotics, motor car anti-vibration systems and computer hard disk drives will demonstrate actual industrial applications in mechatronics based on electrodynamics.

3.1 Motor car production based on electrodynamics

In Fig. 9 we see a graphical overview of the actual topics of this publication concerning motor car production and influences. The field numerical optimisation of the actual holding and stacking system in world wide motor car production is the special focus in chapter 3.1.

The principle of mechanical motor car production is shown in **Fig. 9a.**

This computer-aided development was a combination of designing the necessary electrodynamic actuator (in **Fig. 9b**) and optimising both the aerodynamic flight of metal plates and the elastodynamics respectively plastic stacking in the stopping equipments.

This holding and stacking system, based on an international patent by Thyssen in Dortmund (inventors W. Stanek et al), has been used world wide in motor car plants for years (Stanek et al., 1984)

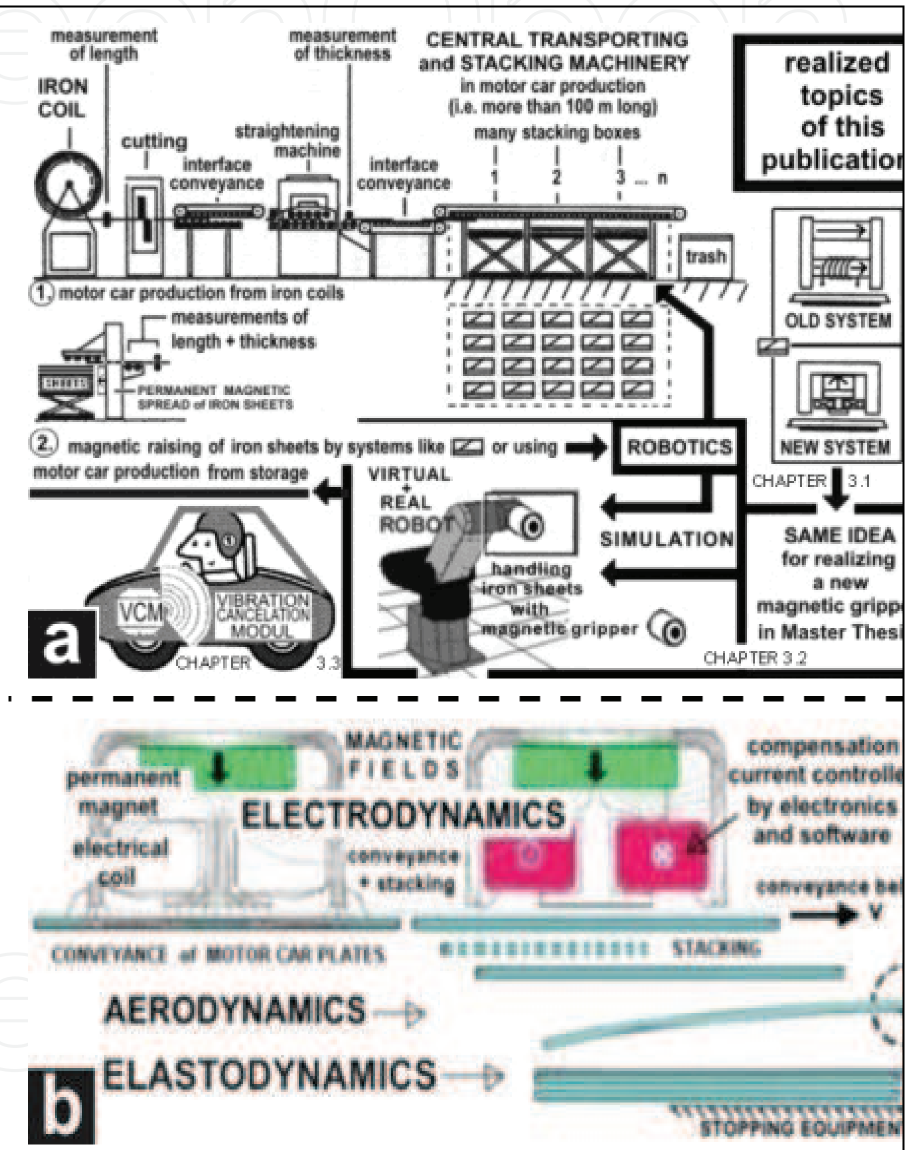

Fig. 9. Mechanical motor car production based on electrodynamics (Stanek, 2002+2010).

3.2 Gripper design in robotics based on electrodynamics

Based on the idea for the controlled actuator in motor car production, the following magnetic gripper was developed, simulated and realised in Fig. 10.

The 4 steps in the pictures shown on the right are necessary for each development with respect to electrodynamic actuators and sensors in robotics from idea to end product. This new magnetic gripper was developed by a Master's Thesis in Mechatronics in cooperation between SGU advisor W. Stanek from University of Applied Sciences Koblenz and Swiss German University (SGU) in Indonesia.

This development also shows the necessity for a mechatronics engineer to be flexible in working within several physical disciplines, including automated production, complex environments and both software controls and simulations.

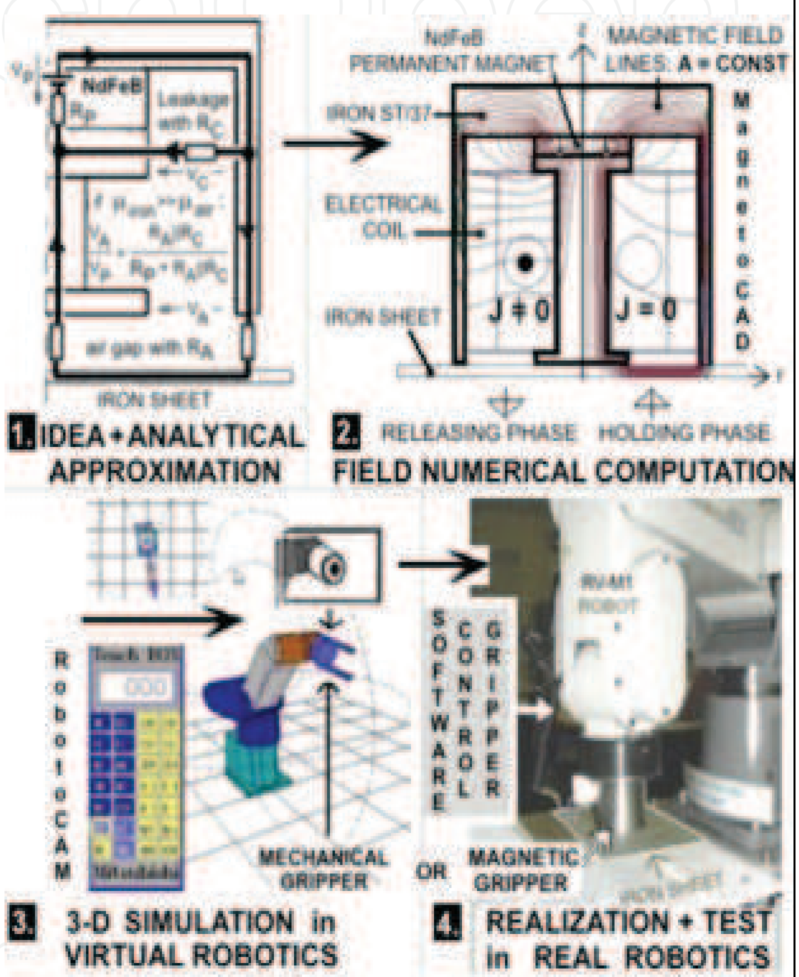

Fig. 10. New magnetic gripper design for handling metal sheets in 4 steps (Andries, 2003; Stanek & Grueneberg, 2003).

3.3 Motor car anti-vibration system based on electrodynamics

The cancellation of noise inside motor cars, using software controlled actuators, is of great importance in all motor car plants. The design of such anti-vibration systems (i.e. VCM) in Fig. 11 involves several interdisciplinary areas in physics such as acoustics, electrodynamics, thermodynamics, hydrodynamics, mechanics, elastodynamics and sound design, too.

Integrated simulation processes were needed for mechanical design of spring and damping in relation to electrodynamically and mechanically produced forces.

This new actuator, integrated in the software controlled VCM-circuit was parametrised, optimised and realised by a Diploma Thesis at Trelleborg Automotive in cooperation with Prof. Stanek (University of Applied Sciences Koblenz). In the pictures shown on the right the focus on electrodynamics is emphasised.

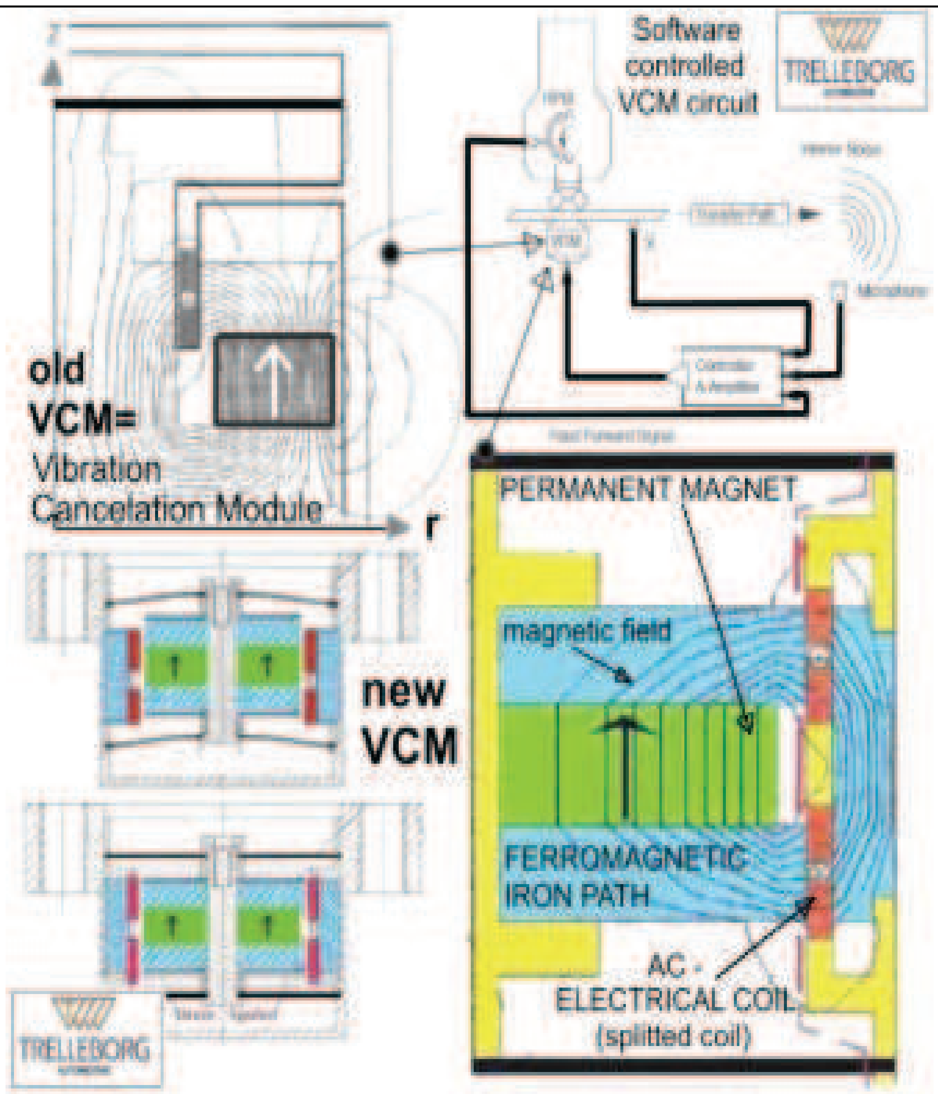

Fig. 11. Motor car anti-vibration system based on electrodynamics R&D report 2000 (Stanek, Graeve, Loehr, 2001)

3.4 Computer hard disk drives

3.4.1 Basic construction and basic governing equations

Complex concepts and applications of electrodynamics are the basis for a great variety of Hard Disk Drives in computers (i.e. often like in Fig. 12 or other special variants). Though very different in construction details, all hard disk drives are consisting of electrical coils, permanent magnets, iron parts and often additional copper plates or closed coils in form of a “shorted turn” (ref. to Fig. 13 and 14, the principle of a Winchester-Hard-Disk-Drive). The main task of these drives is to perform and to control the accelerated movements of magnetic heads for an exact and fast reading and writing of data on the magnetic hard disk.

Combined analytic modelling and computer aided simulation of mechanical and electromagnetic devices in mechatronics is necessary to solve and to simulate the behaviour of computer hard disk drives, i.e. Winchester drives.

Fig 12. Often constructed hard disk drive (photo)

For analytical calculation of electromagnetic fields in mechatronic systems and interdisciplinary analogies: Thinking in magnetics with concentrated field elements (R, L and often C) and solving dynamics by well known electrical circuit methods (i.e. with MATLAB, Simulink aided by FEMLAB, MAXWELL & MagnetoCAD) Simulation, Design in cooperation between W. Stanek and SGU Mechatronics

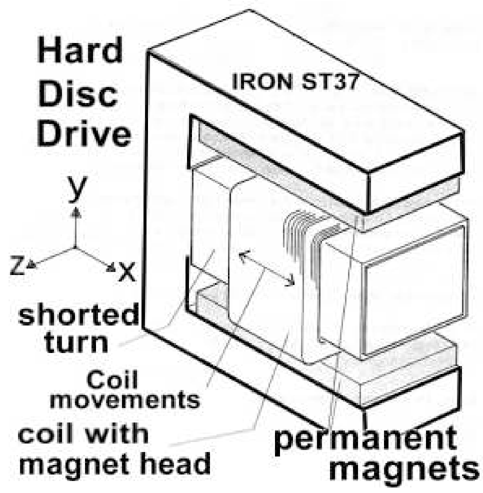

Fig 13. Principle of Winchester hard disk drive (Cassing, Stanek, Erd, 2002)

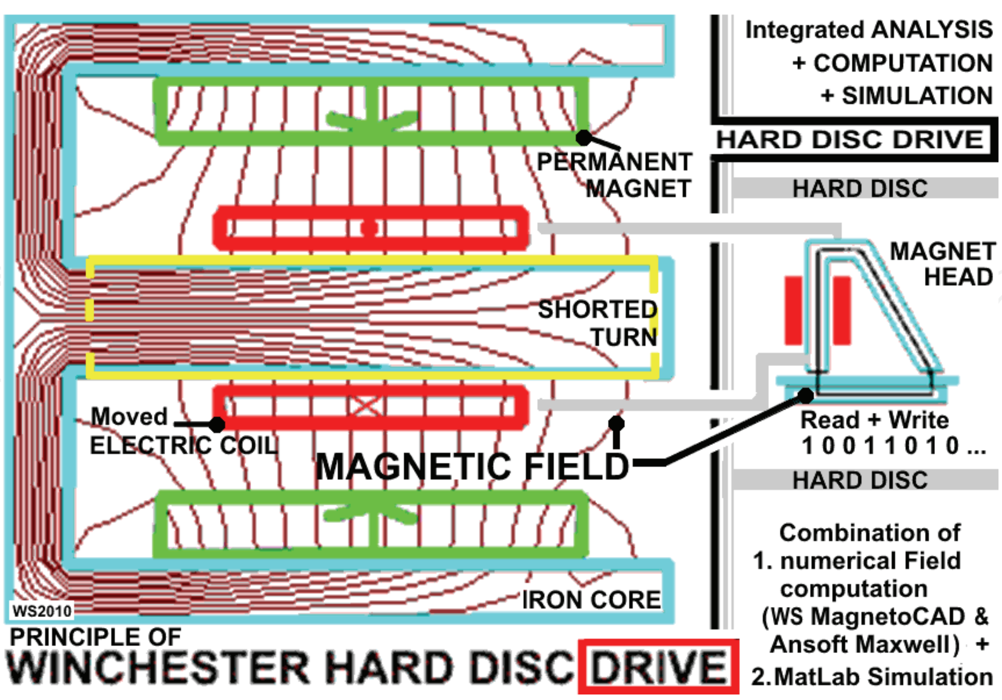

Fig 14. Winchester hard disk drive with magnetic field values for eq. (28-33) and eddy current equation from Maxwell (Stanek, 2008)

3.4.2 Modeling, analysis and simulation of Winchester hard disk drive unit

As one application for the significance of unit checks and its application to mechatronical system modeling and design, mechanical system of a computer hard disk drive is being explored. The physical structure may be seen in Figure 12 & 13 while the pattern of magnetic field inside the disk drive may be seen in the Figure 14.

The analytical equations (28 – 31) are shown later considering **N**o "**S**horted turn" (index "**nS**"). Modeling the influence of the "**S**horted turn" (index "**S**") as a transformer with "1" turn on the secondary side we can use the equations (32 & 33). The flow pattern of the magnetic field in a Winchester hard disk drive can be seen from the Figure 14, where there are two windings, the moving electric coil and the shorted turn. The corresponding magnet head will directly move with the movement of the electric coil.

We will analyse first the relationship of each parameter of this electromechanical system, as to produce the inter-connected equations needed to build a transfer function which express the output as the function of input parameter. This is started with the unit checks, and will be explained as far as the design and performance of the system response.

From the electrical circuit law, the current conducting coil will give relationship:

$$u_{1,ns}(t) = R_1 i_1(t) + \frac{d\left(L_1 i_1(t)\right)}{dt} + u_{ind}(t) \tag{28}$$

- A particle or body moving with a uniform speed v in a magnetic field B:
  Then by analysing the units check for $\vec{v}\times\vec{B}$ is $\frac{m}{s}\bullet\frac{V.s}{m^2}=\frac{V}{m}$ which shows that is the unit of Electric field, $\vec{E}$, that confirms the Lorentz Law of Electric Field, $\vec{v}\times\vec{B}=\vec{E}$.
- A current carrying conductor moving with speed v in **B** is given by $\vec{J}\times\vec{B}$, with unit check gives $\frac{A}{m^2}\bullet\frac{Vs}{m^2}=\frac{Ws}{m^4}=\frac{Nm}{m^4}=\frac{N}{m^3}$. And the result confirms the relationship of Lorentz law of spatial force density, $\vec{J}\times\vec{B}=\vec{f}$.
- The relationship of induced voltage which is the closed line integral of the electric field is given by $u_{ind}(t)=\oint\vec{E}dl$ and as l is constant then $u_{ind}\propto\vec{E}$. Given $\vec{E}=\vec{v}\times\vec{B}$ then as $\vec{B}$ is perpendicular to $\vec{v}$, then it can be represented as a scalar product $\vec{E}=\vec{v}\bullet\vec{B}$. As B is constant then it may be stated as $\vec{E}\propto\vec{v}$. Because of perpendicular relation of r & ω then $\vec{v}=\vec{r}\times\vec{\omega}$ can be reduced to, $\vec{v}=\vec{r}\bullet\vec{\omega}$,therefore with r being constant $v\propto\omega$, which yields:

$$u_{ind}(t) = k_1.\omega(t) \tag{29}$$

- The torque equation may be expressed as:

$$\frac{d\left(J_{mec}.\omega(t)\right)}{dt} = T_m(t) - T_L(t) \tag{30}$$

For the moving Torque $\vec{T}_m=\vec{r}\times\vec{F}$ as perpendicular to each other then $\vec{T}_m=\vec{r}\bullet\vec{F}$ so $\vec{T}_m\propto\vec{F}\propto\vec{f}$. And as $\vec{f}=\vec{J}\times\vec{B}\propto\vec{J}$ due to B is constant, the result is $f\propto i$ and we get:

$$u_{ind}(t) = k_1.\omega(t) \tag{31}$$

Similarly for the condition of considering the influence of the "shorted turn":
The electrical circuit equations may be expressed as:

$$u_{2,s}(t) = R_1 i_1(t) + \frac{d(L_1 i_1(t))}{dt} + u_{ind}(t) + \frac{d(M i_2(t))}{dt} \tag{32}$$

and

$$0 = R_2 i_2(t) + \frac{d(L_2 i_2(t))}{dt} + \frac{d(M i_1(t))}{dt} \tag{33}$$

If inductances L_1, L_2, mutual inductance M and mass moment of inertia J_{mec} are constant, equations (28-33) can easily be simplified: i.e. d(L·i)/dt = L di/dt + i dL/dt, where the last term is zero. MATLAB® and Simulink are mighty systems for simulating problems in mechatronics. But without the numerical computation of central electromagnetic field values, primarily L and M, analytical simulations may yield false results not usable for optimised applications in practice. Directly from equations (28-33) we can sketch the block diagram and the automation graph.

Design considering no shorted turn

	Time Relation	Laplace Transformation
The Motor Torque	$T_m(t) = K_2 i_1(t)$	$T_m(s) = K_2 I_1(s)$
The Voltage induced	$u_{ind} = K_1 \omega(t)$	$U_{ind}(s) = K_1 \Omega(s)$
Electrical Circuit Eq.	$u_{1,ns}(t) = R_1 i_1(t) + \frac{d(L_1 i_1(t))}{dt} + u_{ind}(t)$	$U_{1,ns}(s) = (sL_1 + R_1) I_1(s) + U_{ind}(s)$
Torque Relations	$\frac{d(J_{mec}.\omega(t))}{dt} = T_m(t) - T_L(t)$	$J_{mec} s \Omega(s) = T_m(s) - T_L(s)$

Rearranging all the Laplace form equation in the table and simplifying, the overall equations can be represented in the well-known block diagram relationship as shown in Figure 15.

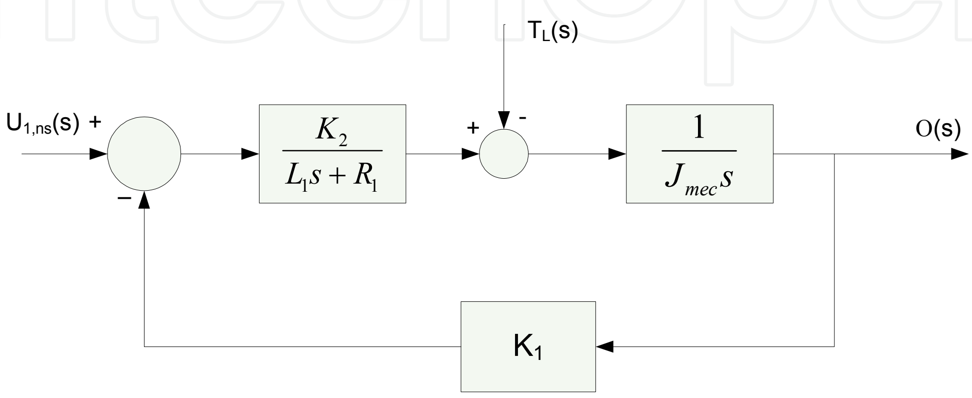

Fig. 15. Non-shorted hard disk drive System block diagram

By inserting general values of the variables and simulate the system response when subjected to a step input, we can obtain the system response of the angular velocity, current as well as torque produces shown on the next figures. The values chosen are general approximations based on common application of DC electric motor or hard disk drives, etc.
From the graph on the left, it can be seen the response of the angular velocity of the hard disk drive magnetic arm.
It can be seen that by the help of the MATLAB® and Simulink tools, the response of the model that has been designed may be observed. Graphical presentation of the current and the corresponding torque are shown below.

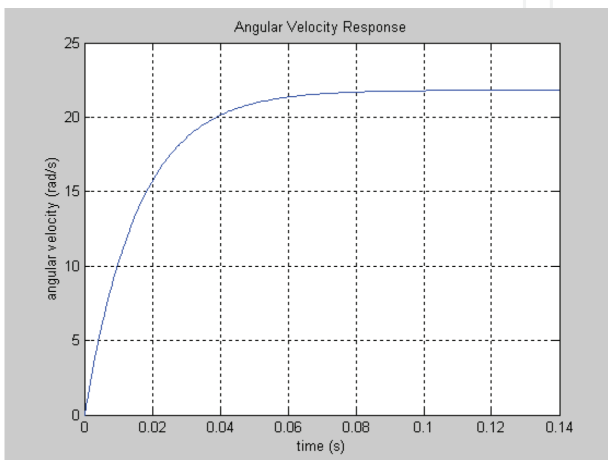

Fig. 16. a Angular Speed Response

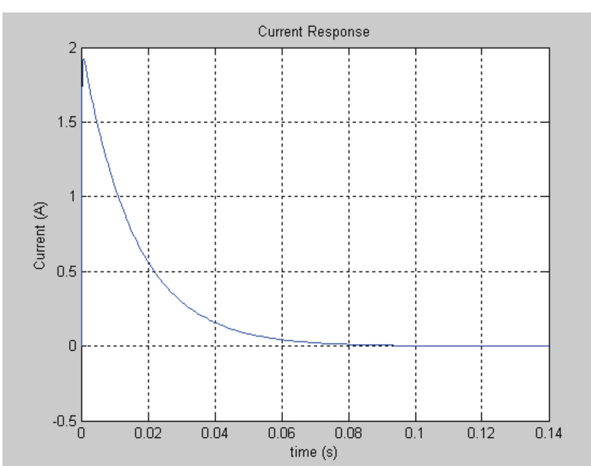

Fig. 16b Current Response

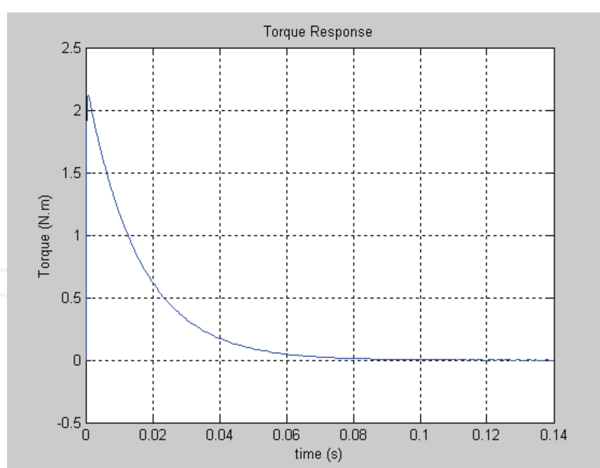

Fig. 16c. Torque Response

Fig. 16. Some excerpts of simulation results for a hard disk without shorted turn.

Also, it can be observed that the system response as depicted by Figure 16 resembles that of the system response of permanent magnet DC motor.

Design considering shorted turn

	Time Relation	Laplace Transformation
The Motor Torque	$T_m(t) = K_2 i_1(t)$	$T_m(s) = K_2 I_1(s)$
The Voltage induced	$u_{ind} = K_1 \omega(t)$	$U_{ind}(s) = K_1 \Omega(s)$
Electrical Circuit Equation (moving coil)	$u_{1,s}(t) = u_{1,ns}(t) + \frac{d\left(M.i_1(t)\right)}{dt}$	$U_{1,s}(s) = (L_1 s + R_1) I_1(s) + U_{ind}(s) + MsI_2(s)$
Electrical Circuit Eq. (single turn)	$0 = R_2 i_2(t) + \frac{d\left(L_2 i_2(t)\right)}{dt} + \frac{d\left(Mi_1(t)\right)}{dt}$	$0 = (L_2 s + R_2) I_2(s) + MsI_1(s)$
Torque Relations	$\frac{d\left(J_{mec}.\omega(t)\right)}{dt} = T_m(t) - T_L(t)$	$J_{mec} s \Omega(s) = T_m(s) - T_L(s)$

Rearranging all the Laplace form equations in the table and simplifying, the overall equations can be represented in the well-known block diagram relationship as shown in Figure 17.

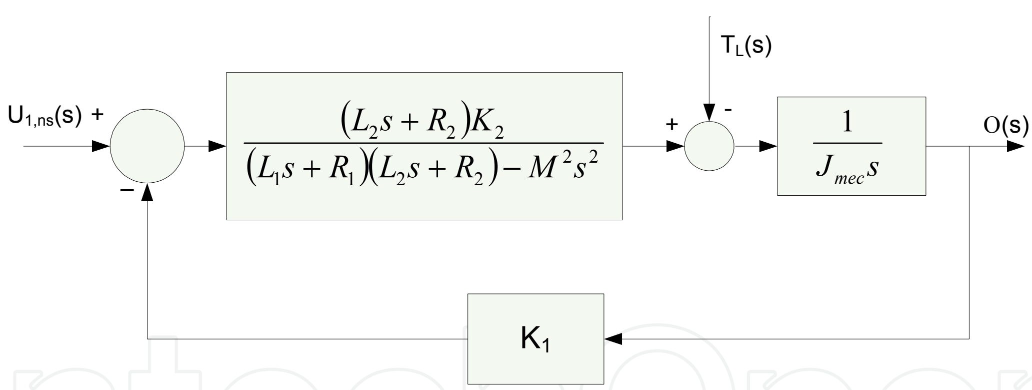

Fig. 17. Shorted hard disk drive system block diagram

From the transfer function in the block diagram, the order has increased by one and by analysing the characteristics equation in the first block diagram, and doing the similar methods as the non-shorted simulation shown previously which will give us necessary information or results that are required.

Mathematical and graphics tools such as MATLAB® & Simulink, are great tools to solve and describe the performance of the system, but it is most important to know that for engineering application, the understanding of electrodynamics is the key to obtain the model to be simulated by those tools.

The application of the magic unit checks for physics and extended field theory based on interdisciplinary electrodynamics in this Mechatronical System is successfully derived therefore it is possible to apply it on other mechatronic and automation systems.

4. Conclusion

The high aim of optimising the integration of mechanical engineering, electrical engineering and information technology in mechatronics can often be reached by preferred usage of advanced field theory in electrodynamics. Working with extended Maxwell's equations, electrodynamics in mechatronics often leads to new developments and interdisciplinary influences which are easier and faster to approximate. Quick derivation of interdisciplinary and complicated equations in physics can be achieved by using extremely helpful and mighty unit checks. Furthermore other electrodynamic influences especially caused by external waves and fields with respect to electro-magnetic compatibility problems can be handled and corrected.

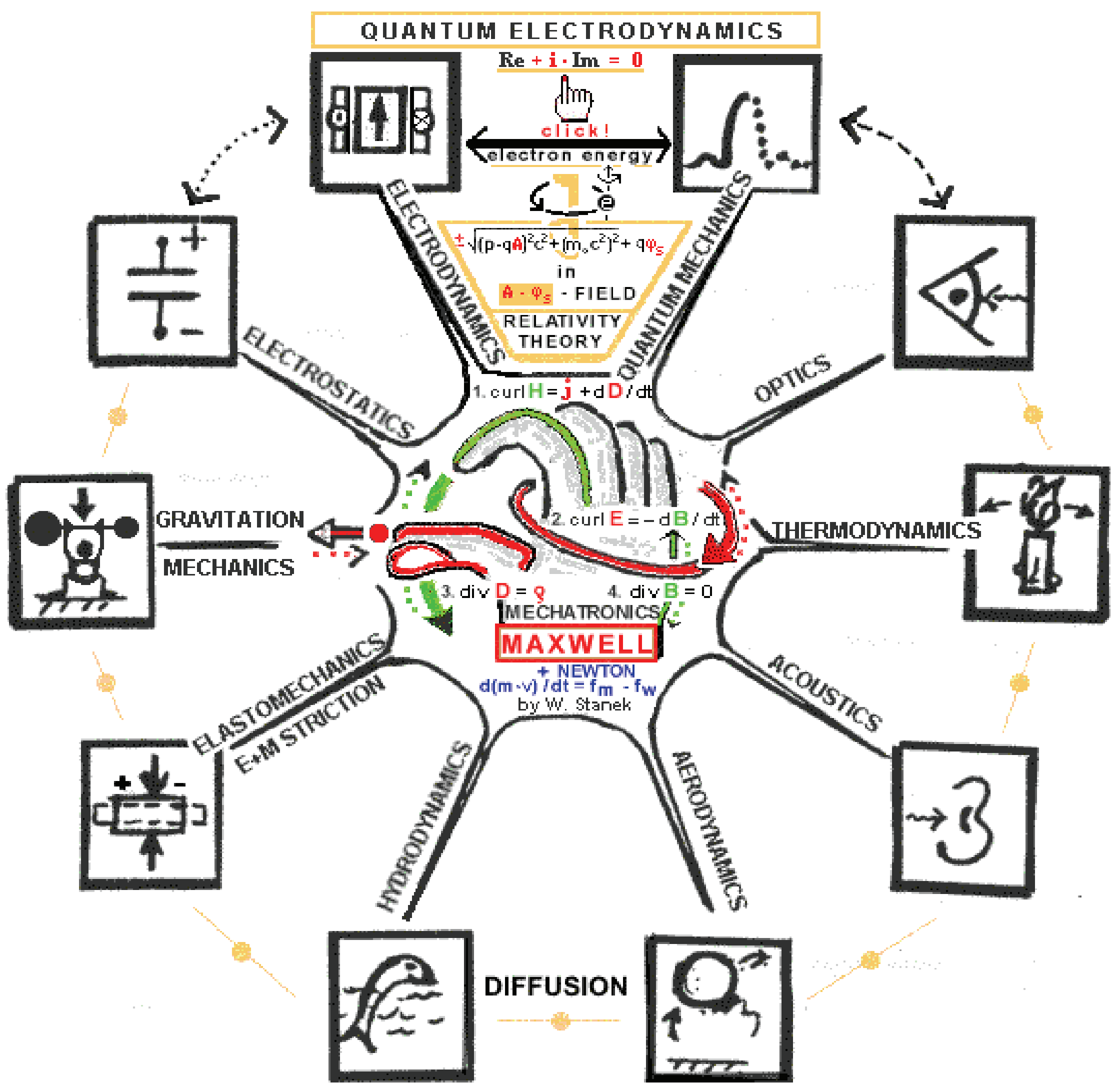

Fig 18. Interdisciplinary analogies in mechatronics based on extended Maxwell's equations (Stanek, 2002+ 2010)

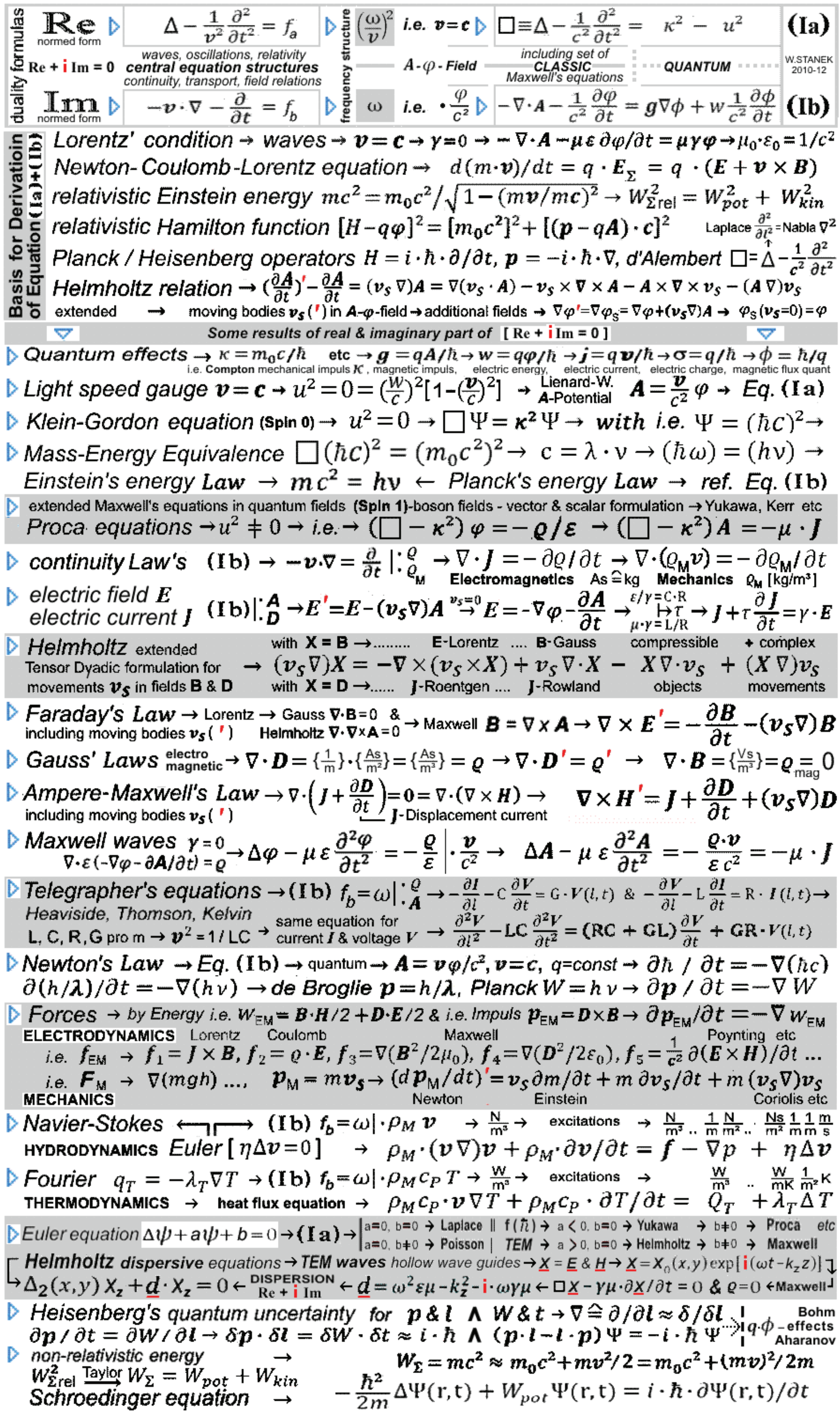

Fig. 19. Compact equation for most central equations in classic, relativistic and quantum electrodynamics (Stanek, 2010)

The focus on four described developments such as motor car production, magnetic gripper design in robotics, motor car anti-vibration systems and computer hard disc drives show the necessity for a mechatronics engineer to be flexible in working with several physical disciplines (refer to Mind Map with Memo Maps in Fig. 18), in highly automated car production including complex environments and with both a variety of different software controls and simulations. Most central equations for the interdisciplinary engineers and physicists can be derived from the very compact equations shown in Fig.19. This unified equation for relativistic quantum electrodynamics applies most central relations and analogies from section 2 and spectrum of interdisciplinary disciplines in advanced mechatronics. It is important to use a spectrum of background disciplines rather than just one discipline.
The compact equation for most central equations in extended electrodynamics was developed by the main author W. Stanek based on Faraday's law, Einstein's relativistic energy, including quantum mechanics in complex notation.
This compact unified equation, Re + i . Im = 0, consists of Maxwell's equations in rest and moving bodies, Lorentz-Einsteins' relativistic energy relations, Klein-Gordon's equations, relativistic Schroedinger's equation, Proca's extended Maxwell's equations, central relations in quantum mechanics and classical Newton mechanics itself, too.

5. Acknowledgements

Thanks of main author Prof. Dr. W. Stanek to his appreciated colleagues and co-authors Ir. Arko Djajadi, Ph.D and Pro Rector Edward Boris P Manurung, MEng from SGU – Asia for adaptation and MATLAB® & Simulink simulation based on W. Staneks' research and publication (refer to list of publications).

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Products and Services; from R&D to Final Solutions

Edited by Igor Fuerstner

ISBN 978-953-307-211-1
Hard cover, 422 pages
Publisher Sciyo
Published online 02, November, 2010
Published in print edition November, 2010

Todayâ€™s global economy offers more opportunities, but is also more complex and competitive than ever before. This fact leads to a wide range of research activity in different fields of interest, especially in the so-called high-tech sectors. This book is a result of widespread research and development activity from many researchers worldwide, covering the aspects of development activities in general, as well as various aspects of the practical application of knowledge.

How to reference

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Wolfram Stanek, Arko Djajadi and Edward Boris P Manurung (2010). Magic Unit Checks for Physics and Extended Field Theory Based on Interdisciplinary Electrodynamics with Applications in Mechatronics and Automation, Products and Services; from R&D to Final Solutions, Igor Fuerstner (Ed.), ISBN: 978-953-307-211-1, InTech, Available from: http://www.intechopen.com/books/products-and-services--from-r-d-to-final-solutions/magic-unit-checks-for-physics-and-extended-field-theory-based-on-interdisciplinary-electrodynamics-w

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