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1 Mechanisms of elastic wave generation by EMAT in ferromagnetic media

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21 ABSTRACT

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11 Elastic wave generation

12 Ferromagnetic materials

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22 The present paper deals with the problem of elastic wave generation mechanisms
 23 (WGMs) by an electromagnetic-acoustic transducer (EMAT) in ferromagnetic
 24 materials. The paper seeks to prove that taking into account all the WGMs must be a
 25 general rule to quantitatively predict the elastic waves generated by an EMAT in such
 26 materials. Existing models of the various physical phenomena involved, namely magnetic
 27 and magnetostrictive, electromagnetic, and ultrasonic, are combined to solve the
 28 multiphysics wave generation problem. The resulting model shows that WGMs (*i.e.*,
 29 electromagnetic force, magnetostrictive strain, and magnetic traction) strongly depend
 30 on material properties and EMAT design and excitation. To illustrate this, four
 31 magnetic materials (nickel, AISI410, Z20C13, and low carbon steel) with similar elastic
 32 but contrasting electromagnetic properties are studied. A given EMAT of fixed
 33 excitation and geometry yields WGMs with highly different amplitudes in these
 34 materials, with a WGM dominant in one material being negligible in another.
 35 Experimental results make it possible to validate the accuracy of certain predictions of
 36 the model developed. In summary, the present work shows that considering all WGMs
 37 is the general rule when working with ferromagnetic materials. Furthermore, it offers a
 38 generic model that can be integrated into various numerical tools to help optimize
 39 EMAT design and give reliable data interpretation.

40

41 1. Introduction

42 In ultrasonic non-destructive techniques, piezoelectric
 43 transducers, laser-ultrasonic systems, and electromagneto-
 44 acoustic transducers (EMAT) are the most widespread
 45 means for generating elastic waves in metallic structures.
 46 The piezoelectric techniques use piezoelectric ceramic
 47 transducers bound to the structure or radiating from a
 48 coupling medium (either solid or fluid). These techniques'
 49 need for mechanical contact impedes their potential use
 50 in numerous applications. Although optical techniques
 51 (using a laser source) do not suffer from this drawback,
 52 they are difficult to implement, requiring the surface
 53 condition of the part to be inspected, which is sometimes

54 very difficult to ensure industrially. The use of EMAT is
 55 restricted to the inspection of conductive and/or magnetic
 56 materials. They nonetheless compensate for this
 57 shortcoming by being non-contact. They are versatile
 58 thanks to the flexibility of their design (*i.e.*, one or several
 59 coils and one or several magnets). EMAT has been used
 60 on nonmagnetic conductive structures (*i.e.*, aluminum) to
 61 generate SH₀ (the fundamental shear horizontal mode of
 62 plate) [1], SH (bulk shear/transverse horizontal wave) [2],
 63 longitudinal wave [3,4], Rayleigh waves [5], S₀ (the
 64 fundamental Lamb-symmetric mode) [6], and A₀ (the
 65 fundamental Lamb-antisymmetric mode) [7], and on
 66 ferromagnetic structures to generate SH [8], S₀ [9], and
 67 A₀ guided waves [10]. By virtue of its nature (*i.e.*, an

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68 electromagnetic (EM) source) EMAT can generate a wave
 69 in ferromagnetic (FM) materials through three
 70 mechanisms: a) Lorentz force (Lf), b) magnetic force, and
 71 c) magnetostriction strain. While the first two are indeed
 72 forces, the last one is an eigenstrain (like thermal
 73 expansion) caused by the magnetic field and can – for
 74 convenience – be represented by a fictitious equivalent
 75 force term. Though the theory of wave generation by
 76 EMAT in nonmagnetic conductive materials – in which
 77 only Lf is created – is rather simple and well established
 78 (Gaerttner *et al.* [11]), that, for the case of ferromagnetic
 79 (FM) materials is far more complex to establish. Such
 80 materials are widely used across various industries. Their
 81 ultrasonic characterization – like that of nonmagnetic
 82 materials – often requires the transducer to select specific
 83 types of waves, which can be done using EMATs (see [1-
 84 10]). The fact that wave generation mechanisms for
 85 ferromagnetic materials can interact constructively or
 86 destructively hinders the ability to select or even generate
 87 elastic waves. Several attempts combining distinct
 88 theoretical models have been proposed to solve the EMAT
 89 wave generation problem in ferromagnetic materials,
 90 which led to some contentions in the recent ultrasonic
 91 literature. To understand why, it is recalled that various
 92 methods exist to model the EM force (the combination of
 93 Lorentz and magnetic forces) exerted on a FM object in
 94 an EM field. For instance, the equivalent magnetic sources
 95 method (see [12,13]), formulates the problem in terms of
 96 the interactions of the EM field with equivalent magnetic
 97 currents and charges, Kelvin's method (see [14]), in terms
 98 of the interactions with magnetic moments, Korteweg-
 99 Helmholtz (see [14,15]) and Maxwell stress tensor (Max-
 100 ST) methods (see [16,17]) both use the virtual work
 101 principle applied to the EM energy. All four formulations
 102 give the same global force exerted on the object (see [18])
 103 as the sum of volume and surface terms. However, they
 104 yield different force distributions. As a result, some bad
 105 practices arose, in which the volume term from one
 106 method is combined with the surface term from another
 107 method. Such operation in ultrasonic applications – where
 108 the generated wave type is governed largely by the
 109 distribution of force – led, unescapably, to consequential
 110 discrepancies. A detailed discussion on the hazardous
 111 nature of this approach is provided by Seher and Nagy [19].
 112 In addition to the theoretical intricacies, practical
 113 questions regarding the dominant wave generation
 114 mechanism (WGM) were raised. Magnetostriction was the
 115 only mechanism considered by Ribichini *et al.* [20], in which
 116 the EMAT static and dynamic magnetic fields were
 117 perpendicular. Such EMAT was used to generate SH0 in
 118 a nickel plate. Another EMAT, for which the static and
 119 dynamic magnetic fields were parallel (see [21,22]) was
 120 studied. Only Lorentz force (Lf) was considered when such
 121 EMAT was used to generate SH0 in steel. In [20,21] the
 122 EMAT coil was a single current-carrying wire, and in [22]
 123 a rectangular spiral coil. An EMAT with a meander coil
 124 was studied by Thompson [23] where, in contrast with

125 previously cited works with parallel static and magnetic
 126 fields, Lf was not neglected by the model and was shown
 127 to be dominant in comparison to magnetostriction for
 128 large static magnetic field. This was observed for three
 129 different FM materials. For low static magnetic field,
 130 magnetostriction was the dominant mechanism. Whilst
 131 agreement between the model and experiment was mostly
 132 good, the latter showed tendencies that the model did not
 133 predict, and the author suggested a third WGM, that later
 134 on [24] was shown to be the magnetic force. Ashigwuike *et*
 135 *al.* [25] considered the two WGMs previously studied but
 136 split Lf into two parts (due to dynamic and static
 137 magnetic fields). They numerically compared the
 138 contributions of these mechanisms as functions of current
 139 for ten steel grades. The dynamic Lf was found to be the
 140 dominant mechanism at high currents, while the
 141 magnetostriction contribution depended strongly on the
 142 material. Although EMATs were used to generate various
 143 types of waves, only a few works compared the various
 144 WGMs to each other and linked them to the type of
 145 generated elastic wave(s). Moreover, when comparison
 146 took place, magnetic forces (volume and surface) were
 147 deemed insignificant to study or overlooked by the
 148 authors. While this does not pose a problem in specific
 149 configurations – as seen in Thompson [23] – it should not
 150 be regarded as the general rule.

151 The present work aims to propose a unified model for all
 152 three mechanisms of electromagnetic-acoustic
 153 transduction in ferromagnetic media and to use this model
 154 to highlight, through parametric studies, the need to
 155 consider all three. Our findings are presented as follows.
 156 In Sec.2, the theoretical model of elastic wave generation
 157 (WG) by EMAT in FM is derived. The WG problem is
 158 solved in four steps. In the first (Sec.2.1), the
 159 electromagnetic problem consisting in obtaining eddy
 160 currents, magnetization and magnetostriction from
 161 radiated EM fields is solved under the assumption of
 162 infinitesimal strain hypothesis (ISH). Such a solution
 163 incorporates magnetic and magnetostrictive constitutive
 164 laws that were either measured or obtained following
 165 multi-scale (Daniel *et al.* [26]) or phenomenological (Jiles
 166 [27]) approaches into the solver CIVA-ET [28]. In Sec.2.2,
 167 elastic WGMs (volume force distributions) are given in
 168 terms of quantities obtained in Sec.2.1. Here, we follow
 169 the works of Bossavit [17] and Henrotte *et al.* [29] to present
 170 Maxwell stress tensor method as an adequate tool to
 171 formulate EMAT wave generation mechanisms in
 172 ferromagnetic materials. Such formulation is carried out
 173 under the piezomagnetic behavior hypothesis (PMH). In
 174 Sec.2.3, the volume WGMs are converted – for
 175 computational purposes – into equivalent surface stress
 176 distributions using a previously developed tool by Clause
 177 and Lhémercy [30]. In the last step (Sec.2.4), the
 178 elastodynamic problem of calculating the elastic wave
 179 radiation from the surface stress distributions is solved
 180 semi-analytically (based on Lhémercy [31]), using the

181 convolution of the appropriate Green's tensor and
 182 equivalent surface stress distributions. Sec. 3 is dedicated
 183 to experimental studies to verify the validity of ISH
 184 (Sec.3.1) and PMH (Sec. 3.2). In Sec.3.3, measured and
 185 simulated radiated field distributions of both longitudinal
 186 (L) and transverse (T) waves are compared to validate the
 187 overall modelling approach. Finally, in Sec.4, parametric
 188 studies are carried out to compare all WGMs generated
 189 by a given EMAT in four different FM materials. Each
 190 component of each transduction mechanism is treated
 191 separately to ease their comparison. In Sec. 4.1 WGMs
 192 and their corresponding radiated waves are studied as
 193 functions of material properties. Four ferromagnetic
 194 materials (*i.e.*, nickel and three grades of steel) are treated.
 195 These have similar elastic but contrasting electromagnetic
 196 properties. In Sec. 4.2 WGMs, are studied as functions of
 197 EMAT excitation (*i.e.*, the current in the coil, and the
 198 static magnetic field of the magnet). Sec.5 summarizes
 199 the main findings of the paper.

200 2. The theoretical model of EMAT generation in 201 ferromagnetic media

202 An EMAT is an EM source made of a coil (or of several
 203 coils) and a magnet (or several magnets) that radiates
 204 dynamic fields (electric (\mathbf{E}) and magnetic (\mathbf{H}_d)) and a
 205 static magnetic field (\mathbf{H}_s). The dynamic source is an
 206 alternative current (\mathbf{I}_e) circulating in the coil(s), and the
 207 static source is the magnet(s). \mathbf{E} induces eddy currents
 208 (\mathbf{J}_e) in electrically conductive materials. These currents
 209 give rise to Lorentz forces in the presence of magnetic
 210 fields. \mathbf{H}_d and \mathbf{H}_s induce a magnetization (\mathbf{M}) in magnetic
 211 materials. As a consequence, magnetic forces are exerted
 212 on the material by an EMAT and a magnetostriction
 213 strain (ϵ^{ms}) is also induced. Owing to the dynamic nature
 214 of \mathbf{E} and \mathbf{H}_d , these forces and strain create local dynamic
 215 strain/displacement in the part of the medium near the
 216 EMAT, thus radiating elastic waves in the medium.
 217 Throughout the present work, the infinitesimal strain
 218 hypothesis (ISH) is maintained: the strain associated with
 219 the elastic wave is sufficiently small for EM fields to be
 220 accurately computed on the undeformed shape of the part.
 221 When valid, ISH allows for the decoupling of
 222 electromagnetic problems (Steps 1 and 2 in what follows)
 223 and the elastodynamic problem (*i.e.*, the wave radiation
 224 problem: steps 3 and 4). ISH is almost always accepted in
 225 the case of EMAT on conductive nonmagnetic materials
 226 since the wave displacement (few *nm* [32]) is at least three
 227 orders of magnitude smaller than the characteristic length
 228 of the elastic wave source (given generally by the skin
 229 depth (μm)). However, the case of ferromagnetic
 230 materials is different as it involves a static initial
 231 deformation due to magnetic force and magnetostriction
 232 strain (caused by the presence of the magnet). As a result,
 233 ISH is checked in the present work in the case of FM
 234 materials.

235 Elastic wave generation in FM materials by EMAT is a
 236 multiphysics problem. To solve it, we divided it into four
 237 sub-problems, each of them specific to a given physics.
 238 Methods of solutions to these problems have already been
 239 developed – separately – in the literature, sometimes by
 240 one of the authors of the present paper. They are
 241 combined and ordered in the present work following four
 242 steps (see Fig.1) to reach the solution to the complete
 243 wave generation problem (WGP). For conciseness, they
 244 are only briefly reported hereafter, with references to their
 245 detailed derivations being provided.

246 2.1. Step 1: Computing \mathbf{J}_e , \mathbf{M} and ϵ^{ms}

247 The first step deals with the calculation of induced eddy
 248 currents (\mathbf{J}_e), magnetization (\mathbf{M}) and magnetostriction
 249 strain (ϵ^{ms}) from radiated fields (\mathbf{E} , \mathbf{H}_d and \mathbf{H}_s). We start
 250 with the simpler case of conductive nonmagnetic materials
 251 in which only eddy currents are induced. To compute
 252 them, the solver CIVA-ET [28] is used. It operates under
 253 ISH and uses analytic solutions for \mathbf{H}_s , while the finite
 254 element method is used for computing \mathbf{E} and \mathbf{H}_d . Both
 255 the coil and a region of interest in the test piece are
 256 meshed. This region is defined as the volume in which \mathbf{E}
 257 and \mathbf{H}_d are considered nonnegligible. It represents the
 258 location of the elastic wave source previously defined. The
 259 case of FM materials is more complex and requires the
 260 definition of magnetic and magnetostrictive constitutive
 261 laws ($\mathbf{M}(\mathbf{H})$ and $\epsilon^{ms}(\mathbf{H})$). These laws can be obtained
 262 experimentally or theoretically. In the present work, when
 263 not obtained experimentally, they are either assumed
 264 linear or obtained using one of the two following models:
 265 the simplified multi-scale model (SMSM) by Daniel *et al.*
 266 [26] (derived from the full model [34]) and the
 267 phenomenological model by Jiles [27]. In their full forms,
 268 they model hysteretic and anhysteretic magnetic and
 269 magnetostrictive constitutive laws as functions of both
 270 applied magnetic field and mechanical stress. Daniel *et al.*
 271 model [34] is derived from first principles and treats the
 272 magneto-mechanical problem in a bottom-up fashion,
 273 starting at the domain scale and working its way– through
 274 homogenization schemes – up to the polycrystal scale. It
 275 is predictive as it uses only parameters obtained from
 276 stress-free measurements to predict behaviors under
 277 stress. Conversely, that proposed by Jiles [27] is a
 278 macroscopic phenomenological model, requiring
 279 parameters obtained from measurements under stress. To
 280 prove the premise of the present work (*i.e.*, all WGMs
 281 should be included when designing an EMAT), materials
 282 need not be under stress, and hysteresis can be neglected.
 283 As a result, only stress-free versions of magneto-
 284 mechanical models are used. Within this framework, that
 285 by Daniel *et.al.* [26] uses the following three material
 286 parameters to describe the anhysteretic behavior: the
 287 initial magnetic susceptibility (χ^0), and both the
 288 magnetization (M_s) and the magnetostriction strain (λ_s)
 289 at saturation. That by Jiles. [27] uses five material

290 parameters: a dimensionless parameter representing the
 291 interdomain coupling (α), M_s , a parameter characterizing
 292 the shape of the anhysteretic magnetization (a), two
 293 parameters fitted on the anhysteretic magnetostriction
 294 curve (γ_{11} and γ_{21}). Experimental procedures from which
 295 one identifies the parameters of both models are given in
 296 [33] and [35], respectively. Expressions of magnetization
 297 and magnetostriction strain as functions of \mathbf{H} and material
 298 parameters are not reported here due to lack of space and
 299 are readily found in [26-27]. Expressions of magnetic and
 300 magnetostrictive constitutive laws are then incorporated
 301 into the solver CIVA-ET [28] to obtain the induced eddy
 302 currents (\mathbf{J}_e), magnetization (\mathbf{M}) and magnetostriction
 303 strain (ϵ^{ms}).

304 2.2. Step 2: computing \mathbf{f}^{em} , \mathbf{f}^{ms} and \mathbf{t}^m

305 Once the quantities (\mathbf{J}_e , \mathbf{M} and ϵ^{ms}) are computed, they
 306 are converted into body forces. The forces in question are
 307 the electromagnetic force \mathbf{f}^{em} (combination of Lorentz
 308 force and the volume magnetic force) the equivalent
 309 magnetostriction force \mathbf{f}^{ms} and the surface magnetic
 310 traction \mathbf{t}^m . All these forces can be represented using the
 311 *augmented Maxwell tensor* given below (see Bossavit [17] for
 312 detailed derivation) under the assumption that magnetic
 313 induction ($\mathbf{B} = \mu_0(\mathbf{M} + \mathbf{H})$) and field (\mathbf{H}) are collinear:

$$\sigma^{Mx} = \mathbf{B} \otimes \mathbf{H} + G(\mathbf{H})\mathbf{I} - \mathbf{C} : \epsilon^{ms} \quad (1)$$

314 where \mathbf{H} obeys the following Maxwell's equations in
 315 matter given by $\nabla \times \mathbf{H} = \mathbf{J}_e$ and $\nabla \cdot \mathbf{H} = -\nabla \cdot \mathbf{M}$. The
 316 second order tensor $\mathbf{B} \otimes \mathbf{H}$ is given by $(\mathbf{B} \otimes \mathbf{H})_{ij} = B_i H_j$
 317 and \mathbf{C} is the elastic stiffness tensor. Finally, $G(\mathbf{H})$ denotes
 318 the Gibbs energy, defined as (see Henrotte *et al.* [29]):

$$G(\mathbf{H}) = - \int^{|\mathbf{H}|} B(\mathbf{h}) \cdot d\mathbf{h} \quad (2)$$

319 In EMAT applications, the magnetic field and,
 320 consequently, all quantities dependent on it
 321 (magnetization and magnetostriction) can be decomposed
 322 into two parts: a static part stemming from the permanent
 323 magnet(s) and a dynamic part from the coil(s). In general,
 324 $|\mathbf{H}_d| \ll |\mathbf{H}_s|$ (*i.e.*, the hypothesis of piezomagnetism
 325 (PMH)). Under this hypothesis, one can write (using
 326 Taylor series expansion to the first order):

$$\mathbf{B}(\mathbf{H}_s + \mathbf{H}_d) = \mathbf{B}_s + \left[\frac{\partial \mathbf{B}}{\partial \mathbf{H}} \right]_{\mathbf{H}_s} \cdot \mathbf{H}_d \quad (3)$$

$$\epsilon^{ms}(\mathbf{H}_s + \mathbf{H}_d) = \epsilon_s^{ms} + \left[\frac{\partial \epsilon^{ms}}{\partial \mathbf{H}} \right]_{\mathbf{H}_s} \cdot \mathbf{H}_d \quad (4)$$

$$G(\mathbf{H}_s + \mathbf{H}_d) = G_s + \left[\frac{\partial G}{\partial \mathbf{H}} \right]_{\mathbf{H}_s} \cdot \mathbf{H}_d \quad (5)$$

327 where in Eq. (3) (resp Eq. (4)) the quantity in brackets is
 328 the static differential magnetic permeability μ_s (resp the

329 magnetostrictive coupling tensor \mathbf{d}^{ms}). Recalling that
 330 $\mathbf{B}_s \parallel \mathbf{H}_s$, one can readily show that $\left[\frac{\partial G}{\partial \mathbf{H}} \right]_{\mathbf{H}_s} = \mathbf{B}_s$

331 Substituting Eq. (3), (4) and (5) into Eq. (1) yields three
 332 terms: (a) a static term (b) a term that depends on the
 333 product of $\mathbf{B}_s \cdot \mathbf{H}_d$ and (c) a term of higher orders in \mathbf{H}_d .
 334 Owing to its nature, the static term does not generate
 335 waves. The one with higher orders of \mathbf{H}_d is disregarded
 336 due to its relatively small amplitude (under PMH), so only
 337 the second term is of interest in the present work. The
 338 divergence of this term gives $\mathbf{f}^{em} + \mathbf{f}^{ms}$ and the jump of
 339 its magnetic part (*i.e.*, without $-\mathbf{C} : \epsilon^{ms}$) across the interface
 340 (Γ) of two media with different magnetic permeabilities
 341 gives \mathbf{t}^m . These expressions are given by:

$$\mathbf{f}^{em} = \nabla \cdot (\mathbf{B}_s \otimes \mathbf{H}_d + \mu_s \mathbf{H}_d \otimes \mathbf{H}_s - (\mathbf{B}_s \cdot \mathbf{H}_d)\mathbf{I}) \quad (6)$$

$$\mathbf{f}^{ms} = -\nabla \cdot (\mathbf{C} : (\mathbf{d}^{ms} \cdot \mathbf{H}_d)) \quad (7)$$

$$\mathbf{t}^m = [\mathbf{B}_s \otimes \mathbf{H}_d + \mu_s \mathbf{H}_d \otimes \mathbf{H}_s - (\mathbf{B}_s \cdot \mathbf{H}_d)\mathbf{I}]_{\Gamma} \quad (8)$$

342 These force densities are the EMAT elastic wave
 343 generation mechanisms (WGMs) in ferromagnetic media
 344 under the assumption of piezomagnetic behavior and
 345 collinearity of \mathbf{B} and \mathbf{H} . As \mathbf{H}_d is a common factor in all
 346 three WGMs, wave sources are mostly located near the
 347 surface (within ten skin depths) where the EMAT
 348 operates. This observation allows for important
 349 simplifications, as shown in the next step.

350 2.3. Step 3: Converting \mathbf{f}^{em} and \mathbf{f}^{ms} into equivalent 351 surface stresses.

352 Apart from the surface magnetic traction, the two other
 353 source terms are distributed over a volume. An
 354 intermediate step in the overall model consists of
 355 converting body force into equivalent surface stress
 356 distribution. It is introduced to lighten the computational
 357 burden. Details of the method allowing such conversion
 358 are provided in [33] for planar and in [30] for arbitrary
 359 surfaces. The method assumes the volume force
 360 distribution to be confined near the surface so that the
 361 elastic wavelength should be larger than the force
 362 distribution dimension in the piece thickness. Such an
 363 assumption is almost always valid in the case of EMAT in
 364 ferromagnetic media since the force distribution dimension
 365 in the thickness is governed by \mathbf{H}_d which does not
 366 penetrate such media more than a few skin depths. Given
 367 typical frequencies in EMAT applications, the magnetic
 368 permeability, and elastic properties of ferromagnetic
 369 media, the elastic wavelength is at least two orders of
 370 magnitude larger than the skin depth. By using a Taylor
 371 series expansion to the second order of the radiation
 372 integral of a body force distribution (given in Eq.9), the
 373 method [30] makes it possible to rewrite the volume
 374 integrals in the form of a surface integral over an
 375 equivalent stress distribution (Eq.10). The full derivation
 376 [30, 33] was proposed under the assumption of an

377 elastically isotropic material, but the anisotropic case can
378 be treated the same way (see [36]). We have:

$$\forall \mathbf{x} \in \Omega, u_k(\mathbf{x}) = \int_{\mathbf{x}_0 \in \Omega_\delta} \mathbf{G}_k(\mathbf{x}, \mathbf{x}_0) \cdot \mathbf{f}(\mathbf{x}_0) d\Omega_\delta \quad (9)$$

$$\forall \mathbf{x} \in \Omega, u_k(\mathbf{x}) \approx \int_{\mathbf{x}_0 \in \partial\Omega_\delta} \mathbf{G}_k(\mathbf{x}, \mathbf{x}_0) \cdot \tilde{\boldsymbol{\sigma}}_f(\mathbf{x}_0) d\Gamma \quad (10)$$

379 Where u , Ω , Ω_δ and $\partial\Omega_\delta$ denote respectively, the
380 displacement field, the test piece volume, the volume in
381 which the force distribution (\mathbf{f}) is nonnegligible and its
382 surface. The depth of Ω_δ is given by a few skin depths.
383 u_k (resp. \mathbf{G}_k) is the k -th component of the displacement
384 field (resp. row of Green's tensor). Expressions of the
385 equivalent surface stress distributions $\tilde{\boldsymbol{\sigma}}_f$ as functions of
386 moments of \mathbf{f} and elastic constants are cumbersome and
387 are provided in [30,33].

388 Applying this conversion procedure to both \mathbf{f}^{em} and \mathbf{f}^{ms}
389 yields two equivalent surface distributions $\boldsymbol{\sigma}^{em}$ and
390 $\boldsymbol{\sigma}^{ms}$. The total surface distribution is finally given as the
391 sum of three terms of surface stress as $\boldsymbol{\sigma}^{tot} = \boldsymbol{\sigma}^{em} +$
392 $\boldsymbol{\sigma}^{ms} + \mathbf{t}^m$.

393 2.4. Step 4: computing radiated elastic wave(s) \mathbf{u}

394 Once $\boldsymbol{\sigma}^{tot}$ (i.e., the wave source) has been obtained, the
395 elastodynamic wave radiation problem written as

$$(\Omega) \nabla \cdot \boldsymbol{\sigma} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \quad (11)$$

$$(\partial\Omega_\delta) \boldsymbol{\sigma} \cdot \mathbf{n} = \boldsymbol{\sigma}^{tot} \quad (12)$$

396 can be solved – under the infinitesimal strain hypothesis –
397 like any other classical wave radiation problem. To this
398 end, CIVA-UT [28] is used. For illustration, the present
399 work is limited to bulk waves (longitudinal (L) and shear
400 (S)) radiation in elastically isotropic and homogeneous
401 materials. Radiation by a finite-size source (i.e., $\boldsymbol{\sigma}^{tot}$) is
402 solved semi-analytically using the convolution between
403 Green's tensor (the solution for a point source) and the
404 surface distribution $\boldsymbol{\sigma}^{tot}$ (see Lh emery [31] for details).

405 To summarize, the solution of the problem of elastic wave
406 generation by EMAT in FM materials starts with
407 obtaining magnetic and magnetostrictive constitutive
408 laws, which, when introduced into a specific EM solver,
409 give induced eddy currents, magnetization, and
410 magnetostriction strain. These latter quantities are used
411 by Maxwell-tensor method to give body force
412 distributions, which in turn are converted into equivalent
413 surface stress distributions – to lighten the computational
414 burden – using a convenient method. Finally, this surface
415 distribution represents the source term in a problem of
416 elastic wave radiation.

417 The methods used in the various steps for solving the
418 overall problem of transduction by EMAT in
419 ferromagnetic media have already been validated
420 separately. In the present work, two fundamental
421 hypotheses (ISH and PMH) are made. Elements of their
422 experimental validation are given in the next section to
423 strengthen the proposed overall solution.

424

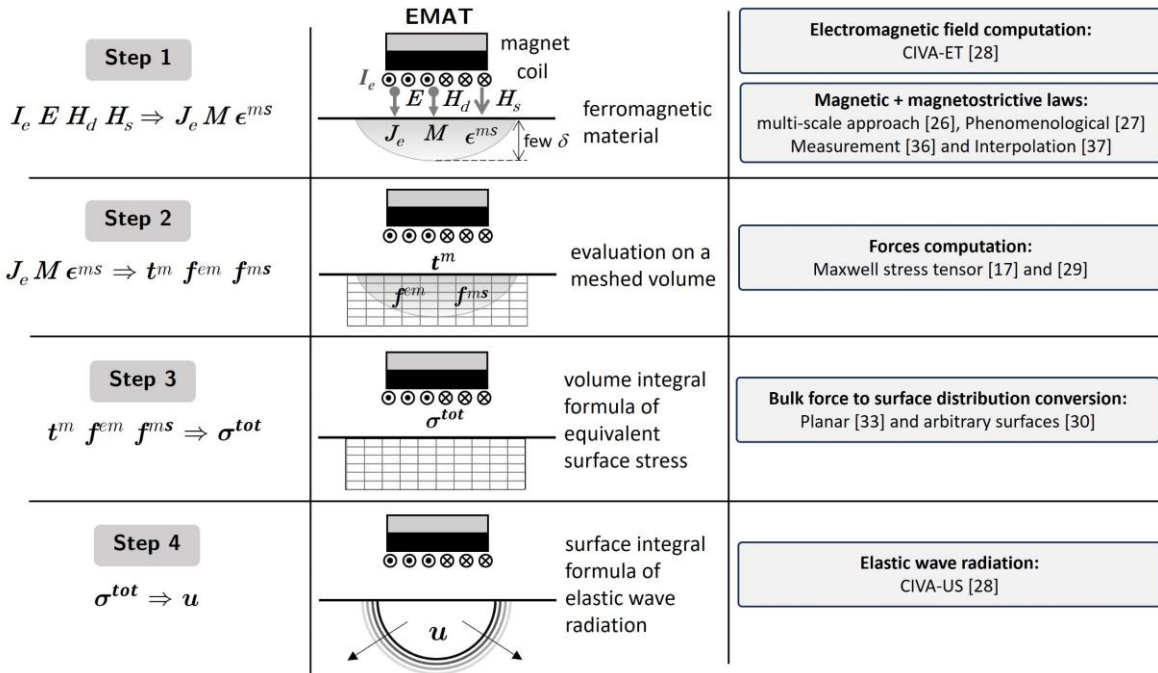


Fig. 1. Schematic representation of the four-step solution of the problem of EMAT generation of elastic wave in ferromagnetic materials. Where the inputs, outputs methods and models of each step alongside their corresponding references are recalled. 1: Computing induced eddy currents, magnetization, and magnetostriction strain. 2: Computing bulk forces distributions. 3: Converting bulk force distributions to surface force distribution. 4: Computing radiated elastic waves.

426 3. Experimental validations

427 The first two subsections of this section treat the validity
 428 of infinitesimal strain and piezomagnetic hypotheses. The
 429 third presents some experimental validation of the overall
 430 model. Obviously, fully validating a multiphysics model as
 431 that presented herein is not conceivable, considering the
 432 number of parameters involved and their possible
 433 interdependence. In what follows, the EMAT used (see
 434 Fig.2) is composed of three parts: (a) a circular spiral
 435 copper coil (electric conductivity 60 MS/m) of 13 turns,
 436 45 mm outer diameter, 3 mm inner diameter, and
 437 0.34 mm² wire section (b) two NdFeB (electric
 438 conductivity 106 S/m) cylindrical magnets of diameter
 439 50 mm, each of 6-mm-height and of normal magnetic
 440 induction 1.33 T (at the center) and (c) a cylindrical steel
 441 block (properties given in Table.1) of diameter 50 mm
 442 and height 45 mm. It was observed experimentally and
 443 shown through simulation that using the cylindrical block
 444 increased the amplitude of the generated wave as a result
 445 of the overall increase in the radiated magnetic field
 446 magnitude.

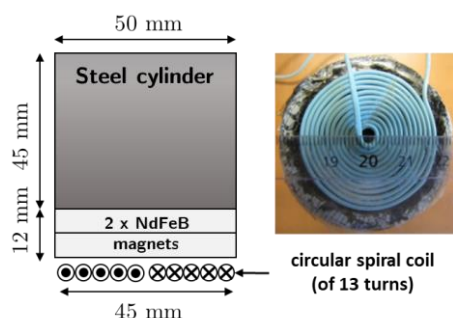


Fig. 2. The EMAT is composed of a circular spiral coil, two NdFeB cylindrical magnets, and a cylindrical steel block.

447 3.1. Infinitesimal strain hypothesis (ISH)

448 The EMAT induces both static and dynamic phenomena
 449 in FM materials. The former stems from the magnet that
 450 exerts a magnetic force and induces a magnetostriction
 451 strain in the material. The latter results from the EM fields
 452 radiated by the coil. Their magnitudes depend on material
 453 properties (elastic, magnetic, and magnetostrictive) and
 454 on electrical excitation. The ISH (needed in the
 455 development of the solution for the wave generation
 456 problem) assumes such deformations to be sufficiently

457 small for the computation of EM fields on the undeformed
 458 shape – of the test piece – to give accurate results.
 459 Because induced EM fields in materials are not measured
 460 directly, we compare measured and computed (by CIVA-
 461 ET) *induced electromotive forces* (EMF) to validate ISH. Two
 462 configurations are studied, in both, the experimental setup
 463 is identical to that in Fig.5 (without the water tank and
 464 PZT sensor). In the first (resp. the second) the EMAT is
 465 placed above a steel (resp. aluminum) test piece at a
 466 distance of 4 mm. In both cases, the current in the coil is
 467 a pulse of 2 MHz center frequency shown on Fig.3a. A
 468 small 2-turn coil (of section 23.8 mm²) is used to measure
 469 the induced EMF, from which the electromagnetic
 470 induction B_d is deduced. This coil is placed between the
 471 EMAT and the test piece and can be moved horizontally
 472 (*i.e.*, parallel to the coil plane). A Rogowski coil is also used
 473 to measure the current in the EMAT coil, this signal being
 474 used in CIVA-ET to compute EM fields. Results from this
 475 experiment are given in Fig.3.b (for steel) and Fig.3.c (for
 476 aluminum). The material properties of each test piece are
 477 given in Table 1. All measurements are made by moving
 478 the 2-turn coil along the EMAT coil diameter and
 479 maintaining its distance from the test piece at 1.5 mm.
 480 $B_d(t)$ signal (not shown) is similar to that of current
 481 (Fig.3a). Figures 3.b and 3.c show the results for
 482 $\max_t |B_d(t)|$ at each position.

Table 1. EM properties for the two test pieces.

Test piece	Steel	Aluminum
Electric conductivity (MS/m)	11.2	35
Relative magnetic permeability	100	1

483

484 Maximum values correspond to EMAT coil center, while
 485 null values correspond to its edges, where the magnetic
 486 field is predominantly horizontal. Beyond the edges, the
 487 normal component of the magnetic field is again
 488 predominant. A little further from the coil, EM fields
 489 vanish. The very good agreement between measured and
 490 simulated signals (assuming ISH) proves the ISH to be
 491 valid in this configuration. As a result, both problems – of
 492 electromagnetic nature – treated in step 1 and 2 can be
 493 dealt with separately from the problems – of
 494 elastodynamic nature – treated in step 3 and 4. Such
 495 separation allows the use of two different *specialized*
 496 numerical solvers (*i.e.*, CIVA-ET and CIVA-UT).

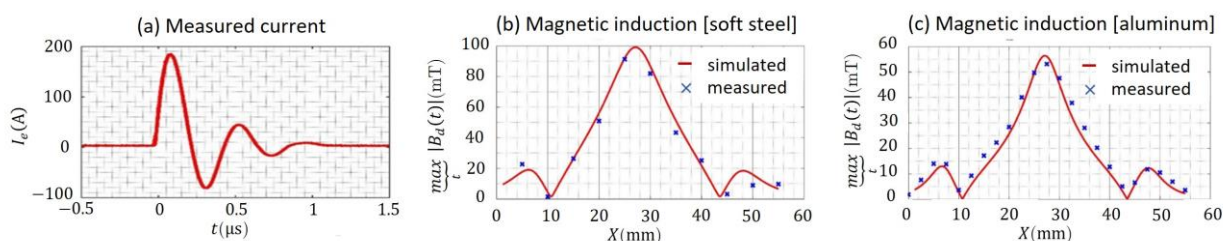


Fig.3. (a) current circulating in the EMAT coil. (b) (resp (c)) comparison of measured and simulated EM induction for different spatial positions along the diameter of the coil (centered at $x = 27.5$ mm, $y = 0$ mm and $z = 4$ mm), the sensor is at $z = 1.5$ mm of the steel (resp. aluminum) sample surface.

497

498 3.2. Piezomagnetic hypothesis (PMH)

499 EMAT induces static (due to the magnet) and dynamic
500 (due to the coil) magnetic fields in FM materials. The
501 PMH assumes the latter to be sufficiently smaller than the
502 former so that the dynamic problem can be treated as a
503 perturbation of the static one. To validate the PMH, we
504 take the example of a test piece (a cylinder of 70 mm
505 diameter and 147 mm height) made of Z20C13 stainless
506 steel. Measured anhysteretic magnetization and
507 magnetostriction curves are given in Fig.4. To avoid issues
508 stemming from EMAT wave detection and to concentrate
509 on wave generation, a focused piezoelectric transducer
510 (PZT) from Olympus Panametrics of 5.5cm focal length
511 and 2MHz central frequency is used for detection. A
512 calibration experiment whose results are not shown helped
513 identify the current range for which the EMAT generates
514 detectable signals. Although sensitive only to the normal
515 displacement component, the focused PZT can detect
516 shear waves due to their oblique incidence. In other words,
517 due to the size of the sample, the S-wavefront is still
518 spherical when it reaches the bottom surface. It has,
519 therefore a normal component which can be detected by
520 the sensor. The experiment is schematized in Fig.5. The
521 EMAT, the test piece and the PZT are of cylindrical shape
522 and are axisymmetrical relatively to the same axis. The
523 distance between the PZT and the bottom surface of the
524 test piece is maintained at 50mm (equal to the PZT focal
525 distance). The lower half of the test piece and the PZT
526 are immersed in a water tank. A Rogowski coil is used to
527 measure the current I_e (5 cycles of 1 MHz) from the signal
528 generator to the EMAT coil. The lift-off is maintained at
529 4 mm. Such configuration generates both longitudinal (L)
530 and shear (S) bulk waves in FM materials.

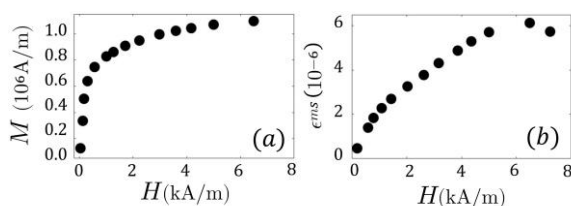


Fig.4. Measured magnetization (a), and magnetostriction (b) as functions of the magnetic field for Z20C13.

531 To reduce noise, measured signals were averaged over 256
532 shots. Throughout the present document, longitudinal and
533 shear waves were separated experimentally using their
534 time-of-flight while the simulation tool for field
535 computation (CIVA) is semi-analytical and modal, thus,
536 gives access to their respective fields separately. It is worth
537 noting that in order to compare the signal shapes, all
538 signals were normalized, and measured signals were time-
539 shifted. This allowed superimposing simulated and

540 measured results. The good agreement (Fig.6. (a), (b),
541 (c) and (d)) indicates that no harmonics were generated,
542 which only happens if the PMH is valid. Note that the
543 relatively larger amplitude of the second peak in Fig.d is
544 most likely due to numerical reasons.

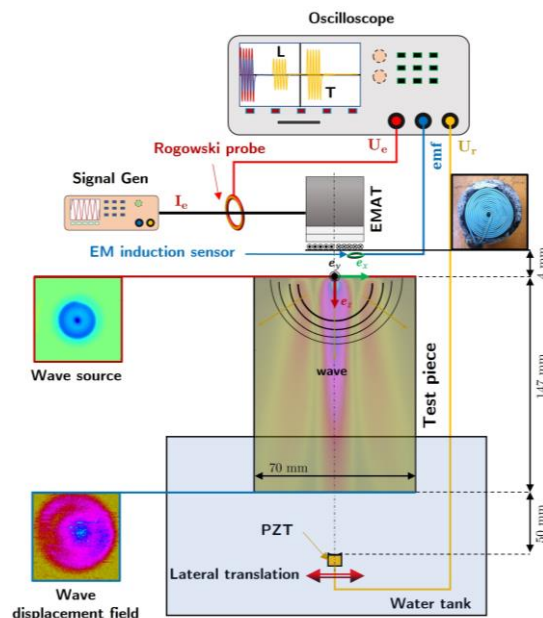


Fig.5. EMAT is placed above the test piece. The current from the signal generator to the EMAT coil is measured by a Rogowski coil. A focused PZT placed beneath the test piece is used for wave detection.

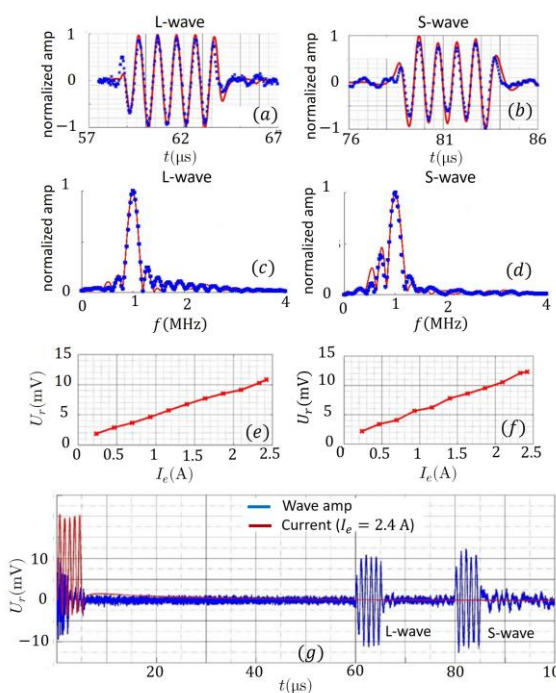


Fig.6. (a) and (b): comparison of measured (blue marker) and simulated (red solid line) time signals for both L and S bulk waves for $I = 2.42A$. (c) and (d): the Fourier transform of the time signals. (e) and (f): the maximum (measured) amplitude of L and S waves as function of current. (g): measured electric current in the excitation coil and the voltage in the PZT sensor.

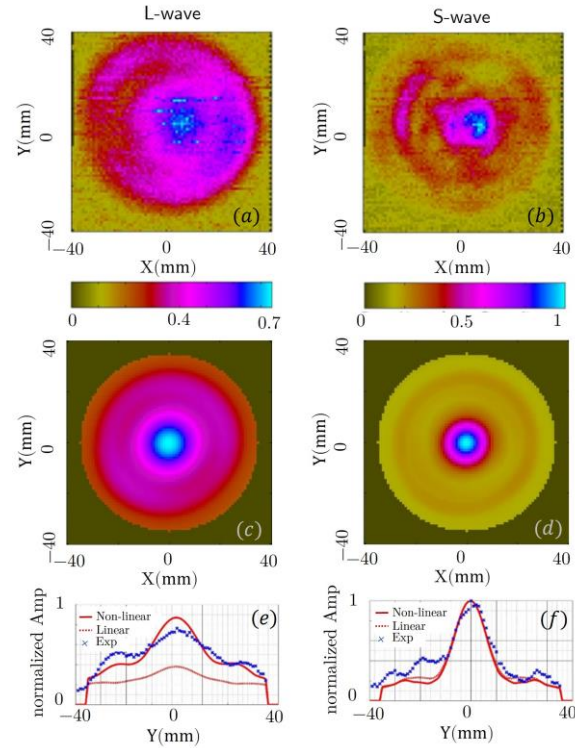


Fig.7. (a) and (b) (resp (c) and (d)): experimental (resp simulated) C-scans for L-wave and S-wave. (e) and (f): comparison of measured (blue markers) and simulated field amplitudes using non-linear (solid red line) and linear (dotted red line) magnetic constitutive laws.

545 To further consolidate this, the maximum amplitudes of
 546 measured signals for both L and S waves as functions of
 547 I_e are given in Fig.6 (e) and (f). One notices a linear
 548 relationship between wave amplitudes and I_e . The latter
 549 is proportional to H_d (Maxwell-Ampère) in consequence,
 550 a similar linear relationship must also exist between H_d
 551 and wave generation mechanisms, which is exactly what
 552 PMH predicts (see Eq.6-8). Finally Fig.6g gives the time
 553 signal of the excitation current and measured voltages by
 554 the PZT sensor. The observed DC offset in current is due
 555 to the excitation systems, it doesn't however effect the
 556 validity of the hypothesis. In conclusion, these results
 557 suggest that higher orders of H_d that would lead to a
 558 nonlinear relationship between current and elastic wave
 559 amplitudes and would distort the time signal are
 560 negligible, thereby consolidating the validity of PMH.

561 3.3. L and S generation and radiation in FM materials

562 Now that both the ISH and PMH are verified, one can
 563 study the ultrasonic field associated with bulk waves of
 564 both polarities radiated by EMAT. For this, the
 565 experimental setup is the same as in the previous
 566 subsection, with the difference that here I_e is maintained
 567 at 2.42 A and the PZT is moved to scan the bottom
 568 surface of the test piece. Regarding the simulation, both
 569 nonlinear (given in Fig.4a) and linear (given by the slope
 570 at the origin of curve in Fig.4a) magnetic constitutive laws
 571 were used. Measured (resp simulated) C-scans (maximum
 572 amplitude of the wave displacement field at each scanning
 573 position) for both L and S waves are presented in Fig.7
 574 (a) and (b) (resp Fig.7 (c) and (d)). A comparison of
 575 simulated and measured results along the test piece
 576 diameter is given in Fig.7 (e) and (f). All results are
 577 normalized using their respective S wave amplitude at the
 578 center of the test piece.

579 The dissymmetry in experimental measurements comes
 580 from that of the coil. The return wire starts from the coil
 581 center and crosses its section: this causes it to tilt (see
 582 Fig.5), thereby breaking the symmetry. This is evidenced
 583 by the slight shift (to the right) of the central blue spot.
 584 Secondary lobes around $\pm 27 mm$ are also present in the
 585 measurements. These are not predicted by simulation
 586 using linear magnetic constitutive laws but are predicted
 587 when using nonlinear laws. Moreover, the former
 588 simulation underestimates the L wave amplitudes along
 589 the diameter, contrary to the latter.

590 4. Parametric studies on EMAT wave generation 591 mechanisms

592 As stated in Sec.2 EMAT generates waves through three
 593 mechanisms: Lorentz force, magnetic force (both volume
 594 and surface), and magnetostriction strain. Whilst this is
 595 well established in the literature (Thompson [24]), no
 596 work, to the best of our knowledge, has considered all
 597 three mechanisms together, and no studies were carried
 598 out to compare these mechanisms to each other, in
 599 different configurations. Such comparison offers important
 600 information that should be considered in designing EMAT
 601 and interpreting measurements made in ferromagnetic
 602 media.

603 Due to the prohibitive number of inputs in an EMAT
 604 experiment (shapes of the coil(s) and magnet(s), current

605 intensity and frequency, lift-off, material properties, ...), it
 606 is extremely difficult to rely solely on the experiment to
 607 carry out parametric studies. Conversely, simulation offers
 608 both the speed and flexibility required to do so. The
 609 present section is divided as follows: In Sec. 4.1 WGMs
 610 and their corresponding radiated waves are studied as
 611 functions of material properties. In Sec. 4.2 they are
 612 studied as functions of EMAT excitation (*i.e.*, the current
 613 in the coil and the static magnetic field of the magnet).

614 4.1. WGMs as functions of material properties

615 Four materials (nickel, Z20C13, AISI410, and low carbon
 616 steel (LCS)) of similar elastic but contrasting
 617 electromagnetic properties are studied. Magnetic
 618 constitutive laws ($\mathbf{M}(\mathbf{H})$) are assumed linear. This
 619 assumption – not the most suitable to accurately describe
 620 experimental data in some cases (see Fig.7) – allows for
 621 consequential computational simplification, which is
 622 needed to carry out parametric studies. Moreover,
 623 nonlinearity is not required to prove the premise of the
 624 paper (*i.e.*, all WGMs should be included when designing
 625 an EMAT). In both subsections, magnetostrictive
 626 constitutive laws are obtained from various approaches.
 627 SMSM [26] was used for the anhysteretic curve of nickel.
 628 It is measured for that of Z20C13 [37]. The
 629 phenomenological approach [27] was used to that of
 630 AISI410. Finally, the curve of LCS was obtained by
 631 interpolating the corresponding curve appearing in Hirao
 632 and Ogi [38]. These curves are shown in Fig.8.
 633 Throughout this subsection, current intensity and
 634 frequency are $I_e = 0.1$ A, and $f = 1$ MHz, and the normal
 635 magnetic induction of the magnet at its center is $B_z =$
 636 1.5 T. Sec.4.1.1 treats WGMs and Sec.4.1.2 their
 637 corresponding radiated waves.

Table 2. Material properties for the four FM materials.

Material	ρ (g/cm^3)	C_L (m/s)	C_T (m/s)	σ_e (MS/m)	μ_i
LCS	7.8	5900	3230	1.39	2
Z20C13	7.89	5790	3100	2	15
AISI410	7.67	5590	3000	2	10
Nickel	8.88	5630	2960	15.4	110

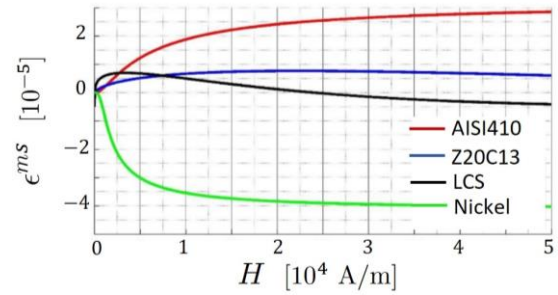


Fig.8. Anhysteretic magnetostrictive curves for nickel, low carbon steel, Z20C13 and AISI410.

638

639

640 4.1.1. $\sigma^{em}, \sigma^{ms}, t^m$ and σ^{tot}

641 The present EMAT would yield in nonmagnetic materials
 642 (where only Lorentz force (Lf) is present) a density
 643 distribution with a predominant tangential component. To
 644 illustrate this, the spatial distribution of WGMs given as
 645 equivalent surface stress distributions for LCS (the
 646 material with the weakest magnetic and magnetostrictive
 647 properties) are shown in Fig.9. The first column relates to
 648 the electromagnetic force, the second to magnetostriction,
 649 the third, to magnetic traction and the last represents the
 650 sum of all previous stress distributions. For a
 651 comprehensive illustration, each component is normalized
 652 using $\max(\max(\sigma_x^{tot}), \max(\sigma_y^{tot}), \max(\sigma_z^{tot}))$. A global
 653 look at LCS results shows – as expected – a little
 654 contribution to the total distribution (σ^{tot}) from
 655 magnetostriction and magnetic traction. As for the
 656 electromagnetic force, one can observe the dominance of
 657 tangential component, primarily due to Lorentz force (Lf).
 658 The magnetic nature of LCS is evidenced by the
 659 nonnegligible normal component σ_z^{em} , due to bulk
 660 magnetic force. We note that the ability to link tangential
 661 components of σ^{em} to Lf, and σ_z^{em} to bulk magnetic force
 662 stems from the fact that both coil and magnet have a
 663 predominant normal magnetic component. This material
 664 shows a case in which the predominant WGMs is the Lf.
 665 We note that it is nonetheless a mistake to consider only
 666 such force in this case since the magnetic bulk force,
 667 however small it may be, generates longitudinal waves
 668 that are almost not generated by tangential Lf (only by
 669 “edge diffraction” which would be nonnegligible only if the
 670 source distribution showed a sharp discontinuity
 671 (Lhémery [39])).

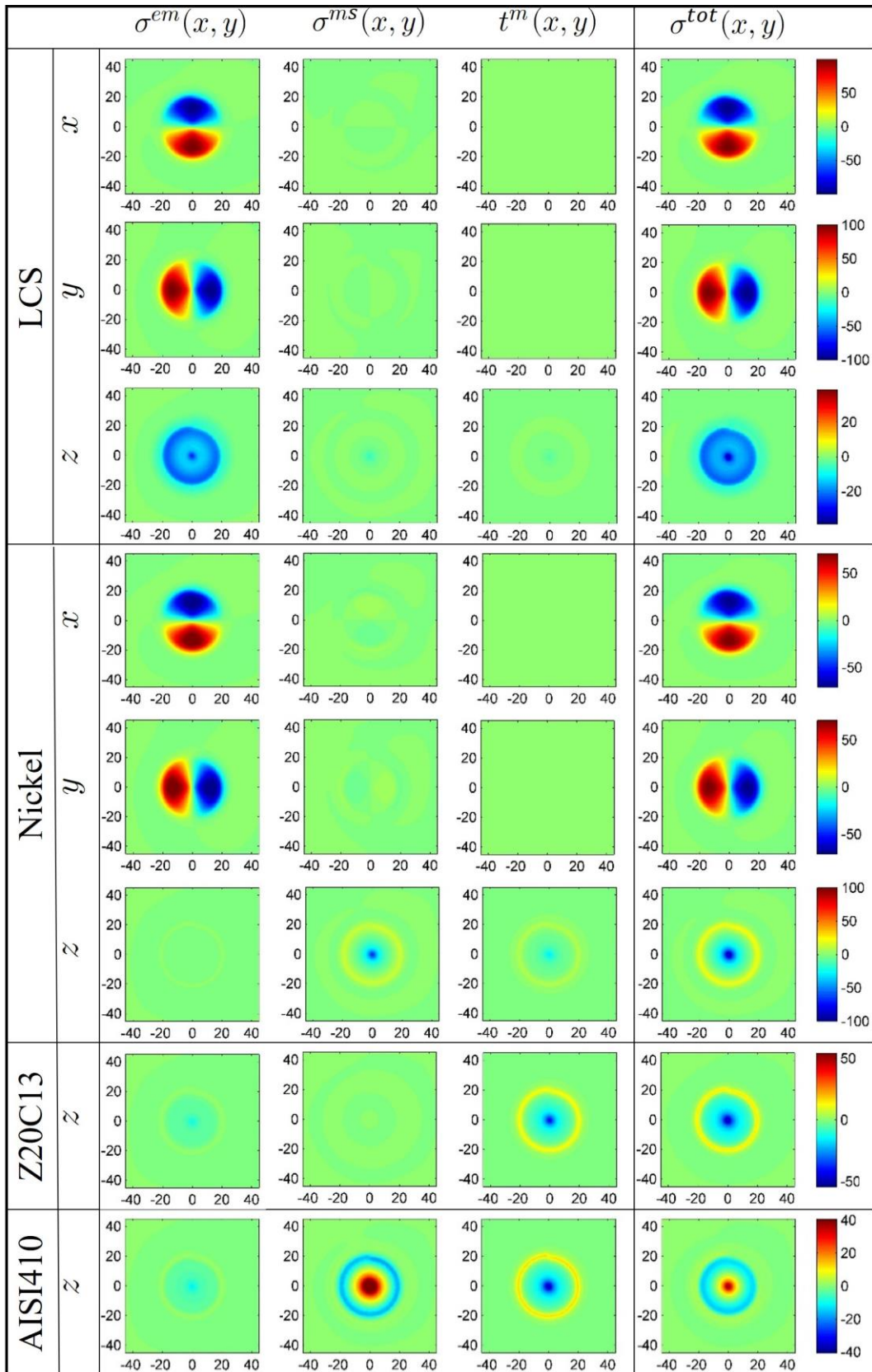


Fig.9. The three wave generation mechanisms for the four studied materials. (For each material) First column: electromagnetic force, second: magnetostriction equivalent force, third: magnetic traction and in the last: total force distribution. For a comprehensive illustration, each component is normalized using $\max(\max(\sigma_x^{tot}), \max(\sigma_y^{tot}), \max(\sigma_z^{tot}))$.

672

673 This point is discussed in more details in Sec.4.1.2.

675 has the strongest electric, magnetic, and magnetostrictive

674 Consider now the case of nickel (see Fig.9). This material

676 properties amongst the four studied materials. Expectedly

677 – from the EMAT geometry – tangential components of
 678 magnetic traction and magnetostriction are small
 679 compared to the electromagnetic force. Looking at σ^{em} ,
 680 one can see that the contribution of bulk magnetic force
 681 (which is primarily represented by σ_z^{em}) is small compared
 682 to that of Lorentz force (represented by $\sigma_{x,y}^{em}$). At first
 683 glance, this seems in contradiction to the fact that this
 684 material has the highest magnetic permeability. Actually,
 685 high permeability means, on the one hand, a high
 686 magnetic traction (as seen in the figure) but also a small
 687 skin depth, which in turn reduces the volume in which the
 688 *bulk* magnetic force operates. The small skin depth also
 689 affects Lorentz's force, which, in the present case, is
 690 slightly smaller than the equivalent force due to
 691 magnetostriction. The large value of the latter force is
 692 attributed to its relatively large magnetostriction strain
 693 (Fig.8). The example of nickel shows a case in which
 694 Lorentz force is no longer the dominant mechanism, and
 695 in contrast to the previous case, the normal component of
 696 the wave source (σ_z^{tot}) is mainly due to magnetostriction
 697 and magnetic traction (instead of the magnetic bulk force
 698 for LCS).

699 EMAT geometry and previous results (for LCS and nickel)
 700 suggest that magnetic and magnetostrictive properties
 701 manifest themselves mostly through the normal
 702 component of WGMs. On this account, for the last two
 703 materials (AISI 410 and Z20C13), only normal
 704 components are shown (in Fig.9), tangential components
 705 being dominated by Lorentz force. Unsurprisingly, the
 706 magnetic bulk force for both materials is relatively small
 707 due to the relatively higher permeability. As for the
 708 contribution to the normal component of the wave source
 709 (σ^{tot}), one sees that it is dominated by magnetic traction
 710 for Z20C13 (due to its relatively weak magnetostriction)
 711 and is almost evenly distributed between magnetostriction
 712 and magnetic traction for AISI410.

713 The unexpected negative magnetic traction stems from
 714 the dynamic problem (wave generation) being treated as
 715 a perturbation of the static one (with a given static
 716 magnetic traction). Therefore, when H_d opposes H_s , the
 717 material is *less* pulled towards the magnet, which
 718 translates into a traction smaller than that in the static
 719 (reference) problem, leading to a negative difference. This
 720 also applies to magnetostriction strain. Finally, the
 721 observed irregularity in the rotundity of the z-components
 722 is caused by the non-axisymmetric shape of the spiral
 723 coil.

724 In conclusion, an EMAT with a fixed excitation and
 725 geometry, would yield in different materials, WGMs with
 726 contrasting magnitudes. A dominant WGM in one
 727 material might be negligible in another one. Furthermore,
 728 due to the vectorial nature of WGMs and the fact that
 729 each elastic wave has a specific particle displacement, each
 730 WGM vectorial component needs to be studied separately.
 731 This point is treated in more detail in the next subsection.

732 4.1.2. Radiated elastic waves

733 Previous wave sources σ^{tot} (for each material) are now
 734 used by CIVA-UT to compute the radiated elastic field. In
 735 this simulation, the test piece is assumed to be semi-
 736 infinite and wave amplitudes are taken below the center
 737 of the EMAT at a depth of $z = 75$ mm. The time-
 738 dependent z-displacement waveforms at this point are
 739 shown in Fig.10. The first wave packet (with the shortest
 740 time of flight $\in [13,14]\mu s$) corresponds to the fastest
 741 wave, *i.e.*, the longitudinal wave (L). As expected, in LCS
 742 the dominant Lorentz force (mostly tangential) gives rise
 743 to a shear (S) wave amplitude larger than that of the
 744 longitudinal L-wave. In nickel, the dominant
 745 magnetostriction equivalent force (mostly normal) gives
 746 rise to an L-wave amplitude larger than that of the S-
 747 wave. For the two intermediate materials (AISI410 and
 748 Z20C13) both L and S waves are generated with similar
 749 magnitudes. Interestingly the L wave time signature seems
 750 to depend on the material, unlike that of the S wave.

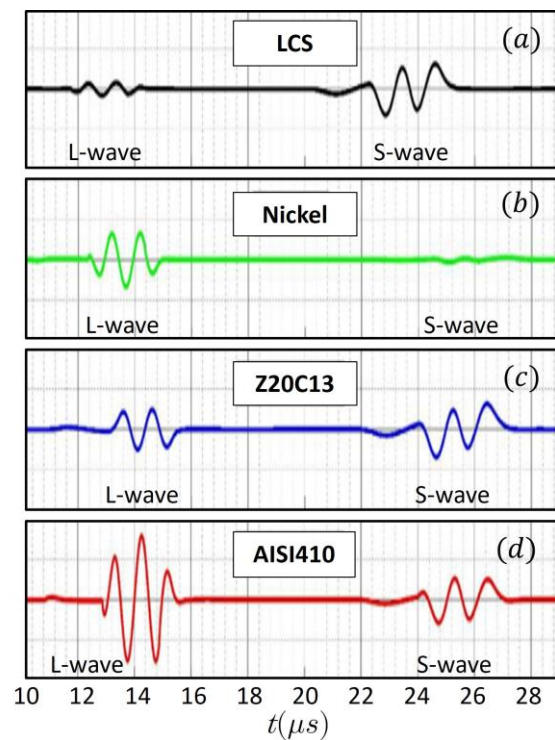


Fig.10. Time-dependent particle displacement L and S waves radiated in the four studied materials. The first packet (with the shortest time of flight $\in [13,14]\mu s$) corresponds to L wave.

751

752 To understand why this is so, one recalls that the latter is
 753 generated mostly by a single WGM (Lorentz force), while
 754 the former is generated by both magnetic force (bulk and
 755 surface) and magnetostriction. Such WGMs do not always
 756 have the same spatial distribution and can interact
 757 destructively, depending on the material magnetostriction
 758 properties.

759 Field maps (of maximum amplitude of a given quantity)
 760 are presented in Fig.11. Due to lack of space, and the
 761 intimate correlation between maps and previously studied
 762 WGMs spatial distributions, only results of AISI410 are
 763 shown. Each WGM and the total distribution were treated
 764 separately. Whilst S-wave maps show all WGMs to be
 765 dominated by EM force, those for L-wave have
 766 contributions of comparable magnitudes. Curiously EM-
 767 force treated separately leads to a displacement amplitude

768 (for S) larger than that of σ^{tot} ; this illustrates the fact
 769 that WGMs do not always interact constructively. The
 770 present result further confirms the assertion that the rule
 771 when designing an EMAT or trying to understand EMAT
 772 measurements is to evaluate each generation mechanism
 773 contribution and compare their respective vectorial
 774 components, as each component can give rise to a
 775 different wave type.

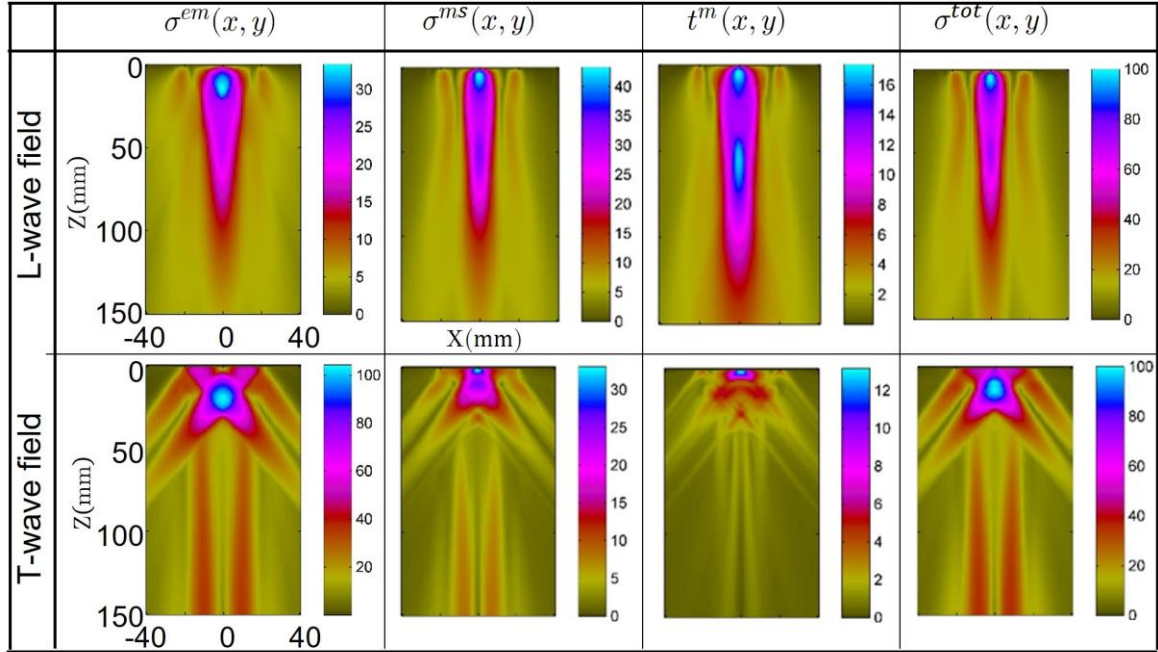


Fig.11. Field maps of L and S waves radiated by the EMAT in AISI410. First to fourth column: $\sigma^{em}, \sigma^{ms}, t^m, \sigma^{tot}$.

776

777 4.2. Influence of EMAT excitation

778 In this subsection, we are interested in WGMs as functions
 779 of EMAT excitation (I_e and B_{sz}). Given that in the present
 780 EMAT configuration, magnetic and magnetostrictive
 781 properties manifest themselves mostly through the normal
 782 component of WGMs, only this component is considered,
 783 for $I_e \in [0; 100]$ A and $B_{sz} \in [0; 4]$ T, while the frequency
 784 is kept constant and equal to 1 MHz. The normalized
 785 maximum amplitude of each WGM is plotted as a function
 786 of I_e for LCS in Fig.12a, and as function of B_{sz} for LCS
 787 in Fig.12b, for Ni in Fig.12c, and for Z20C13 in Fig.12d.
 788 The linear dependency of these maxima on current
 789 intensity is expected since the model was developed under
 790 the hypothesis of piezomagnetic behavior. Such an
 791 assumption is valid even at high intensities, as shown by
 792 Fig.2, (for $I_e = 175$ A). This is also the case for the rest
 793 of the materials, however, due to the lack of space, only
 794 one material is presented here. The normal dynamic
 795 magnetic induction is around 100 mT, which is fifteen
 796 times smaller than that of the static one. This linear
 797 dependency was also observed for the other materials
 798 (whose results are not shown). For the material with the
 799 weakest magnetic and magnetostrictive properties (LCS),
 800 the electromagnetic force – specifically Lorentz force –

801 dominates. Looking now at Fig.12b, one notices that
 802 magnetostriction WGM decreases non-linearly with
 803 increasing B_{sz} . This is due to the nonlinear
 804 magnetostrictive behavior (Fig.8), which shows that for
 805 high B_{sz} , magnetostriction saturates, leading to $d^{ms} = \mathbf{0}$
 806 (see Eq.4). The divergence at low B_{sz} is due to PMH being
 807 invalid in this region. For this material (weak magnetic
 808 properties), electromagnetic WGM – specifically Lorentz
 809 force – dominates that of magnetic traction. The cases of
 810 nickel (Fig.12c) and Z20C13 (Fig.12d) have similar
 811 tendencies. The former shows, once again, that high
 812 magnetic permeability and electric conductivity do not
 813 necessarily lead to strong electromagnetic force, because
 814 of the relatively small skin depth. The latter shows that
 815 WGMs do not always interact constructively, as evidenced
 816 by the dip of σ_z^{tot} (below σ_z^{ms}) at around $B_{sz} = 0.7$ T.

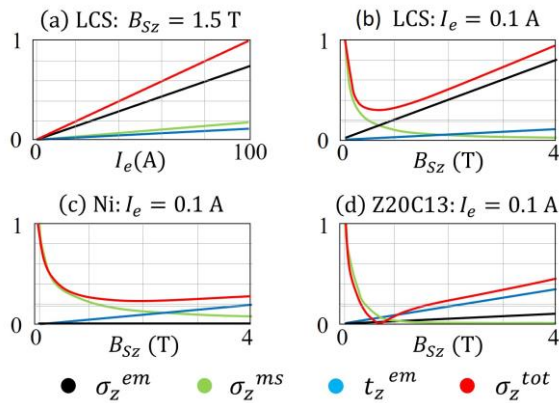


Fig.12. Maximum amplitudes for each WGM for three different materials (LCS, Ni, and Z20C13), as functions of current intensity (a), and static magnetic induction (c) LCS, (d) Ni and (d) Z20C13.

817

818 Present results showed that assuming linear magnetic
819 behavior is sufficient to prove the premise of the paper
820 (*i.e.*, wave generation mechanisms depended strongly on
821 material properties and on EMAT excitation). However,
822 this assumption may lead to inaccuracy, as seen in Fig.7
823 (Sec.3.3), since magnetic behavior is rarely linear.
824 Complementary studies were carried out considering
825 nonlinear behavior. Their conclusion regarding the premise
826 of the present work remains the same as that for linear
827 behavior.

828 5. Conclusion

829 A solution to the problem of elastic wave generation
830 (WGP) by EMAT in ferromagnetic materials has been
831 proposed. The tools used include magnetic and
832 magnetostrictive constitutive laws and numerical solvers
833 for both electromagnetic induction and elastic wave
834 radiation problems. The overall method is based on the
835 two fundamental hypotheses of infinitesimal strain and
836 piezomagnetic behavior. Both hypotheses were verified by
837 experiments. The overall model was used to assess the
838 validity of the premise of this paper, that all WGMs
839 (electromagnetic force, magnetostriction strain, and
840 magnetic traction) should be considered when designing
841 an EMAT for applications involving ferromagnetic media,
842 as none is always negligible. To this end, parametric
843 studies were carried out to evaluate WGMs as functions
844 of material properties and EMAT excitation. For a given
845 EMAT, various excitations and four ferromagnetic
846 materials with contrasting electromagnetic properties
847 (nickel, AISI410, Z20C13, and low-carbon steel) were
848 considered. These studies lead to the conclusion that
849 WGMs depend greatly on material properties and EMAT
850 excitation. A combination of material properties and
851 excitation yields a predominant WGM that is negligible for
852 another combination.

853 The proposed method to solve WGP offers a framework
854 to predict WGMs as functions of material properties,

855 EMAT geometry, and excitation. Such predictions are
856 required in EMAT design for optimal elastic wave
857 radiation in ferromagnetic media. The method is readily
858 usable to deal with pre-stressed ferromagnetic materials,
859 which is the subject of future work.

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