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## GENERIC-MOTIVATED EXTENDED SYMPLECTIC NUMERICAL METHODS FOR DISSIPATIVE MECHANICAL SYSTEMS: A CONCRETE EXAMPLE AND GENERAL MESSAGES

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**Abstract.** The GENERIC (General Equation for the Non-Equilibrium Reversible-Irreversible Coupling) framework is used, first, to present the irreversible thermodynamical formulation of the Rayleigh potential, and, subsequently, to realize the dynamical equations of motion of a supercritical van der Waals fluid separated from the environment by a movable rigid piston. Motivated by the latter, a quasi-symplectic generalization of the symplectic Euler finite-difference numerical scheme is introduced for this setup. A remarkable advantage over the explicit Euler scheme regarding artificial numerical antidissipation is illustrated. The possibility of controlled artificial numerical damping is addressed. The quasi-symplectic scheme is proven to enable efficient simulation of the considerably nonlinear and sensitive processes near the liquid–vapour critical point. A numerically feasible quantitative measure of nonlinearity of time-dependent processes is introduced and applied.

*Mathematical Subject Classification:* 65L12, 65P10, 65Z05, 37M15

*Keywords:* Dynamics, irreversibility, finite-difference numerical methods

### 1. INTRODUCTION

For most dynamical systems, in particular nonlinear ones and dissipative ones, solutions are achievable only numerically. Numerical approximations result in a kind of distortion of the original system and introduce the possibility of

- artificial instability (when the solution diverges with exponentially increasing oscillation),
- dissipation or antidissipation error (energies and amplitudes artificially decreasing or increasing), and

- dispersion error (artificial oscillations emerging at sudden spatial or temporal changes).

Instability ruins the solution completely, artificial (anti)dissipation falsifies the true irreversible dissipation of the system, and true oscillations are difficult to distinguish from artificially emerging oscillations.

Choosing a higher-order numerical scheme may not help in these aspects – for instance, with the 4th-order Runge–Kutta method, energy gradually drifts away from the correct value (see, *e.g.*, [1, 2]) and so does the solution as well.

For reversible Hamiltonian systems, a well-established family of trustworthy numerical schemes is the so-called symplectic schemes (see, *e.g.*, [3]). These methods provide outstanding solutions for large simulated times, since a symplectic scheme actually provides the *exact* solution of a nearby Hamiltonian system. Seminal examples are the symplectic Euler method (the symplectic variant of the explicit Euler one), the Störmer–Verlet method, and the symplectic Runge–Kutta methods. The explicit leapfrog method, popular in molecular dynamics for example, is in fact the Störmer–Verlet method for a Hamiltonian in which kinetic energy depends on only some of the phase-space variables while the potential energy depends only on the rest of the variables.

For dissipative, irreversible, systems, the situation is much less developed (see, *e.g.*, [4]). Also, even for reversible cases it is frequently found advantageous to introduce some irreversibility to damp some of the degrees of freedom – those which only play a minor role in the solution but following which requires very fine discretization and, correspondingly, considerable computational resources. Accordingly, there is a multi-sided need for efficient numerical treatment of – artificially or inherently – irreversible situations.

Now, the native framework for treating irreversible systems is thermodynamics – where thermodynamics is understood in the modern dynamical sense. If a dissipative system is conceived in the whole thermodynamical picture, then one can avoid ad-hoc or partial solutions to the challenges and can have a globally consistent approach. Following the thermodynamics-related additional quantities extends the treatment to a consistent whole and, by monitoring what happens in regard of the Second Law of Thermodynamics, one can see the contribution of each degree of freedom to irreversibility.

Giving account of irreversibility, as well as its coupling to reversible, *e.g.*, mechanical, properties, has serious technological importance. Just one example is supercritical processes, where one can avoid the disadvantages of phase transition but must be careful when being above the critical point where the material possesses strong nonlinearities and sensitivities (see, *e.g.*, [5]).

The symplectic structure of Hamiltonian reversible systems, and thus the possibility to apply symplectic numerical methods, is lost for irreversible cases, but fortunately only partially. The framework running under the acronym GENERIC (which stands for General Equation for the Non-Equilibrium Reversible–Irreversible Coupling) [6–10] restores as much as possible.

Regarding numerical solutions, following a few pioneering works (see, *e.g.*, [11–13]), a program-announcing article is by Shang and Öttinger [14], where a strategy is introduced to preserve qualities from symplectic methods as much as possible, respecting the structure of GENERIC.

After our earlier works where thermodynamical consistency (for balances, state quantities, and the Second Law of Thermodynamics) and resulting benefits have been utilized for irreversible processes [15–18], here we take a further step by presenting a GENERIC-motivated quasi-symplectic numerical scheme.

We start with a presentation of GENERIC along the example of the Rayleigh potential. Next, we summarize the process-oriented dynamical viewpoint of thermodynamics. Then we present a dynamical setup involving a supercritical fluid and construct the GENERIC formulation of the problem. This is followed by more detailed information about symplectic numerical methods for reversible Hamiltonian systems. Then we introduce our quasi-symplectic scheme on our example setup. Four applications follow:

- comparison between the explicit Euler scheme and ours for the reversible but non-Hamiltonian case,
- a test of how the explicit Euler result can be improved via artificial damping,
- comparison of the quasi-symplectic numerical solutions without damping vs. with damping, and
- analysis of the nonlinearity of the process and the influence of the critical point.

Finally, various lessons are drawn in the Conclusion.

## 2. INTRODUCING GENERIC ALONG THE CASE OF THE RAYLEIGH POTENTIAL

We start with a simple illustration of how, from mechanics, one can arrive at GENERIC.

2.1. The motion of a point particle with mass  $m$  is described (with respect to an inertial reference frame) by its position vector  $\mathbf{r}$  as the function of time  $t$ , its velocity  $\mathbf{v}$  is related to the motion as  $\mathbf{v}(t) = \frac{d\mathbf{r}}{dt}$ , the momentum of the particle is defined as

$$\mathbf{p} = m\mathbf{v}, \quad (2.1)$$

and its kinetic energy is

$$K = \frac{m}{2}\mathbf{v}^2 = \frac{1}{2m}\mathbf{p}^2. \quad (2.2)$$

Under the influence of a force field  $\mathbf{F}(\mathbf{r})$ , the motion of the particle satisfies, according to Newton's law:

$$m \frac{d^2\mathbf{r}}{dt^2} = \mathbf{F}(\mathbf{r}), \quad m \frac{d\mathbf{v}}{dt} = \mathbf{F}(\mathbf{r}), \quad \frac{d\mathbf{p}}{dt} = \mathbf{F}(\mathbf{r}). \quad (2.3)$$

Consequently, along a motion, kinetic energy turns out to fulfil

$$\frac{dK}{dt} = \mathbf{F}(\mathbf{r})\mathbf{v} = \mathbf{F}(\mathbf{r})\frac{d\mathbf{r}}{dt}; \quad (2.4)$$

*i.e.*, the rate of change of the kinetic energy equals the power exerted by the force.

In case of a conservative force field, *i.e.*, when  $\mathbf{F}$  can be connected to the gradient of a potential as  $\mathbf{F}(\mathbf{r}) = -\frac{dU}{d\mathbf{r}}$ , we have, along a motion,

$$\frac{d\mathbf{p}}{dt} = -\frac{dU}{d\mathbf{r}}, \quad (2.5)$$

where  $\frac{d\cdots}{d\mathbf{r}}$  denotes the gradient with respect to the vector variable  $\mathbf{r}$ , together with

$$\frac{dK}{dt} = -\frac{dU}{d\mathbf{r}} \frac{d\mathbf{r}}{dt} = -\frac{dU(\mathbf{r}(t))}{dt} \implies \frac{d(K+U)}{dt} = 0. \quad (2.6)$$

In other words, mechanical energy,  $E_{\text{mech}} = K + U$ , is conserved along a motion.

2.2. Since this is a conservative system, its Newtonian description admits an equivalent formulation based on the Lagrangian

$$L(\mathbf{r}, \mathbf{v}) = K(\mathbf{v}) - U(\mathbf{r}) : \quad (2.7)$$

the Newtonian equation of motion (2.3) is equivalent to that, along a motion,

$$\frac{d}{dt} \frac{\partial L}{\partial \mathbf{v}} = \frac{\partial L}{\partial \mathbf{r}} \quad (2.8)$$

(partial derivatives with respect to vectorial variables still denoting the appropriate gradients), understood together with  $\mathbf{v}(t) = \frac{d\mathbf{r}}{dt}$ .

Yet another equivalent formulation is based on the Hamiltonian (the Legendre transform of  $L$  in its second variable)

$$H(\mathbf{r}, \mathbf{p}) = \frac{\partial L}{\partial \mathbf{v}} \mathbf{v} - L = \mathbf{p} \mathbf{v} - L = K + U, \quad (2.9)$$

which actually embodies mechanical energy in the variables  $\mathbf{r}, \mathbf{p}$ . In this version, the motion satisfies the set of first-order differential equations

$$\left. \begin{aligned} \frac{d\mathbf{r}}{dt} &= \frac{\partial H}{\partial \mathbf{p}}, \\ \frac{d\mathbf{p}}{dt} &= -\frac{\partial H}{\partial \mathbf{r}}, \end{aligned} \right\} \quad \text{which can also be written as} \quad \frac{d}{dt} \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \end{pmatrix} = \begin{pmatrix} \mathbf{0} & \mathbf{1} \\ -\mathbf{1} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \frac{\partial H}{\partial \mathbf{r}} \\ \frac{\partial H}{\partial \mathbf{p}} \end{pmatrix}, \quad (2.10)$$

where  $\mathbf{0}$  and  $\mathbf{1}$  are the zero and unit tensor, respectively. For the collection of variables  $\mathbf{x}$ , and with  $\mathbf{\Omega}$ , introduced respectively as

$$\mathbf{x} = \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \end{pmatrix}, \quad \mathbf{\Omega} = \begin{pmatrix} \mathbf{0} & \mathbf{1} \\ -\mathbf{1} & \mathbf{0} \end{pmatrix}, \quad \text{and with the consequence} \quad \frac{dH}{d\mathbf{x}} = \begin{pmatrix} \frac{\partial H}{\partial \mathbf{r}} \\ \frac{\partial H}{\partial \mathbf{p}} \end{pmatrix}, \quad (2.11)$$



(2.10) gains the compact form<sup>1</sup>

$$\frac{d\mathbf{x}}{dt} = \boldsymbol{\Omega} \frac{dH}{d\mathbf{x}}, \quad \text{rewritten for further purposes as} \quad \frac{d\mathbf{x}}{dt} = \boldsymbol{\Omega} \frac{dE_{\text{mech}}}{d\mathbf{x}}. \quad (2.12)$$

2.3. Now let us have an additional, damping-type, force, which is proportional to velocity: then the total force is

$$\mathbf{F}_{\text{tot}} = -\frac{dU}{d\mathbf{r}} - \xi \mathbf{v} = -\frac{dU}{d\mathbf{r}} - \frac{\xi}{m} \mathbf{p} \quad (2.13)$$

with positive constant coefficient  $\xi$ . In this case, mechanical energy is not conserved but is dissipated (decreases) along processes:

$$\frac{dE_{\text{mech}}}{dt} = \frac{d(K + U)}{dt} = \mathbf{F}_{\text{tot}} \mathbf{v} + \frac{dU}{d\mathbf{r}} \frac{d\mathbf{r}}{dt} = -\frac{dU}{d\mathbf{r}} \mathbf{v} - \xi \mathbf{v}^2 + \frac{dU}{d\mathbf{r}} \mathbf{v} = -\xi \mathbf{v}^2 = -\frac{\xi}{m^2} \mathbf{p}^2. \quad (2.14)$$

2.4. Motivated by the benefits of writing a conservative force as a gradient, following Rayleigh, let us write the damping force  $-\xi \mathbf{v}$ , with the aid of the dissipation potential

$$D = \frac{\xi}{2} \mathbf{v}^2 = \frac{\xi}{2m^2} \mathbf{p}^2, \quad (2.15)$$

also as a gradient – now a gradient with respect to velocity; hence, Newton's equation reads

$$m \frac{d\mathbf{v}}{dt} = \mathbf{F}(\mathbf{r}, \mathbf{v}) = -\frac{dU}{d\mathbf{r}} - \frac{dD}{d\mathbf{v}}. \quad (2.16)$$

The two other equivalent formulations now read

$$\frac{d}{dt} \frac{\partial L}{\partial \mathbf{v}} = \frac{\partial L}{\partial \mathbf{r}} - \frac{dD}{d\mathbf{v}}; \quad (2.17)$$

$$\begin{aligned} \frac{d\mathbf{r}}{dt} &= \frac{\partial E_{\text{mech}}}{\partial \mathbf{p}}, \\ \frac{d\mathbf{p}}{dt} &= -\frac{\partial E_{\text{mech}}}{\partial \mathbf{r}} - \frac{dD}{d\mathbf{v}} = -\frac{\partial E_{\text{mech}}}{\partial \mathbf{r}} - m \frac{dD}{d\mathbf{p}}. \end{aligned} \quad (2.18)$$

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<sup>1</sup>As a comment,  $\boldsymbol{\Omega}$  is a so-called symplectic (*i.e.*, antisymmetric and nondegenerate) cotensor on the phase space – the set of possible values of the collection of variables  $\mathbf{x} = \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \end{pmatrix}$  (which set is a six-dimensional vector space) – and induces a corresponding symplectic structure, a conserved (time-independent) antisymmetric nondegenerate two-cotensor field on the set of the solutions of (2.12) (which set is a six-dimensional smooth manifold).

The latter can be brought into a compact form analogous to (2.12):

$$\begin{aligned} \frac{d\mathbf{x}}{dt} &= \frac{d}{dt} \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \end{pmatrix} = \begin{pmatrix} \mathbf{0} & \mathbf{1} \\ -\mathbf{1} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \frac{\partial E_{\text{mech}}}{\partial \mathbf{r}} \\ \frac{\partial E_{\text{mech}}}{\partial \mathbf{p}} \end{pmatrix} - \begin{pmatrix} \mathbf{0} \\ \frac{\partial D}{\partial \mathbf{v}} \end{pmatrix} = \boldsymbol{\Omega} \frac{dE_{\text{mech}}}{d\mathbf{x}} - \begin{pmatrix} \mathbf{0} \\ m \frac{\partial D}{\partial \mathbf{p}} \end{pmatrix} \\ &= \boldsymbol{\Omega} \frac{dE_{\text{mech}}}{d\mathbf{x}} - \frac{d(mD)}{d\mathbf{x}}, \end{aligned} \quad (2.19)$$

which, for future purposes, is worth writing also as

$$\begin{aligned} \frac{d\mathbf{x}}{dt} &= \boldsymbol{\Omega} \frac{dE_{\text{mech}}}{d\mathbf{x}} - \frac{d}{d\mathbf{x}} \underbrace{\left[ \frac{1}{2} (\mathbf{r} \ \mathbf{p}) \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \frac{\xi}{m} \mathbf{1} \end{pmatrix} \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \end{pmatrix} \right]}_{mD} \\ &= \boldsymbol{\Omega} \frac{dE_{\text{mech}}}{d\mathbf{x}} - \frac{d}{d\mathbf{x}} \left[ \frac{1}{2} \mathbf{x}^{\text{transp}} \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \frac{\xi}{m} \mathbf{1} \end{pmatrix} \mathbf{x} \right]. \end{aligned} \quad (2.20)$$

The only aspect missing is a description of the conservation of energy. Namely, we can anticipate – and thermodynamical experience encourages us in this – that a certain total energy is still conserved and the lost mechanical energy is just converted into some other type of energy.

2.5. A minimal modification for this is that we assume a single further type of energy  $E_{\text{int}}$  (referring to “internal energy”) with which  $E_{\text{mech}} + E_{\text{int}}$  is conserved, and that the corresponding additional degree of freedom of the system is  $E_{\text{int}}$  directly. Namely, our collection of variables is increased to

$$\mathbf{x} = \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \\ E_{\text{int}} \end{pmatrix}, \quad (2.21)$$

with which total energy is

$$E_{\text{tot}}(\mathbf{x}) = K(\mathbf{p}) + U(\mathbf{r}) + E_{\text{int}}, \quad (2.22)$$

also implying

$$\frac{dE_{\text{tot}}}{d\mathbf{x}} = \begin{pmatrix} \frac{\partial E_{\text{tot}}}{\partial \mathbf{r}} \\ \frac{\partial E_{\text{tot}}}{\partial \mathbf{p}} \\ \frac{\partial E_{\text{tot}}}{\partial E_{\text{int}}} \end{pmatrix} = \begin{pmatrix} \frac{\partial U}{\partial \mathbf{r}} \\ \frac{\partial K}{\partial \mathbf{p}} \\ 1 \end{pmatrix} = \begin{pmatrix} \frac{\partial U}{\partial \mathbf{r}} \\ \frac{1}{m} \mathbf{p} \\ 1 \end{pmatrix}. \quad (2.23)$$

Along a motion,  $E_{\text{int}}$  is supposed to increase with the same rate  $E_{\text{mech}}$  decreases with: in virtue of (2.14),

$$\frac{dE_{\text{int}}}{dt} = \frac{\xi}{m^2} \mathbf{p}^2. \quad (2.24)$$

The question is whether we can also write the extended set of equations

$$\begin{aligned} \frac{d\mathbf{x}}{dt} &= \frac{d}{dt} \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \\ E_{\text{int}} \end{pmatrix} = \begin{pmatrix} \frac{\partial E_{\text{tot}}}{\partial \mathbf{p}} \\ -\frac{\partial E_{\text{tot}}}{\partial \mathbf{r}} - \frac{\xi}{m} \mathbf{p} \\ \frac{\xi}{m^2} \mathbf{p}^2 \end{pmatrix} = \underbrace{\begin{pmatrix} \mathbf{0} & \mathbf{1} & \mathbf{0} \\ -\mathbf{1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 0 \end{pmatrix}}_{\mathbf{L}} \begin{pmatrix} \frac{\partial E_{\text{tot}}}{\partial \mathbf{r}} \\ \frac{\partial E_{\text{tot}}}{\partial \mathbf{p}} \\ 1 \end{pmatrix} + \begin{pmatrix} \mathbf{0} \\ -\frac{\xi}{m} \mathbf{p} \\ \frac{\xi}{m^2} \mathbf{p}^2 \end{pmatrix} \\ &= \mathbf{L} \frac{dE_{\text{tot}}}{d\mathbf{x}} + \begin{pmatrix} \mathbf{0} \\ -\frac{\xi}{m} \mathbf{p} \\ \frac{\xi}{m^2} \mathbf{p}^2 \end{pmatrix} \end{aligned} \quad (2.25)$$

in some analogously geometric (differential geometric), gradient-based, form as the nonextended counterpart (2.20). This can be done in a somewhat implicit way:

$$\begin{pmatrix} \mathbf{0} \\ -\frac{\xi}{m} \mathbf{p} \\ \frac{\xi}{m^2} \mathbf{p}^2 \end{pmatrix} = \frac{d\Xi}{d\mathbf{x}^*} (\mathbf{x}^* = \frac{dE_{\text{int}}}{d\mathbf{x}}) \quad (2.26)$$

with

$$\Xi(\mathbf{x}^*) = \frac{1}{2} (\mathbf{x}^*)^{\text{transp}} \underbrace{\begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \xi \mathbf{1} & -\frac{\xi}{m} \mathbf{p} \\ \mathbf{0} & -\frac{\xi}{m} \mathbf{p} & \frac{\xi}{m} \mathbf{p}^2 \end{pmatrix}}_{\mathbf{M}} \mathbf{x}^*, \quad \frac{dE_{\text{int}}}{d\mathbf{x}} = \begin{pmatrix} \mathbf{0} \\ \mathbf{0} \\ 1 \end{pmatrix} \quad (2.27)$$

so a new auxiliary variable (namely,  $\mathbf{x}^*$ ) has to be involved, and the matrix  $\mathbf{M}$  that is the heart of the quadratic form  $\Xi$  is not constant but state dependent. Actually, although

$$\Xi\left(\frac{dE_{\text{int}}}{d\mathbf{x}}\right) = mD = \frac{\xi}{2m^2} \mathbf{p}^2 \quad (2.28)$$

as expected, the gradient has to be taken with respect to the auxiliary variable ( $\mathbf{x}^*$ ).

Here, for later purposes, it is useful to observe that the extended set of equations

$$\frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{tot}}}{d\mathbf{x}} + \frac{d\Xi}{d\mathbf{x}^*} (\mathbf{x}^* = \frac{dE_{\text{int}}}{d\mathbf{x}}) \quad (2.29)$$

can also be presented as

$$\frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{tot}}}{d\mathbf{x}} + \mathbf{M} \frac{dE_{\text{int}}}{d\mathbf{x}}. \quad (2.30)$$

2.6. A *constant* (state-independent) matrix  $\mathbf{M}$  and a *simpler* setup can be achieved if we rearrange the setup in such a way that our extended set of state variables is

$$\mathbf{x} = \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \\ E_{\text{tot}} \end{pmatrix} \quad (2.31)$$

and the relationship among the various energies (the constitutive relationship) is expressed as

$$E_{\text{int}}(\mathbf{x}) = E_{\text{tot}} - K(\mathbf{p}) - U(\mathbf{r}), \quad (2.32)$$

also implying

$$\frac{dE_{\text{int}}}{d\mathbf{x}} = \begin{pmatrix} \frac{\partial E_{\text{int}}}{\partial \mathbf{r}} \\ \frac{\partial E_{\text{int}}}{\partial \mathbf{p}} \\ \frac{\partial E_{\text{int}}}{\partial E_{\text{tot}}} \end{pmatrix} = \begin{pmatrix} -\frac{\partial U}{\partial \mathbf{r}} \\ -\frac{\partial K}{\partial \mathbf{p}} \\ 1 \end{pmatrix} = \begin{pmatrix} -\frac{\partial U}{\partial \mathbf{r}} \\ -\frac{1}{m}\mathbf{p} \\ 1 \end{pmatrix}. \quad (2.33)$$

In this variant, a simpler set of equations has to be realized:

$$\begin{aligned} \frac{d\mathbf{x}}{dt} &= \frac{d}{dt} \begin{pmatrix} \mathbf{r} \\ \mathbf{p} \\ E_{\text{tot}} \end{pmatrix} = \begin{pmatrix} -\frac{\partial E_{\text{int}}}{\partial \mathbf{p}} \\ \frac{\partial E_{\text{int}}}{\partial \mathbf{r}} - \frac{\xi}{m}\mathbf{p} \\ 0 \end{pmatrix} = \underbrace{\begin{pmatrix} \mathbf{0} & -\mathbf{1} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 0 \end{pmatrix}}_{\mathbf{L}} \begin{pmatrix} \frac{\partial E_{\text{int}}}{\partial \mathbf{r}} \\ \frac{\partial E_{\text{int}}}{\partial \mathbf{p}} \\ 1 \end{pmatrix} + \begin{pmatrix} \mathbf{0} \\ -\frac{\xi}{m}\mathbf{p} \\ 0 \end{pmatrix} \\ &= \mathbf{L} \frac{dE_{\text{int}}}{d\mathbf{x}} + \begin{pmatrix} \mathbf{0} \\ -\frac{\xi}{m}\mathbf{p} \\ 0 \end{pmatrix}; \end{aligned} \quad (2.34)$$

therefore, a simpler counterpart of (2.26) emerges, with a constant matrix  $\mathbf{M}$ :

$$\begin{pmatrix} \mathbf{0} \\ -\frac{\xi}{m}\mathbf{p} \\ 0 \end{pmatrix} = \frac{d\Xi}{d\mathbf{x}^*}(\mathbf{x}^* = \frac{dE_{\text{int}}}{d\mathbf{x}}) \quad \text{with} \quad \Xi(\mathbf{x}^*) = \frac{1}{2}(\mathbf{x}^*)^{\text{transp}} \underbrace{\begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \frac{\xi}{m}\mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 0 \end{pmatrix}}_{\mathbf{M}} \mathbf{x}^*. \quad (2.35)$$

We still have

$$\Xi\left(\frac{dE_{\text{int}}}{d\mathbf{x}}\right) = mD = \frac{\xi}{2m^2}\mathbf{p}^2, \quad (2.36)$$

and the set of equations

$$\frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{int}}}{d\mathbf{x}} + \frac{d\Xi}{d\mathbf{x}^*}(\mathbf{x}^* = \frac{dE_{\text{int}}}{d\mathbf{x}}) \quad (2.37)$$

also has a simpler equivalent:

$$\frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{int}}}{d\mathbf{x}} + \mathbf{M} \frac{dE_{\text{int}}}{d\mathbf{x}}. \quad (2.38)$$

2.7. Actually, our special system admits an exceptionally direct special realization as well:

$$\begin{pmatrix} \mathbf{0} \\ -\frac{\xi}{m}\mathbf{p} \\ 0 \end{pmatrix} = -\frac{d\Xi}{d\mathbf{x}} \quad \text{with} \quad \Xi(\mathbf{x}) = \frac{1}{2}\mathbf{x}^{\text{transp}} \underbrace{\begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \frac{\xi}{m^2}\mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 0 \end{pmatrix}}_{\mathbf{M}} \mathbf{x} = mD = \frac{\xi}{2m^2}\mathbf{p}^2, \quad (2.39)$$

$$\frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{int}}}{d\mathbf{x}} - \frac{d\Xi}{d\mathbf{x}}, \quad \frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{int}}}{d\mathbf{x}} - \mathbf{M}\mathbf{x}. \quad (2.40)$$

Such an extraordinarily simple formulation is not available for most other dissipative systems.

In fact, damping proportional to velocity is a distinguished case that permits a number of other special treatments as well, including [19, 20] (via a time-dependent Hamiltonian), [21] (a family generalizing the former one including a time-independent, logarithmic, realization), [22, 23] (doubling the degrees of freedom to obtain a time-independent Lagrangian–Hamiltonian–variational formulation), and [24] (adding infinitely many degrees of freedom of harmonic oscillators). On one hand, these many possibilities may indicate that this special model can emerge from rather different physical reasons. On the other hand, these realizations are not robust – even minor generalizations of this model may exclude these peculiar possibilities, and the versions like [22–24] also require fine-tuned initial conditions on the additional degrees of freedom, possibly violating time-translation invariance (which the equation of motion itself possesses). Furthermore, most of these approaches try to minimize what we know about the additional means of energy storing while in most concrete situations thermodynamics does have specific knowledge about them, and the complete model is richer than the damped mechanical part itself. Altogether, for general irreversible situations one needs more robust description.

2.8. The form seen in (2.38) is also special in a sense [compare it to (2.30)]: both matrices act on  $\frac{dE_{\text{int}}}{d\mathbf{x}}$  (so actually we can add  $\mathbf{L}$  and  $\mathbf{M}$ ) – this is typically called a one-generator formalism (the same only  $E_{\text{int}}$  is used in the two terms). Nevertheless, such a one-generator form can be established for most known dissipative systems [25]. What needs to be generalized, both in (2.38) and (2.30), is that, for dissipative systems in general, internal energy does not increase monotonously – it is a further constitutive function, entropy (more precisely, total entropy  $S_{\text{tot}}$ ) that increases monotonously. Accordingly, the general form of the set of equations is<sup>2</sup>

$$\frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{tot}}}{d\mathbf{x}} + \frac{d\Xi}{d\mathbf{x}^*} (\mathbf{x}^* = \frac{dS_{\text{tot}}}{d\mathbf{x}}), \quad \frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{tot}}}{d\mathbf{x}} + \mathbf{M} \frac{dS_{\text{tot}}}{d\mathbf{x}}. \quad (2.41)$$

This is the formulation known by the acronym GENERIC [6–10]. The general standard requirements on the GENERIC form [8],

$$\mathbf{L}^{\text{transp}} = -\mathbf{L} \quad (\text{antisymmetry of } \mathbf{L}), \quad (2.42)$$

$$\mathbf{M}^{\text{transp}} = \mathbf{M} \quad (\text{symmetry of } \mathbf{M}), \quad (2.43)$$

$$\mathbf{L} \frac{dS_{\text{tot}}}{d\mathbf{x}} = \mathbf{0}, \quad \mathbf{M} \frac{dE_{\text{tot}}}{d\mathbf{x}} = \mathbf{0} \quad (\text{transversality conditions}), \quad (2.44)$$

$$\sum_l \left( L_{il} \frac{\partial L_{jk}}{\partial x_l} + L_{jl} \frac{\partial L_{ki}}{\partial x_l} + L_{kl} \frac{\partial L_{ij}}{\partial x_l} \right) = 0 \quad (\text{Jacobi identity for } \mathbf{L}) \quad (2.45)$$

ensure that

- $E_{\text{tot}}$  is constant along any process allowed by (2.41),

---

<sup>2</sup>The second form looks a bit more general than the former but can be incorporated in the former via allowing  $\Xi = \Xi(\mathbf{x}, \mathbf{x}^*)$ .

- $S_{\text{tot}}$  increases along any process allowed by (2.41) except for equilibrium solutions (the stationary – time-independent – ones),
- the reversible part induces time evolution that preserves the  $\mathbf{L}$ -induced Poisson bracket as it happens for Hamiltonian systems (see more on this in [8]).

### 3. TEMPORAL THERMODYNAMICS – THE MODERN DYNAMICAL APPROACH TO THERMODYNAMICAL PROCESSES

GENERIC is a powerful formalism to realize continuum systems but is also valuable for systems with finite degrees of freedom (in other words: for systems with a finite-dimensional state space). It is a natural framework for any irreversible dynamics – in other words, for thermodynamics, where thermodynamics is understood in the modern sense. To better understand the significance of GENERIC, it is useful to overview the development of modern thermodynamics.

Historically, thermodynamics focused on temperature and its relationship to other state-parametrizing quantities (pressure, density etc.), and on energy changes (heat and work) related to changes in temperature and the other state-describing quantities. The relationships among the state-parametrizing quantities were measured under static circumstances or by waiting long enough to reach practically static circumstances, on thermodynamical bodies within which quantities (already) had a homogeneous distribution. Changes were also investigated in the quasi-static regime (always waiting long enough to reach a new static state). Accordingly, time was made irrelevant, and speeds and change rates were out of scope – with the consequence that the dependence of state-describing quantities on speeds and change rates was impossible to observe. In parallel, finitely many spatially homogenized thermodynamical bodies were considered<sup>3</sup>, which is the lumped-parameter picture. With speeds neglected, realizing the balance of momentum was impossible, kinetic energy was also lost, and the focus was on the balance of energy, which became simplified to the balance of internal energy: the change of internal energy  $E_{\text{int}}$  was related to heat-type energy transfer and to mechanical work: in infinitesimal form,

$$\mathrm{d}E_{\text{int}} = \mathrm{d}Q + \mathrm{d}W. \quad (3.1)$$

This was the first formulation of the First Law of Thermodynamics. Mechanical work could be expressed as

$$\mathrm{d}W = -p \mathrm{d}V \quad (3.2)$$

with pressure  $p$  and volume  $V$ , but there was no means of telling *why* – due to what interactions with other thermodynamical bodies – and *how* – at what change rate –  $V$  changes. Moreover, for heat only an inequality was available:

$$\mathrm{d}Q \geq T \mathrm{d}S \quad (3.3)$$

---

<sup>3</sup>As a special example, the environment is a thermodynamical body whose extensive quantities – the ones proportional to extent, *e.g.*, mass, volume, internal energy – can change due to interactions with the other thermodynamical bodies, but these changes are relatively negligible for the “large” body so its intensive quantities – those governing interaction, *e.g.*, temperature, pressure – are considered constant.

with absolute temperature  $T$  and entropy  $S$ , equality for reversible cases and strict inequality for irreversible ones. This setup was not able to reveal what process results from some given interactions plus some initial conditions on the state-describing quantities.

Later in the history of thermodynamics, the role of time became gradually recognized. Onsager's activity (irreversible interactions inducing time dependence of quantities), ideas by Fényes [26, 27] and Gyarmati [28, 29], so-called finite-time thermodynamics [30] (recognizing that there is no infinite time for changes), the endoreversible picture of thermodynamics [31] (that reversibility holds within a thermodynamical body but irreversible interactions occur at the boundaries), and Matolcsi's ordinary thermodynamics [32] (where a closed set of ordinary differential equations holds for the process in time, the equations consisting of the interactions given as state-dependent functions) led to a dynamical picture of thermodynamics. Regarding space dependence of the quantities, the lumped-parameter description may be kept – *i.e.*, with piecewise homogenized quantities –, nevertheless, irreversibility generated inside a thermodynamical body is also possible to describe [33], thus providing models for viscosity, non-Newtonian fluids, viscoelasticity of solids including the Poynting–Thomson–Zener and Kluitenberg–Verhás model families, and plasticity [33].

In this description, called *temporal thermodynamics* hereafter, the First Law of Thermodynamics (3.1) is rewritten: to an infinitesimal change in the state space, an infinitesimal time interval  $dt$  corresponds, we consider the heating *rate*

$$\dot{Q}^* = \frac{dQ}{dt}, \quad (3.4)$$

the working *rate*

$$\dot{W}^* = \frac{dW}{dt} = -p \frac{dV}{dt}, \quad (3.5)$$

and the time derivative of internal energy is related to these energy transfer rates:

$$\frac{dE_{\text{int}}}{dt} = \dot{Q}^* + \dot{W}^*. \quad (3.6)$$

In parallel to this balance of energy, there becomes possibility to realize the balance of momentum, which provides an equation for  $\frac{dV}{dt}$ . If there is a change in mass,  $m$ , or in some further state-describing quantity, then this change is also to be expressed via such equations on time derivatives. In the final form, we have a set of equations where  $\frac{dE_{\text{int}}}{dt}$ ,  $\frac{dV}{dt}$  *etc.* are on the left-hand side while  $\dot{Q}^*$  and everything else on the right-hand sides is given as concrete state-dependent functions, *interaction functions*.<sup>4</sup> For instance, for convective heat transfer between a thermodynamical body with temperature  $T$  and an environment with its ambient temperature  $T_a$ ,  $\dot{Q}^*$  is proportional to  $T - T_a$  while for a thermal-radiation type interaction,  $\dot{Q}^*$  is proportional to  $T^4 - T_a^4$ .

The interactions considered may be reversible or irreversible, and GENERIC provides a means of separating these two kinds. Moreover, in general, the reversible part cannot be formulated using a Lagrangian like in (2.8) or a Hamiltonian like in (2.10)

<sup>4</sup>A full example for this final form follows below.

– such examples are all systems with an odd number of degrees of freedom (with an odd-dimensional state space). Both the separation and the Poisson realization of the reversible part have benefits – both at the conceptual level and for solutions, in particular for numerical solutions. This is demonstrated below.

#### 4. APPLYING GENERIC: TEMPORAL THERMODYNAMICAL MODELLING OF A NONLINEAR PROCESS OF A SUPERCRITICAL FLUID ENCLOSED BY A PISTON

**4.1. Why supercritical? Why GENERIC?** Due to the product  $-p \frac{dV}{dt}$  in the balance of energy (3.6) and the fact that, in general, both  $p$  and  $\frac{dV}{dt}$  change along a process, temporal dynamics is nonlinear in general. In parallel, the dependence of  $p$  on the quantities  $E_{\text{int}}$ ,  $V$ , *etc.* is nonlinear even for the simplest fluid model, ideal gas. Particularly strong is material nonlinearity slightly above the critical point (the point in the state space below which compressibility becomes negative, inducing instability for the thermodynamical body and forming the tip of the phase equilibrium curve).

A process running above the critical point in the state space has technological advantages. For example, the Generation IV type nuclear reactors (Super Critical Water Reactors, SCWR's) utilize supercritical water [34, 35], while other power cycles use supercritical CO<sub>2</sub> [36] or organic fluids with a low boiling point [37]. Because of practical considerations, processes may not run much above the critical point. Material nonlinearities are particularly strong just above the critical point – in the so-called Widom region –, which makes designing supercritical processes a delicate issue (see, *e.g.*, [38]). In this region, the rapidly varying material coefficients (compressibility, thermal expansion coefficient, and specific heat capacities) lead to strongly coupled mechanical–thermal effects, one of which is the “piston effect” (a thermally induced shock wave travelling at the speed of sound) [39–43], and another being heat transfer deterioration and enhancement [44–46]).

Trustworthy computations for such processes are important, in light of the technological applications. Nevertheless, many studies try to avoid incorporating the strong state dependences [39–41] because of difficulties in numerical simulations [47]. Thus, supercritical processes are a good and strongly justified area for seeking reliable numerical methods for irreversible dynamics. Having seen that GENERIC incorporates a number of essential aspects of irreversible dynamics, in what follows, we establish the GENERIC realization of a finite degree-of-freedom setup for a supercritical fluid, and then study numerical schemes for this setup that provide some insight and general lessons regarding reliability.

**4.2. The fluid considered in the supercritical regime.** The (quasi-static) thermal equation of state – also known as the thermal constitutive relationship – of a simple fluid can be given through the function  $p(T, v)$  (for pressure  $p$ , temperature  $T$ , and specific volume  $v = V/m$  with volume  $V$  and mass  $m$ ). For definiteness, we treat here the van der Waals (vdW) model, for which

$$p(T, v) = \frac{RT}{v - \mathbf{b}} - \frac{\mathbf{a}}{v^2} \quad (R > 0, \mathbf{a} > 0, \mathbf{b} > 0). \quad (4.1)$$



In this fluid model, the critical point (the solution of the pair of  $\frac{\partial p}{\partial v}\big|_T = 0$ ,  $\frac{\partial^2 p}{\partial v^2}\big|_T = 0$ , see, *e.g.*, [33]) is characterized by the critical values

$$p_c = \frac{1}{27} \frac{\mathbf{a}}{\mathbf{b}^2}, \quad T_c = \frac{8}{27} \frac{\mathbf{a}}{R\mathbf{b}}, \quad v_c = 3\mathbf{b}. \quad (4.2)$$

In order to ensure that the numerical computations below can work with dimensionless quantities, we introduce the dimensionless reduced quantities

$$\check{p} = \frac{p}{p_c}, \quad \check{T} = \frac{T}{T_c}, \quad \check{v} = \frac{v}{v_c}, \quad (4.3)$$

via which (4.1) becomes

$$\check{p}(\check{T}, \check{v}) = \frac{8\check{T}}{3\check{v} - 1} - \frac{3}{\check{v}^2}. \quad (4.4)$$

In addition, we use the caloric constitutive relationship, with  $e_{\text{int}} = E_{\text{int}}/m$ ,

$$e_{\text{int}}(T, v) = \frac{\mathbf{f}}{2} RT - \frac{\mathbf{a}}{v}, \quad \Rightarrow \quad \check{e}_{\text{int}} = \frac{e_{\text{int}}}{p_c v_c} = \frac{4}{3} \mathbf{f} \check{T} - \frac{3}{\check{v}}, \quad (4.5)$$

which is consistent [33] with the thermal constitutive function (4.1) and gives, in the ideal-gas limit, the case of constant isochoric specific heat  $c_v = \frac{\mathbf{f}}{2} R$ ; the molecular energy-storing degree of freedom  $\mathbf{f}$  is set to 3 in the subsequent computations (the outcomes have proven to be qualitatively the same for other values of  $\mathbf{f}$ ).

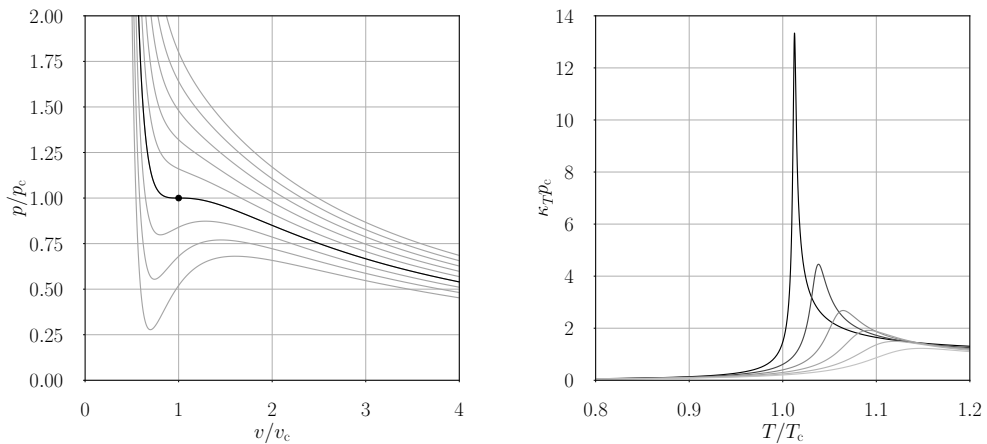


Figure 1. *Left*: isothermal lines of the van der Waals material, and the critical point. *Right*: As pressure approaches critical pressure from above, a sharper-and-sharper maximum is observable in isothermal compressibility. For isobaric thermal expansion and for isobaric specific heat capacity, a similar behaviour is observable.

In any simple fluid model, the isothermal compressibility

$$\kappa_T = -\frac{1}{v} \left. \frac{\partial v}{\partial p} \right|_T = -\frac{1}{v} \frac{1}{\left. \frac{\partial p}{\partial v} \right|_T}, \quad (4.6)$$

the isobaric volumetric thermal expansion coefficient

$$\alpha = \frac{1}{v} \left. \frac{\partial v}{\partial T} \right|_p = -\frac{1}{v} \frac{\left. \frac{\partial p}{\partial T} \right|_v}{\left. \frac{\partial p}{\partial v} \right|_T}, \quad (4.7)$$

and the isobaric specific heat capacity

$$c_p = \frac{1}{m} \left. \frac{dQ}{dT} \right|_p = \left. \frac{\partial e_{\text{int}}}{\partial T} \right|_p + p \left. \frac{\partial v}{\partial T} \right|_p \quad (4.8)$$

are defined [33] and prove to be very informative for a wide range of aspects. If we approach the critical point, from above (in temperature or pressure), then each of these become heavily state dependent and diverge, as illustrated in Fig. 1. The strong state dependence makes processes running near the critical point considerably nonlinear.

A closing comment regarding the constitutive relationships is that the dynamical equations below will determine  $e_{\text{int}}$  and  $v$ . Then  $T$  can be obtained through expressing it from  $e_{\text{int}}(T, v)$  [in our present case, from (4.5)]. Then this  $T(e_{\text{int}}, v)$  can be put into  $p$ :

$$p(T, v) \equiv p(T(e_{\text{int}}, v), v) \equiv p(e_{\text{int}}, v) \quad (4.9)$$

so  $p$  is also available as function of  $e_{\text{int}}$  and  $v$ .

**4.3. The setup considered and its dynamical equations.** The problem we study hereafter is as follows. A fixed amount of supercritical van der Waals fluid is enclosed in a cylinder, separated from the environment by a movable rigid piston (see Fig. 2). We assume adiabatic circumstances, enabling mechanical interaction only. As explained in Section 3, for a temporal, dynamical process, a closed set of ordinary differential equations is needed.

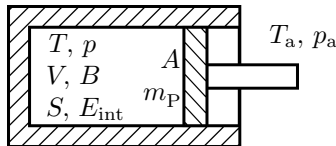


Figure 2. The setup of a supercritical fluid enclosed in a cylinder by a movable rigid piston, and the relevant quantities of the fluid, of the piston, and of the environment (subscript ‘a’ refers to ‘ambient’).

The first of these is the First Law of Thermodynamics – the balance for energy – considered as the relationship (3.6) among the change rate (time derivative) of internal

energy, heating rate and working rate (with the heating rate now actually being zero according to the adiabatic assumption).

In parallel, for the piston, we write Newton's equation of motion, which determines acceleration from the force exerted by the fluid and the force stemming from external (ambient) pressure. This is actually the balance for momentum.

Finally, the change rate of volume is to be connected to the velocity of the piston.

The details are as follows.

The intensive quantities of the large environment are not influenced by the process, so ambient temperature  $T_a$  and ambient pressure  $p_a$  are considered constant:

$$T_a = \text{const.}, \quad p_a = \text{const.} \quad (4.10)$$

The piston is characterized by its mass  $m_P$  and the cross-section area  $A$ .

Corresponding to the step where, in mechanics, the time derivative of position is raised to the level of a physical quantity – velocity – here the time derivative of volume,  $dV/dt$ , is raised to the level of a quantity on its own right, denoted hereafter by  $B$ :

$$V = Ax, \quad \frac{dV}{dt} = A \frac{dx}{dt} : \quad B = Av \quad (4.11)$$

(where  $x$  is the position coordinate of the piston and  $v$  is its velocity).

Due to the rigid piston, there is a conservation rule for the involved volumes, the time derivative of which connects the ambient volume change rate  $B_a$  with the volume change rate  $B$  of the enclosed fluid:

$$V_a = V_{\text{tot}} - V, \quad B_a = -B. \quad (4.12)$$

The conserved total energy,  $E_{\text{tot}}$  consists of the internal energy  $E_{\text{int}}$  of the fluid, the kinetic energy of the piston – expressible as

$$\frac{m_P}{2} \left( \frac{B}{A} \right)^2 = \frac{\chi_P}{2} B^2 \quad \text{with} \quad \chi_P = \frac{m_P}{A^2}, \quad (4.13)$$

and the ambient internal energy, from which only a term  $-p_a V_a = p_a V + \text{const.}$  has time dependence, as we have neglected heat-type interaction and allowed only mechanical work-type interaction:

$$E_{\text{tot}} = E_{\text{int}} + \frac{\chi_P}{2} B^2 + p_a V + \text{const.} \quad (4.14)$$

We mention that, regarding (4.14), the Appendix provides further insight.

In addition to the reversible pressure seen in (4.1), and denoted hereafter by  $p_{\text{rev}}$ , we also allow for an optional irreversible, dissipative, viscosity-type pressure contribution

$$p_{\text{irr}} = -\beta b \quad \text{with} \quad b = \frac{B}{m} \quad (4.15)$$

(where  $\beta \geq 0$  may be state dependent; see, e.g., [48]), so

$$p = p_{\text{rev}} + p_{\text{irr}} = p_{\text{rev}}(T, v) - \beta(T, v, b) \cdot b. \quad (4.16)$$

Then the mentioned three temporal differential equations – the First Law, the kinematic relationship, and the equation of motion of the piston – are concretized as

$$\frac{dE_{\text{int}}}{dt} = -pB, \quad (4.17)$$

$$\frac{dV}{dt} = B, \quad (4.18)$$

$$m_P \frac{d\frac{B}{A}}{dt} = pA - p_a A \implies \frac{dB}{dt} = \frac{1}{\chi_P} (p - p_a), \quad (4.19)$$

they form a closed set of equations, and together ensure conservation of total energy,  $\frac{dE_{\text{tot}}}{dt} = 0$  along a process, as is straightforward to show.

Note that there is an odd number (3) of degrees of freedom here, so even the reversible case  $\beta = 0$  is non-Hamiltonian and cannot have a symplectic structure.

**4.4. GENERIC formulation of the model.** The GENERIC form of our set of temporal differential equations (4.17)–(4.19) should be [see (2.41)]

$$\frac{d}{dt} \mathbf{x} = \mathbf{L} \frac{dE_{\text{tot}}}{d\mathbf{x}} + \mathbf{M} \frac{dS_{\text{tot}}}{d\mathbf{x}}, \quad (4.20)$$

where  $\mathbf{x}$  is a collection of state variables. For (4.17)–(4.19),  $\mathbf{x} = (E_{\text{int}} \quad V \quad B)^{\text{transp}}$ , and  $E_{\text{tot}}$  is given in (4.14). Furthermore, regarding

$$S_{\text{tot}} = S + S_a, \quad dS_{\text{tot}} = dS + dS_a, \quad \frac{dS_{\text{tot}}}{d\mathbf{x}} = \frac{dS}{d\mathbf{x}} + \frac{dS_a}{d\mathbf{x}}, \quad (4.21)$$

the constitutive definition of entropy  $S$  gives (see, *e.g.*, [33]), for constant mass,

$$dS = \frac{1}{T} dE_{\text{int}} + \frac{p_{\text{rev}}}{T} dV \implies \frac{dS}{d\mathbf{x}} = \frac{1}{T} \frac{dE_{\text{int}}}{d\mathbf{x}} + \frac{p_{\text{rev}}}{T} \frac{dV}{d\mathbf{x}}, \quad (4.22)$$

while  $S_a$  does not depend on  $\mathbf{x}$  as it is a constitutive function of the state variables of the environment, not of the state variables of the enclosed fluid. Then it is not difficult to check that the structure (4.20) can be realized as

$$\frac{d}{dt} \begin{pmatrix} E_{\text{int}} \\ V \\ B \end{pmatrix} = \begin{pmatrix} 0 & 0 & -\frac{p_{\text{rev}}}{\chi_P} \\ 0 & 0 & \frac{1}{\chi_P} \\ \frac{p_{\text{rev}}}{\chi_P} & -\frac{1}{\chi_P} & 0 \end{pmatrix} \begin{pmatrix} 1 \\ p_a \\ \chi_P B \end{pmatrix} + \begin{pmatrix} \frac{T\beta}{m} B^2 & 0 & \frac{T p_{\text{irr}}}{\chi_P} \\ 0 & 0 & 0 \\ \frac{T p_{\text{irr}}}{\chi_P} & 0 & \frac{T\beta}{m \chi_P^2} \end{pmatrix} \begin{pmatrix} \frac{1}{T} \\ \frac{p_{\text{rev}}}{T} \\ 0 \end{pmatrix}, \quad (4.23)$$

where the standard requirements (2.42)–(2.45) are straightforwardly fulfilled. It is worth mentioning that, in particular,

$$\frac{dS_{\text{tot}}}{dt} \geq 0 \quad (\text{equality only at equilibrium}) \quad (4.24)$$

is realized as

$$\frac{dS_{\text{tot}}}{dt} = \frac{\beta}{m} \frac{B^2}{T}, \quad (4.25)$$

*i.e.*, the only source of irreversibility (entropy generation) is the optional irreversible pressure contribution.

In order to provide an outlook, in the Appendix, the generalization of (4.23) is presented when adiabaticity is replaced by a nonzero heating rate.

## 5. SYMPLECTIC NUMERICAL SCHEMES AND THE QUASI-SYMPLECTIC EXTENSION INTRODUCED HERE

**5.1. The starting point: symplectic numerical schemes.** If dynamics is reversible,

$$\frac{d\mathbf{x}}{dt} = \mathbf{L} \frac{dE_{\text{tot}}}{d\mathbf{x}}, \quad (5.1)$$

with a nondegenerate  $\mathbf{L}$  – this necessitates an even-dimensional state space (phase space) – and if antisymmetry and the Jacobi property (2.45) are satisfied, then the system is *symplectic*, i.e., with  $\tilde{\mathbf{x}}(t, \mathbf{x}_0)$  denoting the solution at  $t$  for the initial condition  $\mathbf{x}_0$  at  $t_0$ ,

$$\left( \frac{d}{d\mathbf{x}_0} \tilde{\mathbf{x}}(t, \mathbf{x}_0) \right)^{\text{transp}} \mathbf{L}^{-1} \left( \frac{d}{d\mathbf{x}_0} \tilde{\mathbf{x}}(t, \mathbf{x}_0) \right) = \mathbf{L}^{-1}, \quad (5.2)$$

in other words, the left-hand side of (5.2) is  $t$ -independent.

In such cases, via variable transformation,  $\mathbf{x}$  can be transformed to a half-split (partitioned) form

$$\mathbf{x} = \begin{pmatrix} \mathbf{q} \\ \mathbf{p} \end{pmatrix} \quad (5.3)$$

(both  $\mathbf{q}$  and  $\mathbf{p}$  being half as many degrees of freedom as  $\mathbf{x}$ ) in which the dynamical equations become simplified to

$$\frac{d\mathbf{q}}{dt} = \frac{\partial H}{\partial \mathbf{p}}, \quad \frac{d\mathbf{p}}{dt} = -\frac{\partial H}{\partial \mathbf{q}}, \quad (5.4)$$

where the Hamiltonian  $H(\mathbf{q}, \mathbf{p})$  is the transformed form of  $E_{\text{tot}}(\mathbf{x})$ . Equations (5.3) are generalized version of (2.10).

Let us now turn toward numerical, finite-difference solutions of (5.4). An equidistant temporal discretization is considered: in notation, the discrete time instants are  $t^j = j \cdot \Delta t$ ,  $j = 0, 1, \dots, J$ , where  $\Delta t$  is the size of the chosen time step. The value of a function in the  $j$ th time instant is denoted by a superscript  $j$ , for example,  $\mathbf{q}(t^j) = \mathbf{q}^j$ . Time derivatives are discretized as ratios of differences, for instance,  $\frac{\mathbf{q}^{j+1} - \mathbf{q}^j}{\Delta t}$ .

A first-order numerical method is the explicit Euler scheme, which for (5.4) reads

$$\mathbf{q}^{j+1} = \mathbf{q}^j + \Delta t \frac{\partial H}{\partial \mathbf{p}}(\mathbf{q}^j, \mathbf{p}^j), \quad \mathbf{p}^{j+1} = \mathbf{p}^j - \Delta t \frac{\partial H}{\partial \mathbf{q}}(\mathbf{q}^j, \mathbf{p}^j). \quad (5.5)$$

Its variants, the also first-order but much better performing two versions of the so-called symplectic Euler scheme

$$\mathbf{q}^{j+1} = \mathbf{q}^j + \Delta t \frac{\partial H}{\partial \mathbf{p}}(\mathbf{q}^j, \mathbf{p}^{j+1}), \quad \mathbf{p}^{j+1} = \mathbf{p}^j - \Delta t \frac{\partial H}{\partial \mathbf{q}}(\mathbf{q}^j, \mathbf{p}^{j+1}) \quad (5.6)$$

and

$$\mathbf{q}^{j+1} = \mathbf{q}^j + \Delta t \frac{\partial H}{\partial \mathbf{p}}(\mathbf{q}^{j+1}, \mathbf{p}^j), \quad \mathbf{p}^{j+1} = \mathbf{p}^j - \Delta t \frac{\partial H}{\partial \mathbf{q}}(\mathbf{q}^{j+1}, \mathbf{p}^j), \quad (5.7)$$

are examples of symplectic numerical methods (see, *e.g.*, [3, 49]). Symplectic schemes preserve the symplectic structure [see (5.2)], and actually provide the *exact* solution of a nearby Hamiltonian system. This is the background behind their good performance. Other examples of symplectic methods are the Störmer–Verlet scheme (giving the leapfrog method for special cases) and the symplectic Runge–Kutta family.

It is worth mentioning here that Backward Error Analysis (BEA) is able to find the distorted (the nearby) Hamiltonian, to any desired order of  $\Delta t$ . Then compensations can be introduced to improve the performance of the given scheme. This is the technique used in [1] to improve the second-order Newmark method to fourth-order accuracy.

For irreversible systems, the situation is much more difficult but a systematic suggestion to make use of the properties of the symplectic methods and of BEA within GENERIC was made in [14]. This is one way GENERIC can be helpful in this respect. Besides this, at a more general level, GENERIC encourages us to make symplectic schemes “survive” for irreversible systems, in the hope that the benefits are at least partially inherited to the irreversible level.

Accordingly, here, we separate our variables into two groups, to mimic (5.3), and to generalize the symplectic Euler scheme (5.7). The details are as follows.

**5.2. The quasi-symplectic scheme.** We work with dimensionless quantities defined via the units as already introduced in (4.3) while, for time-related quantities,  $\chi_P$  is used as the fourth necessary unit.

Our separation of the degrees of freedom is such that  $\check{v}$  and  $\check{e}_{\text{int}}$  are the “generalized  $\mathbf{q}$ -type” quantities and  $\check{b}$  is the “generalized  $\mathbf{p}$ -type” [cf. (5.3)], and our discretization corresponding to (4.17)–(4.19) is

$$\check{v}^{j+1} = \check{v}^j + \Delta \check{t} \check{b}^j, \quad (5.8)$$

$$\check{e}_{\text{int}}^{j+1} = \check{e}_{\text{int}}^j - \Delta \check{t} \check{p}^j \check{b}^j, \quad (5.9)$$

$$\check{T}^{j+1} = \frac{3}{4\mathbf{f}} \left( \check{e}_{\text{int}}^{j+1} + \frac{3}{\check{v}^{j+1}} \right), \quad (5.10)$$

$$\check{p}_{\text{rev}}^{j+1} = \frac{8\check{T}^{j+1}}{3\check{v}^{j+1} - 1} - \frac{3}{(\check{v}^{j+1})^2}, \quad (5.11)$$

$$\check{p}_{\text{irr}}^{j+1} = -\check{\beta} [(1 - \alpha_p) \check{b}^j + \alpha_p \check{b}^{j+1}], \quad (5.12)$$

$$\check{b}^{j+1} = \check{b}^j + \Delta \check{t} \left[ (1 - \alpha_b) (\check{p}_{\text{rev}}^j + \check{p}_{\text{irr}}^j) + \alpha_b (\check{p}_{\text{rev}}^{j+1} + \check{p}_{\text{irr}}^{j+1}) - \check{p}_a \right], \quad (5.13)$$

$$\check{p}^{j+1} = \check{p}_{\text{rev}}^{j+1} + \check{p}_{\text{irr}}^{j+1} \quad (5.14)$$

where  $\alpha_p$  and  $\alpha_b$  are arbitrary constants between 0 and 1, with which the implicitness of the scheme can be controlled. More closely:

- When the process is reversible, *i.e.*,  $\check{\beta} = 0$ , then  $\alpha_b = 0$  realizes the explicit Euler method, while  $\alpha_b = 1$  results in a quasi-symplectic – generalized symplectic Euler – scheme.
- The case when dissipation is also included, *i.e.*,  $\check{\beta} > 0$ , carries some additional richness. Namely, since equation (5.12) is the discrete version of a constitutive equation – an algebraic one, (4.15) – then the natural choice is  $\alpha_p = 1$ . In this case  $\alpha_b = 0$  still represents the explicit Euler method while  $\alpha_b = 1$  is a thermodynamically extended quasi-symplectic method, where the scheme becomes implicit (namely, (5.12) and (5.13) need to be solved as a coupled pair of equations).

Our aim with the optional viscosity-like damping is twofold. First, in practical applications, it may represent a reasonable model for mechanical losses [48]. Second, even if there is no irreversible pressure contribution in the problem itself,  $\check{p}_{\text{irr}}$  can realize artificial viscosity, which is a typical practice in simulations to counterbalance numerical artifacts. In Subsection 6.2 we show such a study for this technique.

For simplicity, when  $\check{\beta} > 0$ , we consider a constant  $\check{\beta}$ .

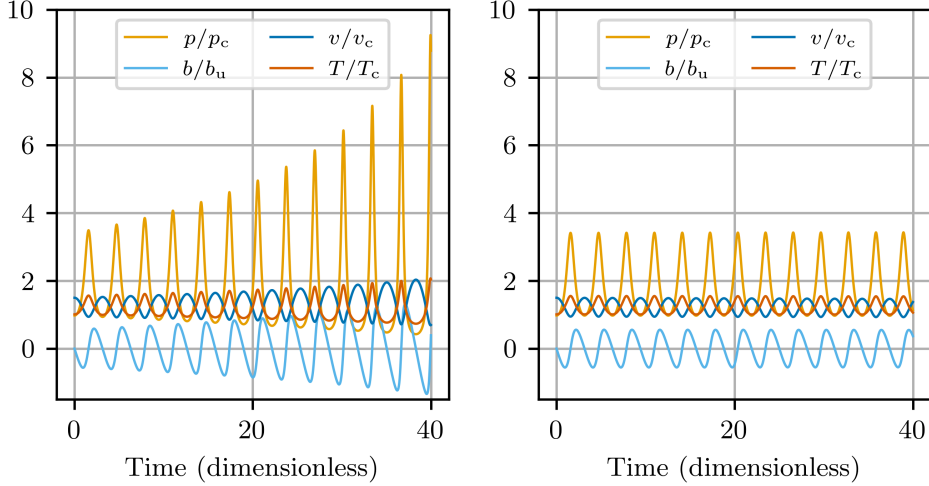
Despite the fact that our problem is an odd-dimensional system and symplectic methods are developed for even-dimensional ones, and despite possibly having an irreversible rather than reversible system, the symplectic starting point yields a better-performing numerical method than the corresponding traditional one, as shown in the following section.

## 6. NUMERICAL RESULTS

**6.1. No damping: explicit Euler vs. quasi-symplectic.** First, the performance of the different numerical schemes is investigated when there is no damping in the system, *i.e.*,  $\check{\beta} = 0$ . As seen above, then the schemes do not depend on the parameter  $\alpha_p$ . The initial conditions used are

$$\check{v}(0) = 1.5, \quad \check{T}(0) = 1.01, \quad \check{b}(0) = 0, \quad (6.1)$$

to which  $\check{p}(0) = 0.9752$  corresponds. Furthermore,  $\check{p}_a = 1.8$  is applied. These values are chosen in such a way that the process will cross the Widom line corresponding to  $\kappa_T$  during oscillation (as will be demonstrated in Fig. 4 below) so that the effect of the suddenly changing compressibility can heavily influence the trajectory of the system. The initial conditions for  $\check{p}(0)$  and  $\check{e}_{\text{int}}(0)$  are computed using the constitutive relations (4.4) and (4.5b).



(a) Result from the explicit Euler scheme. (b) Result from the quasi-symplectic scheme.

Figure 3. (a) The explicit Euler numerical scheme ( $\alpha_b = 0$ ) provides an unacceptable solution, with artificially increasing amplitudes. (b) The quasi-symplectic enhancement of the scheme ( $\alpha_b = 1$ ) yields a much more acceptable outcome, keeping amplitudes approximately constant. (Computations performed with  $\Delta\tilde{t} = 0.001$ .)

Fig. 3a shows the result of a simulation with  $\alpha_b = 0$  (the classic explicit Euler scheme) using time step  $\Delta\tilde{t} = 0.001$  until  $\tilde{t}_{\text{end}} = 40$ . It is apparent that, due to the nonlinearity of the problem, the explicit Euler method is unable to accurately reproduce the system behaviour with these parameters, as the closed and undamped system should oscillate at a constant amplitude. The energy- and, here, amplitude-increasing effect of the explicit Euler scheme is well known [3], but in this case, it is even more pronounced due to the nature of the problem. One could instead use higher-order or implicit schemes such as the 4th-order Runge–Kutta scheme or the implicit midpoint method, or use finer time steps, but all these need increased computing resources. We demonstrate that a more appropriate scheme does not require such measures.

The reliable and satisfactorily accurate quasi-symplectic simulation enables us to examine the nonlinear oscillations in greater depth. Fig. 4 shows, using the results of the quasi-symplectic simulation, that the process indeed crosses the  $\kappa_T$  Widom line.

Namely, if  $\alpha_b = 1$  (yielding our quasi-symplectic scheme) then the method is still first-order accurate and the scheme is still explicit, but the results are significantly more reliable. This is visible in Fig. 3b, where the amplitude of the oscillations is approximately constant during the simulation time. It is worth emphasizing here again that the only difference between the two schemes is whether  $\tilde{p}^j$  or  $\tilde{p}^{j+1}$  is used



for computing  $b^{j+1}$ . The change in accuracy can be attributed to the symplectic-originated symplectic-Euler nature of the quasi-symplectic scheme. This approach is similar, but not identical, to that introduced and applied in [15, 16, 50] for wave propagation with irreversible – non-Newtonian – damping.

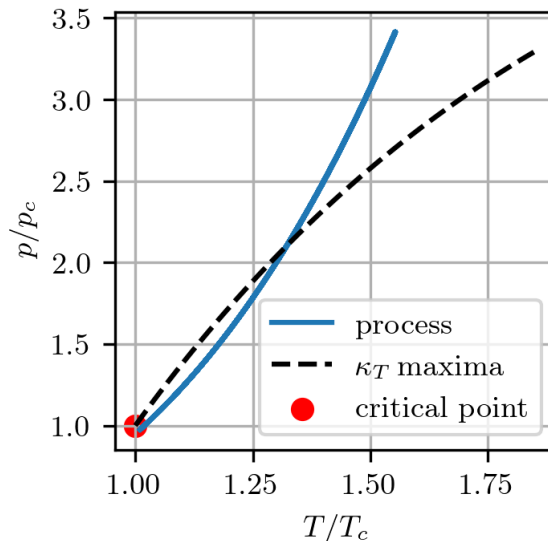
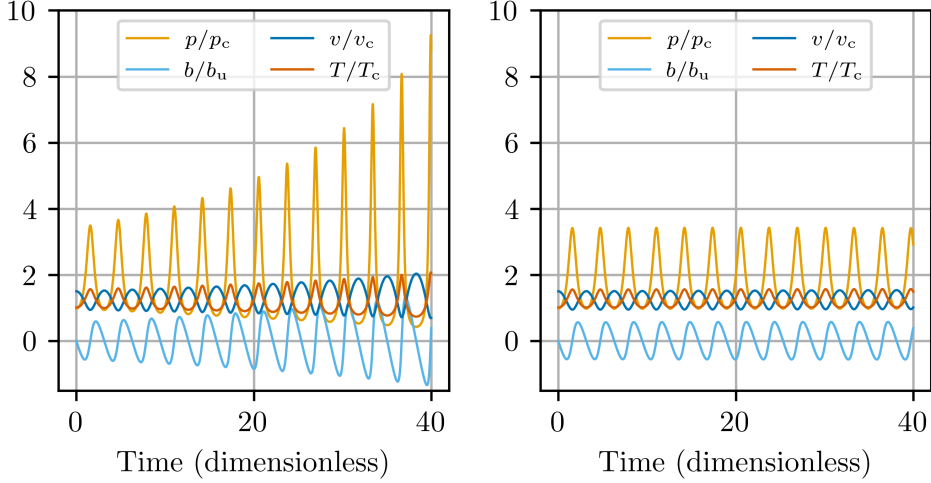


Figure 4. Trajectory of the process in the supercritical region, starting from the vicinity of the critical point, and crossing the  $\kappa_T$  Widom line (the collection of isobaric maxima of  $\kappa_T$  in the state space)

**6.2. Explicit Euler: without and with artificial damping.** As presented above, when dissipation is not taken into consideration, the system exhibits undamped oscillations. In contrast to this, when  $\check{\beta} > 0$ , the system is expected to tend towards an equilibrium solution, with the oscillating quantities having decreasing amplitudes.

Let us now consider the explicit Euler scheme, along with one application of nonzero dissipation.

As we have already mentioned, the dissipation may be part of the physical system or may be introduced in the numerical scheme for the role of artificial dissipation, which may compensate for artificial tendencies in the numerical solution. As seen in Fig. 3a, the explicit Euler scheme makes a nondissipative system “antidissipative”. The increase of the amplitudes could be “tamed” by switching on some amount of dissipation – with an appropriate value of the damping coefficient  $\check{\beta}$ , the amount of artificial dissipation may render the amplitudes approximately constant. Fig. 5 shows that this can in fact be carried out.



(a) Explicit Euler solution, no damping ( $\beta = 0$ ).

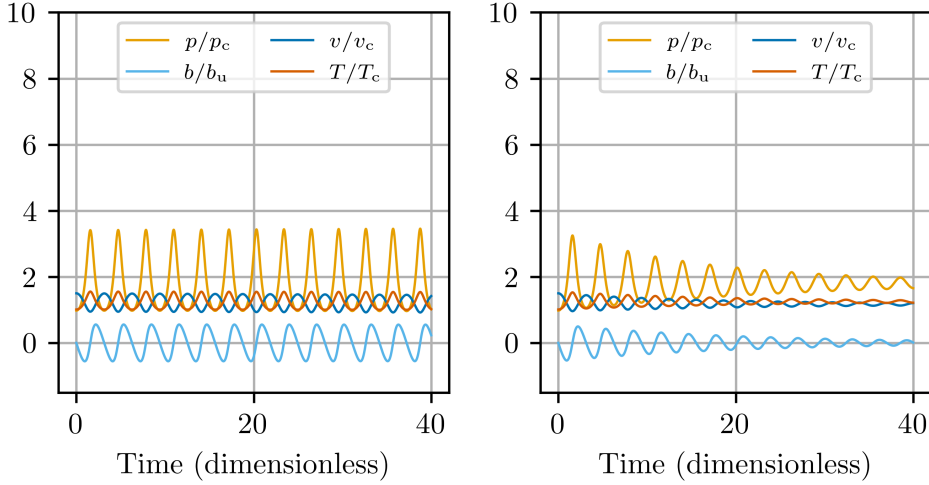
(b) Explicit Euler solution with damping ( $\beta = 0.04$ ).

Figure 5. The gradually exploding oscillations produced by the explicit Euler numerical scheme for a nondissipative system (a) can be corrected to approximately constant amplitudes (b) via a suitable amount of artificial dissipation added. ( $\alpha_b = 0$ ,  $\alpha_p = 0$ ,  $\Delta t = 0.01$ ).

We mention, nevertheless, that this technique of artificial damping is not yet an automatically performable one: it is not some general algorithm that determines the optimal value of the artificial damping coefficient for a given system and given initial conditions. A compensation method to counterweigh the scheme-induced damping has recently been worked out for linear differential equations [1] so a nonlinear generalization of this approach may, in the future, provide such an algorithm.

**6.3. Quasi-symplectic: without and with damping.** With such an alternative, a much more reliable quasi-symplectic variant ( $\alpha_b = 1$ ,  $\alpha_p = 1$  in our above scheme), one can study real, physical, dissipation satisfactorily. Fig. 6 compares a solution for the nondissipative system with that for a dissipative one. Amplitudes are approximately constant in Fig. 6a and decrease in Fig. 6b as they should.

**6.4. Studying nonlinearity.** As already mentioned above, the remarkable state dependence of the thermophysical parameters makes oscillations considerably nonlinear. Fig. 3b already displays that the oscillations themselves are nonlinear, *i.e.*, nonsinusoidal, tilted, and distorted; nevertheless, we would also like to *quantify* the extent of nonlinearity.



(a) Quasi-symplectic solution, no damping ( $\tilde{\beta} = 0$ ).

(b) Quasi-symplectic solution for damping  $\tilde{\beta} = 0.1$ .

Figure 6. Nondissipative (a) and dissipative (b) oscillations computed via the implicit quasi-symplectic scheme ( $\alpha_b = 1$ ,  $\alpha_p = 1$ ,  $\Delta\tilde{t} = 0.01$ ).

If we had harmonic oscillations, then, due to the structure of the governing equation of an undamped linear (harmonic) oscillator

$$\ddot{v} = -\omega^2 (v - v_{\text{eq}}) = -\omega^2 v + \text{const.} \quad (6.2)$$

(overdot abbreviating time derivative), the trajectory of the process would be a straight line in the plane  $\ddot{v}$ - $v$ . Deviation from this straight line characterizes non-linearity. To quantify this, we introduce a measure of nonlinearity, in the form

$$\zeta = \frac{\max_j |\ddot{v}^j - (\bar{A}\ddot{v}^j + \bar{B})|}{\max_j \ddot{v}^j - \min_j \ddot{v}^j}, \quad (6.3)$$

where  $\bar{A}$  and  $\bar{B}$  realize the straight-line trajectory of the corresponding harmonic oscillator between the two given endpoints:

$$\bar{A} = \frac{\ddot{v}(\ddot{v}_{\text{max}}) - \ddot{v}(\ddot{v}_{\text{min}})}{\ddot{v}_{\text{max}} - \ddot{v}_{\text{min}}}, \quad \bar{B} = \ddot{v}(\ddot{v}_{\text{min}}) - \bar{A}\ddot{v}_{\text{min}} \quad (6.4)$$

with the endpoint values of  $\ddot{v}$ ,

$$\ddot{v}_{\text{min}} = \min_j \ddot{v}^j, \quad \ddot{v}_{\text{max}} = \max_j \ddot{v}^j, \quad (6.5)$$

and  $\ddot{v}(\ddot{v}_{\text{min}})$ ,  $\ddot{v}(\ddot{v}_{\text{max}})$  being the two endpoint values of  $\ddot{v}$ . The measure  $\zeta$  is dimensionless, equals 0 for a linear oscillation, and increases with the maximal vertical deviation from the linear trajectory. Emerging non-linear behavior near the critical point is illustrated via Figure 7.

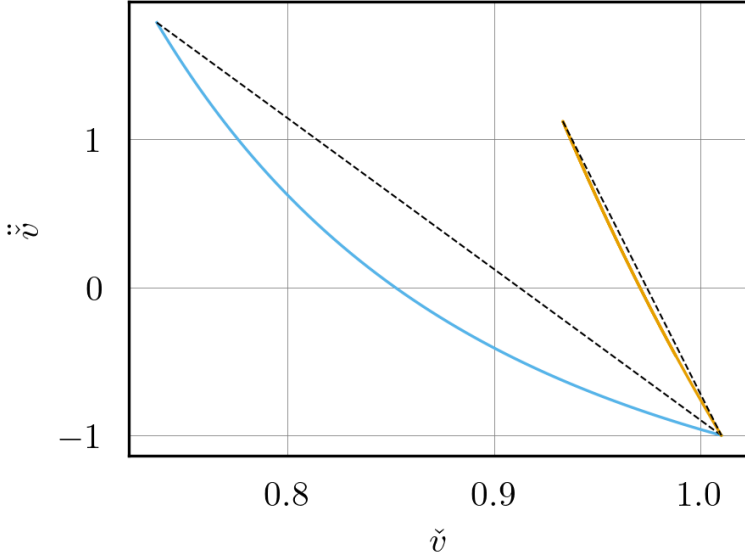


Figure 7. Nonlinearity of the resulting oscillations demonstrated. Orange: approximately linear oscillation ( $\zeta = 0.0434$ ) far from the critical point, with initial conditions  $\tilde{T}(0) = 3.0$ ,  $\tilde{v}(0) = 1.01$ ,  $\Rightarrow \tilde{p}(0) = 8.8818$ . Blue: nonlinear oscillation ( $\zeta = 0.2195$ ) near the critical point, with initial conditions  $\tilde{T}(0) = 0.999$ ,  $\tilde{v}(0) = 1.01$ ,  $\Rightarrow \tilde{p}(0) = 0.9960$ . In order to ensure a fair comparison, in both cases,  $\tilde{p}_a = \tilde{p}(0) + 1$ . The gray dashed lines illustrate the trajectories of the corresponding linear oscillators.

Unlike other, already known, measures for nonlinearity (see, e.g., [51–53]), our new measure defined by (6.3) does not require the data to be described by a function (which, for some existing measures, also needs to be continuous or even differentiable). This property makes it applicable for datasets from simulations. Naturally, if needed, some smoothing of the data is possible. Furthermore, our measure respects the differing dimensionality of the two axes while being nondimensional itself. (Note that there is no “orthogonal” distance in a plane of dimensionally differing axes.)

## 7. DISCUSSION

The quasi-symplectic Euler scheme introduced here performed considerably better than the explicit Euler one, although both are first-order methods. As such, it was possible to compute a process crossing the Widom line in the very sensitive supercritical domain much more reliably. Among other aspects, dissipation was treated

much more properly. This enabled us to investigate a deliberately introduced artificial viscosity, for which further study is needed to automatize computation of the corresponding artificial viscosity coefficient.

In order to characterize the nonlinearity of processes, both a visualization and an informative and quantitative measure that is easily determinable numerically were defined and illustrated. These demonstrated that processes in the vicinity of the critical point are remarkably nonlinear.

As a future step, higher-order symplectic methods like the Störmer–Verlet method could also be generalized to the present test problem. In the Störmer–Verlet case, for example, not only the higher order is expected to help but the balance-friendly nature of the Störmer–Verlet (leapfrog) structure also, which was already observed in [15–18].

The nonadiabatic generalization of our setup – detailed in the Appendix – offers further possibilities for future investigations. Connected to this additional source of irreversibility, more could be learned about devising optimal artificial damping.

GENERIC – the framework in which both the investigated system and its non-adiabatic counterpart have been realized here – is a motivating force for establishing numerical schemes for irreversible dynamical systems that are symplectic methods for reversible Hamiltonian special cases. Furthermore, research along the lines of [14] is expected to lead to better structure-preserving schemes for irreversible dynamical systems, preserving both the GENERIC structure and the underlying balances.

The entropy-based version of the GENERIC dynamical equations constructed here promises extra good performance for these schemes since the revealed operator content is more robust against numerical error due to the fact that the reversible operator is state-independent. This also carries the general message that thermodynamically appropriate variables and thermodynamically appropriate discretizations may be beneficial, since a considerable part of the strong thermodynamical structure can be preserved during discretization.

**Author contributions.** T. Fülöp: the Rayleigh case, GENERIC equations for the piston problem, conceptual aspects regarding the numerical schemes, supervision, manuscript text. M. Szücs: contribution to the Rayleigh case, numerical computations for damping and for nonlinearity, manuscript text. D. M. Takács: quasi-symplectic numerical scheme vs. explicit Euler scheme, conceptual idea for artificial damping, measure of nonlinearity, visualization method for nonlinearity, manuscript text.

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## APPENDIX A. WITH HEAT TRANSFER THROUGH THE PISTON

Here, we present the generalization of (4.23) when, in addition to the mechanical interaction with the environment with working rate  $\dot{W} \equiv \frac{dW}{dt} = -p \frac{dV}{dt} = -pB$ , adiabaticity [see (4.17)] is replaced by a nonzero heating rate  $\dot{Q} \equiv \frac{dQ}{dt}$ . Then an additional state variable becomes necessary for the description of the dynamics. A good choice for this is  $S_a$ , which proves to be constant in the adiabatic case but becomes time-dependent for a nonzero heating rate:

$$\frac{dS_a}{dt} = \frac{\dot{Q}_a}{T_a} = -\frac{\dot{Q}}{T_a} \quad (\text{A.1})$$

since, for heat transfer interaction functions in general [*e.g.*, convective  $\dot{Q} \sim (T - T_a)$  or radiative  $\dot{Q} \sim (T^4 - T_a^4)$ ],  $\dot{Q}_a = -\dot{Q}$  (see, *e.g.*, [33]). In parallel to that, due to Euler homogeneity, for a fluid with constant mass,

$$E_{\text{int}} = TS - pV + \text{const.} \quad (\text{A.2})$$

(see, *e.g.*, [33]), for the environment

$$E_{\text{int}_a} = T_a S_a - p_a V_a + \text{const.}, \quad (\text{A.3})$$

holds. In light of (4.12a), total energy can be written as

$$E_{\text{tot}} = E_{\text{int}} + \frac{\chi_P}{2} B^2 + p_a V + T_a S_a + \text{const.} \quad (\text{A.4})$$

[being the generalization of (4.14b)].

The GENERIC realization for  $\mathbf{x} = (E_{\text{int}} \quad V \quad B \quad S_a)^T$  is

$$\begin{aligned} \frac{d}{dt} \begin{pmatrix} E_{\text{int}} \\ V \\ B \\ S_a \end{pmatrix} &= \begin{pmatrix} 0 & 0 & -\frac{p_{\text{rev}}}{\chi_P} & 0 \\ 0 & 0 & \frac{1}{\chi_P} & 0 \\ \frac{p_{\text{rev}}}{\chi_P} & -\frac{1}{\chi_P} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ p_a \\ \chi_P B \\ T_a \end{pmatrix} \\ &+ \begin{pmatrix} \frac{T_a T}{T_a - T} \dot{Q} + \frac{T\beta}{m} B^2 & 0 & \frac{T p_{\text{irr}}}{\chi_P} & -\frac{T}{T_a - T} \dot{Q} \\ 0 & 0 & 0 & 0 \\ \frac{T p_{\text{irr}}}{\chi_P} & 0 & \frac{T\beta}{m \chi_P^2} & 0 \\ -\frac{T}{T_a - T} \dot{Q} & 0 & 0 & \frac{T}{T_a (T_a - T)} \dot{Q} \end{pmatrix} \begin{pmatrix} \frac{1}{T} \\ \frac{p_{\text{rev}}}{T} \\ 0 \\ 1 \end{pmatrix}. \end{aligned} \quad (\text{A.5})$$

If we perform a variable transformation to the new, purely entropic, set of variables  $\mathbf{x} = (V \quad B \quad S \quad S_a)^T$  then the GENERIC form proves to be

$$\frac{d}{dt} \begin{pmatrix} V \\ B \\ S \\ S_a \end{pmatrix} = \begin{pmatrix} 0 & \frac{1}{\chi_P} & 0 & 0 \\ -\frac{1}{\chi_P} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} p_a - p_{\text{rev}} \\ \chi_P B \\ T \\ T_a \end{pmatrix}$$

$$+ \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{T\beta}{m\chi_P^2} & \frac{p_{irr}}{\chi_P} & 0 \\ 0 & \frac{p_{irr}}{\chi_P} & \frac{T_a}{T(T_a-T)}\dot{Q} + \frac{\beta}{T_m}B^2 & -\frac{1}{T_a-T}\dot{Q}^* \\ 0 & 0 & -\frac{1}{T_a-T}\dot{Q}^* & \frac{T}{T_a(T_a-T)}\dot{Q}^* \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \\ 1 \end{pmatrix}. \quad (\text{A.6})$$

In this latter realization, the reversible operator  $\mathbf{L}$  is simpler and is state-independent – see the Discussion on its benefits.

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# GOVERNING EQUATIONS AND FUNDAMENTAL SOLUTIONS FOR ISOTROPIC MICROPOLAR THERMOELASTIC MEDIUM WITH TRIPLE POROSITY AND MICROTEmPERATURES

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**Abstract.** This paper aims to establish the fundamental governing equations and develop corresponding fundamental solutions for a medium exhibiting isotropic micropolar thermoelastic properties, encompassing triple porosity and microtemperatures. By considering the unique characteristics of the material, we formulate a comprehensive framework to describe its behavior under various conditions, including steady-state, pseudo-static, quasi-static oscillations, and equilibrium.

*Mathematical Subject Classification:* 74A15, 74A20, 74B05, 74E10, 74F05.

*Keywords:* Triple porosity, microtemperature, pores, steady oscillations

## 1. INTRODUCTION

The micropolar theory of elasticity provides a valuable conceptual framework for understanding the microstructural motion of diverse materials, including polycrystalline materials and those with fibrous structures. By incorporating both displacement and microrotation vectors, this theory offers a comprehensive description of solid motion. Building upon this foundation, several researchers (referenced as [1–6]) have extended the micropolar theory to incorporate thermal effects, leading to the development of the micropolar theory of thermoelasticity. This expanded theory introduces a coupling between mechanical deformation and temperature changes in materials, enabling a deeper understanding of their behavior.

The three levels of porosity in triple porosity can be categorized based on their size or connectivity. For example, the primary porosity refers to the macroscopic or larger-scale voids within the material, such as large pores or fractures. The secondary porosity corresponds to intermediate-scale voids, which may include smaller fractures or microfractures. The tertiary porosity represents the smallest-scale voids, often at the microscale, such as pores within the grains or microcracks.

Each level of porosity contributes to the overall permeability and fluid flow characteristics of the material. The presence of multiple porosity levels can significantly

affect the behavior of porous media, including their mechanical, thermal, and transport properties. Triple porosity models are commonly employed in various fields, such as geomechanics, hydrogeology, petroleum engineering, and material science, where accurate characterization of porous materials is essential for understanding their performance and behavior.

The works of Svanadze [7], Straughan [8] and Kansal [9] have contributed to the establishment of governing equations in the field of elasticity and thermoelasticity, specifically addressing the concept of triple porosity. Svanadze [10–15] further investigated boundary value problems related to elastic solids and thermoelastic solids with triple porosity. The motivation behind developing theories for multiple porosity elasticity lies in the wide range of applications that require such frameworks, which continue to emerge. Straughan [16] has discussed various applications of multiple porosity in his book, shedding light on the practical significance of these theories across different disciplines.

Grot [17] extended the theory of thermodynamics of elastic bodies with microstructure by considering microelements with different temperatures. He modified the Clausius-Duhem inequality to incorporate microtemperatures and introduced first-order moment of energy equations to the basic balance laws. These modifications aimed to determine the microtemperatures of a continuum. Iesan and Quintanilla [18] constructed a linear theory for elastic materials with an inner structure that includes microtemperatures in addition to the classical displacement and temperature fields. They focused on the existence of solutions for initial boundary value problems using semigroup theory. They proved an existence theorem and established the continuous dependence of solutions on the initial data and body loads. Iesan [19] established the field equations of a theory of microstretch thermoelastic bodies with microtemperatures. He specifically worked on the dynamic theory of anisotropic materials and proved a uniqueness theorem. This theorem demonstrates the uniqueness of solutions within the dynamic theory of anisotropic materials, considering the presence of microtemperatures. Iesan [20] also derived a linear theory of microstretch elastic solids with microtemperatures, where each microelement of a continuum possesses mechanical degrees of freedom for rigid rotations and microdilatation, in addition to the classical translation degrees of freedom. Furthermore, he established a uniqueness result within the dynamical theory of anisotropic bodies, providing insights into the uniqueness of solutions in this context.

Indeed, fundamental solutions play a crucial role in solving boundary value problems, particularly in the context of elasticity and thermoelasticity. The use of fundamental solutions allows for an integral representation of the solution to a boundary value problem, which is often more amenable to numerical methods than directly solving a differential equation with specified boundary and initial conditions. In the investigation of boundary value problems within the theories of elasticity and thermoelasticity using the potential method, it becomes necessary to construct fundamental solutions for the corresponding systems of partial differential equations and establish their basic properties. These fundamental solutions serve as building blocks for solving more complex problems and provide insights into the behavior of the underlying

physical phenomena. Kansal [9, 21] and Svanadze [7, 22] has made contributions in this regard by constructing fundamental solutions using elementary functions in the theory of elasticity and thermoelasticity with triple porosity. By utilizing elementary functions, the solutions become more accessible and amenable to analysis and numerical techniques, facilitating the study and solution of boundary value problems within these theories.

This paper presents a comprehensive analysis of anisotropic generalized micropolar thermoelasticity with triple porosity and microtemperatures. The focus is on deriving the constitutive relations and field equations for this complex material system. Section 2 outlines the derivation of the constitutive equations and simplification of the anisotropic system into an isotropic system, facilitating analysis and interpretation. Sections 3 and 4 present the construction of the fundamental solution for steady oscillations, expressed in terms of elementary functions for ease of analysis. Section 5 extends the analysis to pseudo-static, quasi-static oscillations, and equilibrium, providing a comprehensive understanding of the material's behavior under different conditions. Section 6 establishes fundamental properties of the fundamental matrix to enhance the understanding of the obtained solutions and their implications.

## 2. BASIC EQUATIONS

Following [1–5], the equations of motions of a linear micropolar elasticity are

$$\sigma_{ji,j} + \rho \tilde{F}_i = \rho \ddot{u}_i, \quad (2.1)$$

$$\varepsilon_{ijq} \sigma_{jq} + \mu_{ji,j} + \rho \tilde{G}_i = \rho J_{ij} \ddot{\varphi}_j. \quad (2.2)$$

Following [23], the balance of first moment of energy is given by

$$\rho \dot{\varepsilon}_i = -Q_{ji,j} - q_i + Q_i, \quad (2.3)$$

where  $\sigma_{ji}$  are the components of stress tensor,  $\mu_{ji}$  are the components of couple stress tensor,  $\rho$  is the density,  $u_i$  are the components of the displacement vector  $\mathbf{u}$ ,  $\tilde{F}_i$  are the components of the external forces per unit mass,  $\tilde{G}_i$  are the components of the external applied couple per unit mass,  $\varepsilon_{ijq}$  is the alternating tensor,  $J_{ij}$  are the components of microinertia tensor,  $\varphi_j$  are the components of microrotation vector  $\boldsymbol{\varphi}$ ,  $\varepsilon_i$  is the first moment of energy vector,  $q_i$  is the heat flux vector,  $Q_{ji}$  is the first heat flux moment tensor,  $Q_i$  is the micro heat flux average vector.

The law of conservation of energy for an arbitrary material volume  $V$  bounded by a surface  $A$  at time  $t$  can be written as

$$\begin{aligned} & \int_V \rho [\dot{u}_i \ddot{u}_i + J_{ij} \dot{\varphi}_i \ddot{\varphi}_j + k_1 \dot{\nu}_1 \ddot{\nu}_1 + k_2 \dot{\nu}_2 \ddot{\nu}_2 + k_3 \dot{\nu}_3 \ddot{\nu}_3 + \dot{U}] dV = \\ & \int_V \rho [\tilde{F}_i \dot{u}_i + \tilde{G}_i \dot{\varphi}_i + \Lambda_i \dot{\nu}_i] dV + \int_A [f_i \dot{u}_i + \mu_i \dot{\varphi}_i + \Omega_{ij} \varpi_j \dot{\nu}_i - q_i \varpi_i] dA, \end{aligned} \quad (2.4)$$

where  $U$  is the internal energy per unit mass,  $f_i$  are the components of surface traction vector  $\mathbf{f}$  occurring on the surface  $A$ ,  $\mu_i$  are the components of couple stress vector  $\boldsymbol{\mu}$  occurring on the surface  $A$ ,  $\nu_i$  are the volume fraction fields corresponding to macro-, meso-, micro-pores respectively,  $k_i$  are the coefficients of equilibrated inertia,  $\Lambda_i$  are

extrinsic equilibrated body forces per unit mass associated to macro-, meso-, micro-pores respectively,  $\Omega_{ij}$  are the components of equilibrated stress vectors corresponding to  $\nu_i$  measured per unit area of surface  $A$  respectively,  $\varpi_i$  are the components of outward unit normal vector  $\varpi$  to the surface  $A$ .

The components  $f_i$  and  $\mu_i$  are, respectively, connected to stress and couple stress vectors by the relations

$$f_i = \sigma_{ji}\varpi_j, \quad \mu_i = \mu_{ji}\varpi_j. \quad (2.5)$$

Using equation (2.5) in equation (2.4) and applying divergence theorem, we get

$$\begin{aligned} \int_V \rho[\dot{u}_i \ddot{u}_i + J_{ij} \dot{\varphi}_i \ddot{\varphi}_j + k_1 \dot{\nu}_1 \ddot{\nu}_1 + k_2 \dot{\nu}_2 \ddot{\nu}_2 + k_3 \dot{\nu}_3 \ddot{\nu}_3 + \dot{U}] dV &= \int_V \rho[\tilde{F}_i \dot{u}_i + \tilde{G}_i \dot{\varphi}_i + \Lambda_i \dot{\nu}_i] dV + \\ &\int_V [\sigma_{ji,j} \dot{u}_i + \sigma_{ji} \dot{u}_{i,j} + \mu_{ji,j} \dot{\varphi}_i + \mu_{ji} \dot{\varphi}_{i,j} + \Omega_{ij,j} \dot{\nu}_i + \Omega_{ij} \dot{\nu}_{i,j} - q_{i,i}] dV. \end{aligned} \quad (2.6)$$

Since equation (2.6) is valid for every part of the body, therefore local form of conservation of energy is obtained as

$$\begin{aligned} \rho[\dot{u}_i \ddot{u}_i + J_{ij} \dot{\varphi}_i \ddot{\varphi}_j + k_1 \dot{\nu}_1 \ddot{\nu}_1 + k_2 \dot{\nu}_2 \ddot{\nu}_2 + k_3 \dot{\nu}_3 \ddot{\nu}_3 + \dot{U}] &= \rho[\tilde{F}_i \dot{u}_i + \tilde{G}_i \dot{\varphi}_i + \Lambda_i \dot{\nu}_i] + \\ &\sigma_{ji,j} \dot{u}_i + \sigma_{ji} \dot{u}_{i,j} + \mu_{ji,j} \dot{\varphi}_i + \mu_{ji} \dot{\varphi}_{i,j} + \Omega_{ij,j} \dot{\nu}_i + \Omega_{ij} \dot{\nu}_{i,j} - q_{i,i}. \end{aligned} \quad (2.7)$$

Equation (2.7) with the assistance of equations (2.1) and (2.2) yields a simplified form of conservation of energy

$$\rho \dot{U} = \sigma_{ji} \dot{\varepsilon}_{ji} + \mu_{ji} \dot{\varphi}_{i,j} + \Omega_{ij} \dot{\nu}_{i,j} - q_{i,i} - \Upsilon_i \dot{\nu}_i, \quad (2.8)$$

where  $\varepsilon_{ji}$  and  $\Upsilon_i$ ,  $i = 1, 2, 3$  satisfy the relations

$$\begin{aligned} \varepsilon_{ji} &= u_{i,j} - \varepsilon_{qji} \varphi_q, \quad \Omega_{1j,j} + \Upsilon_1 + \rho \Lambda_1 = \rho k_1 \dot{\nu}_1, \\ \Omega_{2j,j} + \Upsilon_2 + \rho \Lambda_2 &= \rho k_2 \dot{\nu}_2, \quad \Omega_{3j,j} + \Upsilon_3 + \rho \Lambda_3 = \rho k_3 \dot{\nu}_3. \end{aligned} \quad (2.9)$$

The local form of the principle of entropy can be expressed in the form of an inequality called Clausius-Duhem inequality

$$\rho \dot{S} + \frac{q_{i,i}}{T} - \frac{q_i}{T^2} T_{,i} + \frac{Q_{ji,j}}{T} T_i - \frac{Q_{ji}}{T^2} T_{,j} T_i + \frac{Q_{ji}}{T} T_{i,j} \geq 0, \quad (2.10)$$

where  $S$  is entropy per unit mass,  $T$  is absolute temperature,  $T_i$  is the microtemperature vector. Equation (2.8) with the use of equation (2.3) and inequality (2.10) can be expressed as

$$\begin{aligned} \rho[T\dot{S} - \dot{U} - T_i \dot{\varepsilon}_i] + \sigma_{ji} \dot{\varepsilon}_{ji} + \mu_{ji} \dot{\varphi}_{i,j} + \Omega_{ij} \dot{\nu}_{i,j} - \Upsilon_i \dot{\nu}_i - \frac{q_i}{T} T_{,i} - \\ - \frac{Q_{ji}}{T} T_{,j} T_i + Q_{ji} T_{i,j} - (q_i - Q_i) T_i \geq 0. \end{aligned} \quad (2.11)$$

The Helmholtz free energy function  $\Gamma$  is defined as

$$\Gamma = U + T_i \varepsilon_i - TS.$$

Then, relation (2.11) in the context of linear theory becomes

$$\begin{aligned} -\rho[\dot{\Gamma} + \dot{T}S - \dot{T}_i \varepsilon_i] + \sigma_{ji} \dot{\varepsilon}_{ji} + \mu_{ji} \dot{\varphi}_{i,j} + \Omega_{ij} \dot{\nu}_{i,j} - \\ - \Upsilon_i \dot{\nu}_i - \frac{q_i}{T} T_{,i} + Q_{ji} T_{i,j} - (q_i - Q_i) T_i \geq 0. \end{aligned} \quad (2.12)$$



The function  $\Gamma$  can be expressed in terms of the independent variables

$$\varepsilon_{ji}, \varphi_{i,j}, \nu_i, \nu_{i,j}, T, T_i, T_i \text{ and } T_{i,j}.$$

Therefore, we have

$$\dot{\Gamma} = \frac{\partial \Gamma}{\partial \varepsilon_{ji}} \dot{\varepsilon}_{ji} + \frac{\partial \Gamma}{\partial \varphi_{i,j}} \dot{\varphi}_{i,j} + \frac{\partial \Gamma}{\partial \nu_i} \dot{\nu}_i + \frac{\partial \Gamma}{\partial \nu_{i,j}} \dot{\nu}_{i,j} + \frac{\partial \Gamma}{\partial T} \dot{T} + \frac{\partial \Gamma}{\partial T_i} \dot{T}_i + \frac{\partial \Gamma}{\partial T_{i,j}} \dot{T}_{i,j}. \quad (2.13)$$

Inequality (2.12) with the help of equation (2.13) becomes

$$\begin{aligned} & \left[ \sigma_{ji} - \rho \frac{\partial \Gamma}{\partial \varepsilon_{ji}} \right] \dot{\varepsilon}_{ji} + \left[ \mu_{ji} - \rho \frac{\partial \Gamma}{\partial \varphi_{i,j}} \right] \dot{\varphi}_{i,j} + \left[ \Omega_{ij} - \rho \frac{\partial \Gamma}{\partial \nu_{i,j}} \right] \dot{\nu}_{i,j} - \left[ \Upsilon_i + \rho \frac{\partial \Gamma}{\partial \nu_i} \right] \dot{\nu}_i \\ & - \rho \left[ S + \frac{\partial \Gamma}{\partial T} \right] \dot{T} + \rho \left[ \varepsilon_i - \frac{\partial \Gamma}{\partial T_i} \right] \dot{T}_i - \rho \frac{\partial \Gamma}{\partial T_{i,j}} \dot{T}_{i,j} \\ & - \frac{q_i}{T} T_{i,j} + Q_{ji} T_{i,j} - (q_i - Q_i) T_i \geq 0. \end{aligned}$$

Let us introduce the notations

$$\phi = \nu - \nu_0, \quad \theta = T - T_0,$$

where  $\phi = (\phi_1, \phi_2, \phi_3)$ ,  $T_0$  is the reference temperature of the body chosen such that  $|\frac{\theta}{T_0}| \ll 1$ ,  $\nu_0$  are the volume fraction fields in reference configuration.

In the linear theory, the independent variables are  $\varepsilon_{ji}, \varphi_{i,j}, \phi_i, \phi_{i,j}, \theta$  and  $T_i$ . The above inequality should be convinced for all rates  $\dot{\varepsilon}_{ji}, \dot{\varphi}_{i,j}, \dot{\phi}_i, \dot{\phi}_{i,j}, \dot{\theta}, \dot{\theta}_{i,j}, \dot{T}_i$  and  $\dot{T}_{i,j}$ . Hence the coefficients of above variables must vanish, that is,

$$\begin{aligned} \sigma_{ji} &= \rho \frac{\partial \Gamma}{\partial \varepsilon_{ji}}, \mu_{ji} = \rho \frac{\partial \Gamma}{\partial \varphi_{i,j}}, \Omega_{ij} = \rho \frac{\partial \Gamma}{\partial \phi_{i,j}}, \Upsilon_i = -\rho \frac{\partial \Gamma}{\partial \phi_i}, \\ S &= -\frac{\partial \Gamma}{\partial \theta}, \varepsilon_i = \frac{\partial \Gamma}{\partial T_i}, \frac{\partial \Gamma}{\partial T_{i,j}} = \frac{\partial \Gamma}{\partial T_{i,j}} = 0, \\ -q_i \theta_{i,j} + T_0 Q_{ji} T_{i,j} - T_0 (q_i - Q_i) T_i &\geq 0. \end{aligned} \quad (2.14)$$

It is assumed that the undeformed body is free from stresses and has zero intrinsic equilibrated body forces and entropy. If the body has a centre of symmetry, then we have

$$\begin{aligned} 2\rho\Gamma &= c_{jipl}\varepsilon_{ji}\varepsilon_{pl} + d_{jipl}\varphi_{j,i}\varphi_{p,l} - 2a_{ji}\varepsilon_{ji}\theta + 2b_{ji}\varepsilon_{ji}\phi_1 + 2c_{ji}\varepsilon_{ji}\phi_2 \\ &+ 2d_{ji}\varepsilon_{ji}\phi_3 + \alpha_i\phi_i^2 + 2\alpha_4\phi_1\phi_2 + 2\alpha_5\phi_2\phi_3 + 2\alpha_6\phi_3\phi_1 \\ &+ A_{ij}\phi_{1,i}\phi_{1,j} + B_{ij}\phi_{2,i}\phi_{2,j} + C_{ij}\phi_{3,i}\phi_{3,j} + 2D_{ij}\phi_{1,i}\phi_{2,j} + 2E_{ij}\phi_{2,i}\phi_{3,j} \\ &+ 2F_{ij}\phi_{3,i}\phi_{1,j} - 2\ell_i\phi_i\theta - \frac{a\theta^2}{T_0} - s_{ij}T_iT_j - 2r_{ij}\phi_{1,j}T_i - 2t_{ij}\phi_{2,j}T_i - 2v_{ij}\phi_{3,j}T_i. \end{aligned}$$

Here  $c_{jipl}$  is the tensor of elastic constants,  $d_{jipl}$  is the tensor of microrotation constants,  $a_{ji}$  is the tensor of thermal expansion,  $b_{ji}, c_{ji}, d_{ji}, A_{ij}, B_{ij}, C_{ij}, D_{ij}, E_{ij}, F_{ij}$  and  $\alpha_i$ ,  $i = 1, \dots, 6$  are functions which are typical in porous theories,  $\ell_i$  is coupling constant,  $r_{ij}, t_{ij}$  and  $v_{ij}$  are coupling tensors and  $s_{ij}$  is the tensor of microtemperature effect. The constitutive coefficients have the following symmetries

$$\begin{aligned} c_{jipl} &= c_{plji} = c_{ijpl}, & d_{jipl} &= d_{plji} = d_{ijpl}, & a_{ji} &= a_{ij}, & b_{ji} &= b_{ij}, \\ c_{ji} &= c_{ij}, & d_{ji} &= d_{ij}, & A_{ij} &= A_{ji}, & B_{ij} &= B_{ji}, \end{aligned}$$

$$\begin{aligned} C_{ij} &= C_{ji}, & D_{ij} &= D_{ji}, & E_{ij} &= E_{ji}, & F_{ij} &= F_{ji}, \\ s_{ij} &= s_{ji}, & r_{ij} &= r_{ji}, & t_{ij} &= t_{ji}, & v_{ij} &= v_{ji}. \end{aligned}$$

Using the previous equation in the system of equations (2.14), the following constitutive equations are obtained:

$$\sigma_{ji} = c_{jipl}\varepsilon_{pl} + b_{ji}\phi_1 + c_{ji}\phi_2 + d_{ji}\phi_3 - a_{ji}\theta, \quad (2.15)$$

$$\mu_{ji} = d_{ijpl}\varphi_{p,l}, \quad (2.16)$$

$$\begin{aligned} \Omega_{1j} &= A_{ij}\phi_{1,i} + D_{ij}\phi_{2,i} + F_{ij}\phi_{3,i} - r_{ij}T_i, \\ \Omega_{2j} &= D_{ij}\phi_{1,i} + B_{ij}\phi_{2,i} + E_{ij}\phi_{3,i} - t_{ij}T_i, \end{aligned} \quad (2.17)$$

$$\begin{aligned} \Omega_{3j} &= F_{ij}\phi_{1,i} + E_{ij}\phi_{2,i} + C_{ij}\phi_{3,i} - v_{ij}T_i, \\ \Upsilon_1 &= -b_{ji}\varepsilon_{ji} - \alpha_1\phi_1 - \alpha_4\phi_2 - \alpha_6\phi_3 + \ell_1\theta, \\ \Upsilon_2 &= -c_{ji}\varepsilon_{ji} - \alpha_4\phi_1 - \alpha_2\phi_2 - \alpha_5\phi_3 + \ell_2\theta, \\ \Upsilon_3 &= -d_{ji}\varepsilon_{ji} - \alpha_6\phi_1 - \alpha_5\phi_2 - \alpha_3\phi_3 + \ell_3\theta, \end{aligned} \quad (2.18)$$

$$\rho S = a_{ji}\varepsilon_{ji} + \ell_i\phi_i + \frac{a\theta}{T_0}, \quad (2.19)$$

$$\rho\varepsilon_i = -r_{ij}\phi_{1,j} - t_{ij}\phi_{2,j} - v_{ij}\phi_{3,j} - s_{ij}T_j. \quad (2.20)$$

The linear expressions for  $q_i$ ,  $Q_i$  and  $Q_{ij}$  are

$$q_i = -[k_{ij}\theta_{,j} + \kappa_{ij}T_j], \quad (2.21)$$

$$Q_i = (K_{ij} - k_{ij})\theta_{,j} + (-\kappa_{ij} + L_{ij})T_j, \quad (2.22)$$

$$Q_{ij} = m_{ijpl}T_{l,p}, \quad (2.23)$$

where the consecutive coefficients  $k_{ij}$ ,  $\kappa_{ij}$ ,  $K_{ij}$ ,  $L_{ij}$  and  $m_{ijpl}$  satisfy the inequality

$$k_{ij}\theta_{,i}\theta_{,j} + (\kappa_{ji} + T_0K_{ij})\theta_{,j}T_i + T_0L_{ij}T_iT_j + T_0m_{ijpl}T_{l,p}T_{i,j} \geq 0.$$

and the following symmetries

$$k_{ij} = k_{ji}, \quad \kappa_{ij} = \kappa_{ji}, \quad K_{ij} = K_{ji}, \quad L_{ij} = L_{ji}, \quad m_{ijpl} = m_{jipl}$$

The linearized form of inequality (2.10) is

$$\rho T_0 \dot{S} = -q_{i,i}. \quad (2.24)$$

In view of equations (15)-(23), equations (2.1)-(2.3), (2.9) and (2.24) become

$$\begin{aligned} c_{jipl}\varepsilon_{pl,j} + b_{ji}\phi_{1,j} + c_{ji}\phi_{2,j} + d_{ji}\phi_{3,j} - a_{ji}\theta_{,j} + \rho\tilde{F}_i &= \rho\ddot{u}_i, \\ \varepsilon_{ijq}(c_{jqpl}\varepsilon_{pl} + b_{jq}\phi_1 + c_{jq}\phi_2 + d_{jq}\phi_3 - a_{jq}\theta) + d_{ijpl}\varphi_{p,lj} + \rho\tilde{G}_i &= \rho J_{ij}\ddot{\varphi}_j, \\ -b_{ji}\varepsilon_{ji} + A_{ij}\phi_{1,ij} + D_{ij}\phi_{2,ij} + F_{ij}\phi_{3,ij} - \alpha_1\phi_1 - \alpha_4\phi_2 - \alpha_6\phi_3 + \ell_1\theta + \rho\Lambda_1 - r_{ij}T_{i,j} &= \rho k_1\ddot{\phi}_1, \\ -c_{ji}\varepsilon_{ji} + D_{ij}\phi_{1,ij} + B_{ij}\phi_{2,ij} + E_{ij}\phi_{3,ij} - \alpha_4\phi_1 - \alpha_2\phi_2 - \alpha_5\phi_3 + \ell_2\theta + \rho\Lambda_2 - t_{ij}T_{i,j} &= \rho k_2\ddot{\phi}_2, \\ -d_{ji}\varepsilon_{ji} + F_{ij}\phi_{1,ij} + E_{ij}\phi_{2,ij} + C_{ij}\phi_{3,ij} - \alpha_6\phi_1 - \alpha_5\phi_2 - \alpha_3\phi_3 + \ell_3\theta + \rho\Lambda_3 - v_{ij}T_{i,j} &= \rho k_3\ddot{\phi}_3. \\ T_0 \left[ a_{ji}\dot{\varepsilon}_{ij} + \ell_i\dot{\phi}_i \right] + a\dot{\theta} &= k_{ij}\theta_{,ij} + \kappa_{ij}T_{j,i}, \\ m_{jipl}T_{l,pj} - s_{ij}\dot{T}_j - r_{ij}\dot{\phi}_{1,j} - t_{ij}\dot{\phi}_{2,j} - v_{ij}\dot{\phi}_{3,j} &= K_{ij}\theta_{,j} + L_{ij}T_j. \end{aligned} \quad (2.25)$$

If we take

$$c_{jipl} = \lambda\delta_{ji}\delta_{pl} + (\mu + K^*)\delta_{jp}\delta_{il} + \mu\delta_{jl}\delta_{ip}, \quad J_{ij} = J\delta_{ij}, \quad s_{ij} = \chi\delta_{ij},$$

$$\begin{aligned}
d_{jip} &= \alpha \delta_{ji} \delta_{pl} + \gamma \delta_{jp} \delta_{il} + \beta \delta_{jl} \delta_{ip}, a_{ij} = \vartheta \delta_{ij}, \\
b_{ij} &= \mathfrak{R}_1 \delta_{ij}, c_{ij} = \mathfrak{R}_2 \delta_{ij}, d_{ij} = \mathfrak{R}_3 \delta_{ij}, A_{ij} = A_1 \delta_{ij}, B_{ij} = A_2 \delta_{ij}, \\
C_{ij} &= A_3 \delta_{ij}, D_{ij} = A_4 \delta_{ij}, E_{ij} = A_5 \delta_{ij}, F_{ij} = A_6 \delta_{ij}, \\
r_{ij} &= r_1 \delta_{ij}, t_{ij} = r_2 \delta_{ij}, v_{ij} = r_3 \delta_{ij}, m_{ijpl} = \kappa_4 \delta_{ij} \delta_{pl} + \kappa_6 \delta_{ip} \delta_{jl} + \kappa_5 \delta_{il} \delta_{jp}, \\
k_{ij} &= k \delta_{ij}, \kappa_{ij} = \kappa_1 \delta_{ij}, L_{ij} = \kappa_2 \delta_{ij}, K_{ij} = \kappa_3 \delta_{ij},
\end{aligned}$$

where  $\delta_{ij}$  is Kronecker's delta and  $\lambda, \mu, K^*, \alpha, \beta, \gamma, \vartheta, J, \chi, \kappa_1, \dots, \kappa_6, A_1, \dots, A_6, \mathfrak{R}_1, \mathfrak{R}_2, \mathfrak{R}_3, k, r_1, r_2, r_3$  are material constants in equations (2.25), the governing equations for homogeneous isotropic generalized micropolar thermoelasticity with triple porosity and microtemperatures in absence of body forces and couples are obtained as

$$\begin{aligned}
(\mu + K^*) \Delta \mathbf{u} + (\lambda + \mu) \nabla \operatorname{div} \mathbf{u} + K^* \operatorname{curl} \boldsymbol{\varphi} + \mathfrak{R}_i \nabla \phi_i - \vartheta \nabla \theta &= \rho \ddot{\mathbf{u}}, \\
K^* \operatorname{curl} \mathbf{u} + (\gamma \Delta - 2K^*) \boldsymbol{\varphi} + (\alpha + \beta) \nabla \operatorname{div} \boldsymbol{\varphi} &= \rho J \ddot{\boldsymbol{\varphi}}, \\
-\mathfrak{R}_1 \operatorname{div} \mathbf{u} + (A_1 \Delta - \alpha_1) \phi_1 + (A_4 \Delta - \alpha_4) \phi_2 + (A_6 \Delta - \alpha_6) \phi_3 + \ell_1 \theta - r_1 \operatorname{div} \mathbf{w} &= \rho k_1 \ddot{\phi}_1, \\
-\mathfrak{R}_2 \operatorname{div} \mathbf{u} + (A_4 \Delta - \alpha_4) \phi_1 + (A_2 \Delta - \alpha_2) \phi_2 + (A_5 \Delta - \alpha_5) \phi_3 + \ell_2 \theta - r_2 \operatorname{div} \mathbf{w} &= \rho k_2 \ddot{\phi}_2, \\
-\mathfrak{R}_3 \operatorname{div} \mathbf{u} + (A_6 \Delta - \alpha_6) \phi_1 + (A_5 \Delta - \alpha_5) \phi_2 + (A_3 \Delta - \alpha_3) \phi_3 + \ell_3 \theta - r_3 \operatorname{div} \mathbf{w} &= \rho k_3 \ddot{\phi}_3, \\
T_0 [\vartheta \operatorname{div} \dot{\mathbf{u}} + \ell_i \dot{\phi}_i] + a \dot{\theta} &= k \Delta \theta + \kappa_1 \operatorname{div} \mathbf{w}, \\
\kappa_6 \Delta \mathbf{w} + (\kappa_4 + \kappa_5) \nabla \operatorname{div} \mathbf{w} - \chi \dot{\mathbf{w}} - r_i \nabla \dot{\phi}_i &= \kappa_3 \nabla \theta + \kappa_2 \mathbf{w}, \tag{2.26}
\end{aligned}$$

where  $\mathbf{w} = (T_1, T_2, T_3)$  is microrotation vector and  $\Delta, \nabla$  are the Laplacian and Nabla operators, respectively.

### 3. STEADY OSCILLATIONS

Let  $\mathbf{x} = (x_1, x_2, x_3)$  be the point of the Euclidean three-dimensional space  $E^3$ :

$$|\mathbf{x}| = (x_1^2 + x_2^2 + x_3^2)^{\frac{1}{2}}, \quad \mathbf{D}_{\mathbf{x}} = \left( \frac{\partial}{\partial x_1}, \frac{\partial}{\partial x_2}, \frac{\partial}{\partial x_3} \right).$$

The displacement vector, microrotation vector, volume fraction fields, temperature change and microtemperature vector functions are assumed as:

$$\left[ \mathbf{u}(\mathbf{x}, t), \boldsymbol{\varphi}(\mathbf{x}, t), \phi(\mathbf{x}, t), \theta(\mathbf{x}, t), \mathbf{w}(\mathbf{x}, t) \right] = \operatorname{Re} \left[ (\mathbf{u}^*, \boldsymbol{\varphi}^*, \phi^*, \theta^*, \mathbf{w}^*) e^{-i\omega t} \right], \tag{3.1}$$

where  $\omega$  is oscillation frequency.

Using equation (3.1) in the system of equations (2.26) and omitting asterisk (\*) for simplicity, the system of equations for the steady oscillations are obtained as

$$\begin{aligned}
(\mu + K^*) \Delta \mathbf{u} + [(\lambda + \mu) \nabla \operatorname{div} + \rho \omega^2] \mathbf{u} + K^* \operatorname{curl} \boldsymbol{\varphi} + \mathfrak{R}_i \nabla \phi_i - \vartheta \nabla \theta &= \mathbf{0}, \\
K^* \operatorname{curl} \mathbf{u} + \gamma \Delta \boldsymbol{\varphi} + [(\alpha + \beta) \nabla \operatorname{div} - 2K^* + \rho J \omega^2] \boldsymbol{\varphi} &= \mathbf{0}, \\
-\mathfrak{R}_1 \operatorname{div} \mathbf{u} + (A_1 \Delta - \beta_1) \phi_1 + (A_4 \Delta - \alpha_4) \phi_2 + (A_6 \Delta - \alpha_6) \phi_3 + \ell_1 \theta - r_1 \operatorname{div} \mathbf{w} &= 0, \\
-\mathfrak{R}_2 \operatorname{div} \mathbf{u} + (A_4 \Delta - \alpha_4) \phi_1 + (A_2 \Delta - \beta_2) \phi_2 + (A_5 \Delta - \alpha_5) \phi_3 + \ell_2 \theta - r_2 \operatorname{div} \mathbf{w} &= 0, \\
-\mathfrak{R}_3 \operatorname{div} \mathbf{u} + (A_6 \Delta - \alpha_6) \phi_1 + (A_5 \Delta - \alpha_5) \phi_2 + (A_3 \Delta - \beta_3) \phi_3 + \ell_3 \theta - r_3 \operatorname{div} \mathbf{w} &= 0, \\
i\omega T_0 [\vartheta \operatorname{div} \mathbf{u} + \ell_i \phi_i] + [k \Delta + i\omega a] \theta + \kappa_1 \operatorname{div} \mathbf{w} &= 0, \\
i\omega r_i \nabla \phi_i - \kappa_3 \nabla \theta + [\kappa_6 \Delta + (\kappa_4 + \kappa_5) \nabla \operatorname{div} - \kappa_2 + i\omega \chi] \mathbf{w} &= \mathbf{0}, \tag{3.2}
\end{aligned}$$

where  $\beta_i = \alpha_i - \rho\omega^2 k_i$ ,  $i = 1, 2, 3$ .

If we replace  $\omega$  by  $-\iota\tau$ , where  $\tau$  is a complex number and  $Re(\tau) > 0$  in the equations (3.2), we obtain the system of equations for the pseudo-oscillations as:

$$\begin{aligned}
& (\mu + K^*)\Delta \mathbf{u} + [(\lambda + \mu)\nabla \text{div} - \rho\tau^2]\mathbf{u} + K^* \text{curl } \boldsymbol{\varphi} + \Re_i \nabla \phi_i - \vartheta \nabla \theta = \mathbf{0}, \\
& K^* \text{curl } \mathbf{u} + \gamma \Delta \boldsymbol{\varphi} + [(\alpha + \beta) \nabla \text{div} - 2K^* - \rho J \tau^2] \boldsymbol{\varphi} = \mathbf{0}, \\
& -\Re_1 \text{div } \mathbf{u} + (A_1 \Delta - \tilde{\beta}_1) \phi_1 + (A_4 \Delta - \alpha_4) \phi_2 + (A_6 \Delta - \alpha_6) \phi_3 + \ell_1 \theta - r_1 \text{div } \mathbf{w} = 0, \\
& -\Re_2 \text{div } \mathbf{u} + (A_4 \Delta - \alpha_4) \phi_1 + (A_2 \Delta - \tilde{\beta}_2) \phi_2 + (A_5 \Delta - \alpha_5) \phi_3 + \ell_2 \theta - r_2 \text{div } \mathbf{w} = 0, \\
& -\Re_3 \text{div } \mathbf{u} + (A_6 \Delta - \alpha_6) \phi_1 + (A_5 \Delta - \alpha_5) \phi_2 + (A_3 \Delta - \tilde{\beta}_3) \phi_3 + \ell_3 \theta - r_3 \text{div } \mathbf{w} = 0, \\
& \tau T_0 [\vartheta \text{div } \mathbf{u} + \ell_i \phi_i] + [k\Delta + \tau a] \theta + \kappa_1 \text{div } \mathbf{w} = 0, \\
& \tau r_i \nabla \phi_i - \kappa_3 \nabla \theta + [\kappa_6 \Delta + (\kappa_4 + \kappa_5) \nabla \text{div} - \kappa_2 + \tau \chi] \mathbf{w} = \mathbf{0}, \tag{3.3}
\end{aligned}$$

where

$$\tilde{\beta}_i = \alpha_i + \rho\tau^2 k_i, \quad i = 1, 2, 3.$$

If we put  $\rho = 0$ , i.e. neglecting inertial effect in the equations (3.2), we obtain the system of equations of quasi-static oscillations as:

$$\begin{aligned}
& [(\mu + K^*)\Delta + (\lambda + \mu)\nabla \text{div}] \mathbf{u} + K^* \text{curl } \boldsymbol{\varphi} + \Re_i \nabla \phi_i - \vartheta \nabla \theta = \mathbf{0}, \\
& K^* \text{curl } \mathbf{u} + \gamma \Delta \boldsymbol{\varphi} + [(\alpha + \beta) \nabla \text{div} - 2K^*] \boldsymbol{\varphi} = \mathbf{0}, \\
& -\Re_1 \text{div } \mathbf{u} + (A_1 \Delta - \alpha_1) \phi_1 + (A_4 \Delta - \alpha_4) \phi_2 + (A_6 \Delta - \alpha_6) \phi_3 + \ell_1 \theta - r_1 \text{div } \mathbf{w} = 0, \\
& -\Re_2 \text{div } \mathbf{u} + (A_4 \Delta - \alpha_4) \phi_1 + (A_2 \Delta - \alpha_2) \phi_2 + (A_5 \Delta - \alpha_5) \phi_3 + \ell_2 \theta - r_2 \text{div } \mathbf{w} = 0, \\
& -\Re_3 \text{div } \mathbf{u} + (A_6 \Delta - \alpha_6) \phi_1 + (A_5 \Delta - \alpha_5) \phi_2 + (A_3 \Delta - \alpha_3) \phi_3 + \ell_3 \theta - r_3 \text{div } \mathbf{w} = 0, \\
& \iota\omega T_0 [\vartheta \text{div } \mathbf{u} + \ell_i \phi_i] + [k\Delta + \iota\omega a] \theta + \kappa_1 \text{div } \mathbf{w} = 0, \\
& \iota\omega r_i \nabla \phi_i - \kappa_3 \nabla \theta + [\kappa_6 \Delta + (\kappa_4 + \kappa_5) \nabla \text{div} - \kappa_2 + \iota\omega \chi] \mathbf{w} = \mathbf{0}. \tag{3.4}
\end{aligned}$$

If we put  $\omega = 0$  in the equations (3.2), we obtain the system of equations in equilibrium theory of micropolar thermoelasticity with triple porosity and microtemperatures as:

$$\begin{aligned}
& [(\mu + K^*)\Delta + (\lambda + \mu)\nabla \text{div}] \mathbf{u} + K^* \text{curl } \boldsymbol{\varphi} + \Re_i \nabla \phi_i - \vartheta \nabla \theta = \mathbf{0}, \\
& K^* \text{curl } \mathbf{u} + \gamma \Delta \boldsymbol{\varphi} + [(\alpha + \beta) \nabla \text{div} - 2K^*] \boldsymbol{\varphi} = \mathbf{0}, \\
& -\Re_1 \text{div } \mathbf{u} + (A_1 \Delta - \alpha_1) \phi_1 + (A_4 \Delta - \alpha_4) \phi_2 + (A_6 \Delta - \alpha_6) \phi_3 + \ell_1 \theta - r_1 \text{div } \mathbf{w} = 0, \\
& -\Re_2 \text{div } \mathbf{u} + (A_4 \Delta - \alpha_4) \phi_1 + (A_2 \Delta - \alpha_2) \phi_2 + (A_5 \Delta - \alpha_5) \phi_3 + \ell_2 \theta - r_2 \text{div } \mathbf{w} = 0, \\
& -\Re_3 \text{div } \mathbf{u} + (A_6 \Delta - \alpha_6) \phi_1 + (A_5 \Delta - \alpha_5) \phi_2 + (A_3 \Delta - \alpha_3) \phi_3 + \ell_3 \theta - r_3 \text{div } \mathbf{w} = 0, \\
& k\Delta \theta + \kappa_1 \text{div } \mathbf{w} = 0, \\
& -\kappa_3 \nabla \theta + [\kappa_6 \Delta + (\kappa_4 + \kappa_5) \nabla \text{div} - \kappa_2] \mathbf{w} = \mathbf{0}. \tag{3.5}
\end{aligned}$$

We introduce the second order matrix differential operators with constant coefficients

$$\mathbf{F}^{(i)}(\mathbf{D}_{\mathbf{x}}) = \left( F_{gh}^{(i)}(\mathbf{D}_{\mathbf{x}}) \right)_{13 \times 13}, \tag{3.6}$$

where  $F_{gh}^{(i)}(\mathbf{D}_{\mathbf{x}})$ ;  $g, h = 1, \dots, 13$  are given in Appendix A.

Here  $i = 1, 2, 3, 4$  corresponds to static, pseudo-, quasi-static oscillations and equilibrium theory of micropolar thermoelasticity with triple porosity and microtemperatures respectively. The matrices  $\mathbf{F}^{(i)}(\mathbf{D}_\mathbf{x})$ ,  $i = 2, 3, 4$  can be obtained from matrix  $\mathbf{F}^{(1)}(\mathbf{D}_\mathbf{x})$  by taking  $\omega = -\iota\tau$ ,  $\rho = 0$  and  $\omega = 0$ , respectively:

$$\tilde{\mathbf{F}}(\mathbf{D}_\mathbf{x}) = \left( \tilde{F}_{gh}(\mathbf{D}_\mathbf{x}) \right)_{13 \times 13},$$

where  $\tilde{F}_{gh}(\mathbf{D}_\mathbf{x})$ ,  $g, h = 1, \dots, 13$  are given in Appendix A.

The system of equations (3.2)-(3.5) can be represented as

$$\mathbf{F}^{(i)}(\mathbf{D}_\mathbf{x})\mathbf{U}(\mathbf{x}) = \mathbf{0}, \quad i = 1, 2, 3, 4,$$

where  $\mathbf{U} = (\mathbf{u}, \boldsymbol{\varphi}, \phi, \theta, \mathbf{w})$  is a thirteen-component vector function on  $E^3$ . The matrix  $\tilde{\mathbf{F}}(\mathbf{D}_\mathbf{x})$  is called the principal part of operator  $\mathbf{F}^{(i)}(\mathbf{D}_\mathbf{x})$ .

**Definition 1:** The operator  $\mathbf{F}^{(i)}(\mathbf{D}_\mathbf{x})$ ,  $i = 1, 2, 3, 4$  is said to be elliptic if  $|\tilde{\mathbf{F}}(\mathbf{m})| \neq 0$ , where  $\mathbf{m} = (m_1, m_2, m_3) \neq \mathbf{0}$ .

Since

$$\begin{aligned} |\tilde{\mathbf{F}}(\mathbf{m})| &= \tilde{\mu}^2 \gamma^2 \tilde{\lambda} \tilde{\alpha} \varrho k \kappa_6^2 \kappa_7 |\mathbf{m}|^{26}, \\ \tilde{\lambda} &= \lambda + 2\mu + K^*, \\ \tilde{\alpha} &= \alpha + \beta + \gamma, \\ \kappa_7 &= \kappa_4 + \kappa_5 + \kappa_6, \\ \varrho &= \begin{vmatrix} A_1 & A_4 & A_6 \\ A_4 & A_2 & A_5 \\ A_6 & A_5 & A_3 \end{vmatrix}, \end{aligned}$$

it follows that the operator  $\mathbf{F}^{(i)}(\mathbf{D}_\mathbf{x})$  is an elliptic differential operator if

$$\tilde{\mu} \gamma \tilde{\lambda} \tilde{\alpha} \varrho k \kappa_6 \kappa_7 \neq 0. \quad (3.7)$$

**Definition 2:** The fundamental solutions of the system of equations (3.2)-(3.5) (fundamental matrices of operators  $\mathbf{F}^{(i)}$ ) are the matrices

$$\mathbf{G}^{(i)}(\mathbf{x}) = \left( G_{gh}^{(i)}(\mathbf{x}) \right)_{13 \times 13}$$

satisfying conditions

$$\mathbf{F}^{(i)}(\mathbf{D}_\mathbf{x})\mathbf{G}^{(i)}(\mathbf{x}) = \delta(\mathbf{x})\mathbf{I}(\mathbf{x}), \quad i = 1, 2, 3, 4, \quad (3.8)$$

where  $\delta(\mathbf{x})$  is the Dirac delta,  $\mathbf{I} = (\delta_{gh})_{13 \times 13}$  is the unit matrix and  $\mathbf{x} \in E^3$ .

#### 4. CONSTRUCTION OF $\mathbf{G}^{(1)}(\mathbf{x})$ IN TERMS OF ELEMENTARY FUNCTIONS

Let us consider the system of non-homogeneous equations

$$\tilde{\mu} \Delta \mathbf{u} + [(\lambda + \mu) \nabla \operatorname{div} + \rho \omega^2] \mathbf{u} + K^* \operatorname{curl} \boldsymbol{\varphi} - \Re_i \nabla \phi_i + \iota \omega \vartheta T_0 \nabla \theta = \mathbf{H}, \quad (4.1)$$

$$K^* \operatorname{curl} \mathbf{u} + [\gamma \Delta + \tilde{K} + (\alpha + \beta) \nabla \operatorname{div}] \boldsymbol{\varphi} = \mathbf{V}, \quad (4.2)$$

$$\Re_1 \operatorname{div} \mathbf{u} + (A_1 \Delta - \beta_1)\phi_1 + (A_4 \Delta - \alpha_4)\phi_2 + (A_6 \Delta - \alpha_6)\phi_3 + \omega T_0 \ell_1 \theta + \omega r_1 \operatorname{div} \mathbf{w} = L_1, \quad (4.3)$$

$$\Re_2 \operatorname{div} \mathbf{u} + (A_4 \Delta - \alpha_4)\phi_1 + (A_2 \Delta - \beta_2)\phi_2 + (A_5 \Delta - \alpha_5)\phi_3 + \omega T_0 \ell_2 \theta + \omega r_2 \operatorname{div} \mathbf{w} = L_2, \quad (4.4)$$

$$\Re_3 \operatorname{div} \mathbf{u} + (A_6 \Delta - \alpha_6)\phi_1 + (A_5 \Delta - \alpha_5)\phi_2 + (A_3 \Delta - \beta_3)\phi_3 + \omega T_0 \ell_3 \theta + \omega r_3 \operatorname{div} \mathbf{w} = L_3, \quad (4.5)$$

$$-\vartheta \operatorname{div} \mathbf{u} + \ell_i \phi_i + (k\Delta + \omega a)\theta - \kappa_3 \operatorname{div} \mathbf{w} = Z, \quad (4.6)$$

$$-r_i \nabla \phi_i + \kappa_1 \nabla \theta + [\kappa_6 \Delta + (\kappa_4 + \kappa_5) \nabla \operatorname{div} + \kappa_8] \mathbf{w} = \mathbf{X}, \quad (4.7)$$

where  $\mathbf{H}, \mathbf{V}, \mathbf{X}$  are three-component vector functions on  $E^3$ ;  $L_i$  and  $Z$  are scalar functions on  $E^3$ .

The system of equations (4.1)-(4.7) may also be written in the form

$$\mathbf{F}^{(1)tr}(\mathbf{D}_\mathbf{x})\mathbf{U}(\mathbf{x}) = \mathbf{Q}(\mathbf{x}), \quad (4.8)$$

where  $\mathbf{F}^{(1)tr}$  is the transpose of matrix  $\mathbf{F}^{(1)}$ ,  $\mathbf{Q} = (\mathbf{H}, \mathbf{V}, L_i, Z, \mathbf{X})$  and  $\mathbf{x} \in E^3$ .

Applying operator  $\operatorname{div}$  to the equations (4.1), (4.2) and (4.7), we obtain

$$[\tilde{\lambda}\Delta + \rho\omega^2] \operatorname{div} \mathbf{u} - \Re_i \Delta \phi_i + \omega \vartheta T_0 \Delta \theta = \operatorname{div} \mathbf{H}, \quad (4.9)$$

$$[\tilde{\alpha}\Delta + \tilde{K}] \operatorname{div} \boldsymbol{\varphi} = \operatorname{div} \mathbf{V}, \quad (4.10)$$

$$-r_i \Delta \phi_i + \kappa_1 \Delta \theta + [\kappa_7 \Delta + \kappa_8] \operatorname{div} \mathbf{w} = \operatorname{div} \mathbf{X}. \quad (4.11)$$

Equations (4.3)-(4.6), (4.9) and (4.11) may be expressed in the form

$$\mathbf{N}^{(1)}(\Delta)\mathbf{S} = \tilde{\mathbf{Q}}, \quad (4.12)$$

where  $\mathbf{N}^{(1)}$ ,  $\mathbf{S}$  and  $\tilde{\mathbf{Q}}$  are given in Appendix B.

Equations (4.3)-(4.6), (4.9) and (4.11) may also be written in the determinant form as

$$\Gamma^{(1)}(\Delta)\mathbf{S} = \boldsymbol{\Psi}, \quad (4.13)$$

where  $\Gamma^{(1)}$  and  $\boldsymbol{\Psi}$  are defined in Appendix B.

On expanding  $\Gamma^{(1)}(\Delta)$ , we can see that

$$\Gamma^{(1)}(\Delta) = \prod_{i=1}^6 (\Delta + \lambda_i^2),$$

where  $\lambda_i^2$ ,  $i = 1, \dots, 6$  are the roots of the equation  $\Gamma^{(1)}(-m) = 0$  (with respect to  $m$ ).

Applying operators  $\gamma\Delta + \tilde{K}$  and  $K^*$  curl to equations (4.1) and (4.2), respectively, we obtain

$$\begin{aligned} & (\gamma\Delta + \tilde{K}) \left[ \tilde{\mu}\Delta + (\lambda + \mu) \nabla \operatorname{div} + \rho\omega^2 \right] \mathbf{u} + (\gamma\Delta + \tilde{K}) K^* \operatorname{curl} \boldsymbol{\varphi} \\ & = (\gamma\Delta + \tilde{K}) \left[ \mathbf{H} + \Re_i \nabla \phi_i - \omega \vartheta T_0 \nabla \theta \right], \end{aligned} \quad (4.14)$$

and

$$(\gamma\Delta + \tilde{K})K^* \operatorname{curl} \boldsymbol{\varphi} = -K^{*2} \operatorname{curl} \operatorname{curl} \mathbf{u} + K^* \operatorname{curl} \mathbf{V}. \quad (4.15)$$

Now

$$\operatorname{curl} \operatorname{curl} \mathbf{u} = \nabla \operatorname{div} \mathbf{u} - \Delta \mathbf{u}. \quad (4.16)$$

Using equations (4.15) and (4.16) in equation (4.14) and applying operator  $\Gamma^{(1)}(\Delta)$  to the resulting equation with the help of equation (4.13), we get

$$\Gamma^{(1)}(\Delta)\Lambda^{(1)}(\Delta)\mathbf{u} = \boldsymbol{\Psi}', \quad (4.17)$$

where  $\Lambda^{(1)}(\Delta)$  and  $\boldsymbol{\Psi}'$  are given in Appendix B.

It can be seen that

$$\Lambda^{(1)}(\Delta) = (\Delta + \lambda_7^2)(\Delta + \lambda_8^2),$$

where  $\lambda_7^2, \lambda_8^2$  are the roots of the equation  $\Lambda^{(1)}(-m) = 0$  (with respect to  $m$ ).

It follows From equation (4.10) that

$$(\Delta + \lambda_9^2) \operatorname{div} \boldsymbol{\varphi} = \frac{1}{\tilde{\alpha}} \operatorname{div} \mathbf{V} = \Psi_7, \lambda_9^2 = \frac{\tilde{K}}{\tilde{\alpha}}. \quad (4.18)$$

Applying operators  $K^* \operatorname{curl}$  and  $\tilde{\mu}\Delta + \rho\omega^2$  to the equations (4.1) and (4.2), respectively, we acquire

$$[\tilde{\mu}\Delta + \rho\omega^2]K^* \operatorname{curl} \mathbf{u} = K^* \operatorname{curl} \mathbf{H} - K^{*2} \operatorname{curl} \operatorname{curl} \boldsymbol{\varphi}, \quad (4.19)$$

and

$$\begin{aligned} (\tilde{\mu}\Delta + \rho\omega^2)(\gamma\Delta + \tilde{K})\boldsymbol{\varphi} + (\alpha + \beta)(\tilde{\mu}\Delta + \rho\omega^2) \nabla \operatorname{div} \boldsymbol{\varphi} \\ + K^*(\tilde{\mu}\Delta + \rho\omega^2) \operatorname{curl} \mathbf{u} = (\tilde{\mu}\Delta + \rho\omega^2)\mathbf{V}. \end{aligned} \quad (4.20)$$

Now

$$\operatorname{curl} \operatorname{curl} \boldsymbol{\varphi} = \nabla \operatorname{div} \boldsymbol{\varphi} - \Delta \boldsymbol{\varphi}. \quad (4.21)$$

Using equations (4.19) and (4.21) in equation (4.20) and applying the operator  $\Delta + \lambda_9^2$  to the resulting equation with the help of equation (4.18), we get

$$\Lambda^{(1)}(\Delta)(\Delta + \lambda_9^2)\boldsymbol{\varphi} = \boldsymbol{\Psi}'', \quad (4.22)$$

where  $\boldsymbol{\Psi}''$  is defined in Appendix B.

Applying the operator  $\Gamma^{(1)}(\Delta)$  to the equation (4.7), we obtain

$$\Gamma^{(1)}(\Delta)(\Delta + \lambda_{10}^2)\mathbf{w} = \boldsymbol{\Psi}''', \quad (4.23)$$

where  $\lambda_{10}^2$  and  $\boldsymbol{\Psi}'''$  are given in Appendix B.

From equations (4.13), (4.17), (4.22) and (4.23), we obtain

$$\boldsymbol{\Theta}^{(1)}(\Delta)\mathbf{U}(\mathbf{x}) = \hat{\boldsymbol{\Psi}}, \quad (4.24)$$

where  $\hat{\boldsymbol{\Psi}}$  and  $\boldsymbol{\Theta}^{(1)}(\Delta)$  are given in Appendix C.

The expressions for  $\boldsymbol{\Psi}'$ ,  $\boldsymbol{\Psi}''$ ,  $\boldsymbol{\Psi}'''$  and  $\Psi_p, p = 2, \dots, 5$  can be rewritten in the form

$$\boldsymbol{\Psi}' = \left[ \frac{1}{\tilde{N}}(\gamma\Delta + \tilde{K})\Gamma^{(1)}(\Delta)\mathbf{J} + w_{11}^{(1)}(\Delta) \nabla \operatorname{div} \right] \mathbf{H} + w_{21}^{(1)}(\Delta) \operatorname{curl} \mathbf{V}$$

$$\begin{aligned}
& + \sum_{i=2}^5 w_{i+1;1}^{(1)}(\Delta) \nabla w_i + w_{71}^{(1)}(\Delta) \nabla \operatorname{div} \mathbf{X}, \\
\boldsymbol{\Psi}'' &= w_{12}^{(1)}(\Delta) \operatorname{curl} \mathbf{H} + \left[ \frac{1}{\tilde{N}} (\Delta + \lambda_9^2) (\tilde{\mu} \Delta + \rho \omega^2) \mathbf{J} + w_{22}^{(1)}(\Delta) \nabla \operatorname{div} \right] \mathbf{V}, \\
\boldsymbol{\Psi}''' &= w_{17}^{(1)}(\Delta) \nabla \operatorname{div} \mathbf{H} + \sum_{i=2}^5 w_{i+1;7}^{(1)}(\Delta) \nabla w_i + \left[ \frac{1}{\kappa_6} \Gamma^{(1)}(\Delta) \mathbf{J} + w_{77}^{(1)}(\Delta) \nabla \operatorname{div} \right] \mathbf{X}, \\
\Psi_p &= w_{1;p+1}^{(1)}(\Delta) \operatorname{div} \mathbf{H} + \sum_{i=2}^5 w_{i+1;p+1}^{(1)}(\Delta) w_i + w_{7;p+1}^{(1)}(\Delta) \operatorname{div} \mathbf{X}, \quad p = 2, \dots, 5, \quad (4.25)
\end{aligned}$$

where  $\mathbf{J} = (\delta_{ij})_{3 \times 3}$  and  $w_{ij}^{(1)}(\Delta)$ ,  $i, j = 1, \dots, 7$  are defined in Appendix C.

From equations (4.25), we have

$$\hat{\boldsymbol{\Psi}}(\mathbf{x}) = \mathbf{R}^{tr}(\mathbf{D}_{\mathbf{x}}) \mathbf{Q}(\mathbf{x}), \quad (4.26)$$

where  $\mathbf{R}(\mathbf{D}_{\mathbf{x}})$  is also given in Appendix C.

From equations (4.8), (4.24) and (4.26), we obtain

$$\mathbf{F}^{(1)}(\mathbf{D}_{\mathbf{x}}) \mathbf{R}(\mathbf{D}_{\mathbf{x}}) = \boldsymbol{\Theta}^{(1)}(\Delta). \quad (4.27)$$

We assume that

$$\lambda_p^2 \neq \lambda_l^2 \neq 0; \quad p, l = 1, \dots, 10; \quad p \neq l.$$

Let

$$\begin{aligned}
\mathbf{Y}^{(1)}(\mathbf{x}) &= \left( Y_{ij}^{(1)}(\mathbf{x}) \right)_{13 \times 13}, \quad Y_{pp}^{(1)}(\mathbf{x}) = \sum_{g=1}^8 r_{1g}^{(1)} \varsigma_g(\mathbf{x}), \quad Y_{p+3;p+3}^{(1)}(\mathbf{x}) = \sum_{g=7}^9 r_{2g}^{(1)} \varsigma_g(\mathbf{x}), \\
Y_{ll}^{(1)}(\mathbf{x}) &= \sum_{g=1}^6 r_{3g}^{(1)} \varsigma_g(\mathbf{x}), \quad Y_{p+10;p+10}^{(1)}(\mathbf{x}) = \sum_{g=1}^{6,10} r_{4g}^{(1)} \varsigma_g(\mathbf{x}), \quad Y_{ij}^{(1)}(\mathbf{x}) = 0, \\
&\quad p = 1, 2, 3; \quad l = 7, \dots, 10; \quad i, j = 1, \dots, 13; \quad i \neq j
\end{aligned}$$

where

$$\begin{aligned}
\varsigma_g(\mathbf{x}) &= -\frac{e^{\iota \lambda_g |\mathbf{x}|}}{4\pi |\mathbf{x}|}, \quad r_{1l}^{(1)} = \prod_{i=1, i \neq l}^8 (\lambda_i^2 - \lambda_l^2)^{-1}, \quad r_{2h}^{(1)} = \prod_{i=7, i \neq h}^9 (\lambda_i^2 - \lambda_h^2)^{-1}, \\
r_{3q}^{(1)} &= \prod_{i=1, i \neq q}^6 (\lambda_i^2 - \lambda_q^2)^{-1}, \quad r_{4p}^{(1)} = \prod_{i=1, i \neq p}^{6,10} (\lambda_i^2 - \lambda_p^2)^{-1}, \\
&\quad g = 1, \dots, 10; \quad l = 1, \dots, 8; \quad h = 7, 8, 9; \quad q = 1, \dots, 6; \quad p = 1, \dots, 6, 10. \quad (4.28)
\end{aligned}$$

**Lemma 1:** The matrix  $\mathbf{Y}^{(1)}$  defined above is the fundamental matrix of operator  $\boldsymbol{\Theta}^{(1)}(\Delta)$ , i.e.

$$\boldsymbol{\Theta}^{(1)}(\Delta) \mathbf{Y}^{(1)}(\mathbf{x}) = \delta(\mathbf{x}) \mathbf{I}(\mathbf{x}). \quad (4.29)$$

**Proof:** To prove the lemma, it is sufficient to prove that

$$\Gamma^{(1)}(\Delta) \Lambda^{(1)}(\Delta) Y_{11}^{(1)}(\mathbf{x}) = \delta(\mathbf{x}), \quad (4.30)$$



$$\Lambda^{(1)}(\Delta)(\Delta + \lambda_9^2)Y_{44}^{(1)}(\mathbf{x}) = \delta(\mathbf{x}), \quad (4.31)$$

$$\Gamma^{(1)}(\Delta)Y_{77}^{(1)}(\mathbf{x}) = \delta(\mathbf{x}), \quad (4.32)$$

$$\Gamma^{(1)}(\Delta)(\Delta + \lambda_{10}^2)Y_{11;11}^{(1)}(\mathbf{x}) = \delta(\mathbf{x}). \quad (4.33)$$

Consider

$$\sum_{i=1}^8 r_{1i}^{(1)} = \frac{\sum_{j=1}^8 (-1)^j z_j}{z_9}, \quad (4.34)$$

where  $z_i$ ,  $i = 1, \dots, 9$  are given in Appendix D.

By simplifying the right hand side of the above relation, we obtain

$$\sum_{i=1}^8 r_{1i}^{(1)} = 0. \quad (4.35)$$

Similarly, we find that

$$\begin{aligned} \sum_{i=2}^8 r_{1i}^{(1)}(\lambda_1^2 - \lambda_i^2) &= 0, \sum_{i=3}^8 r_{1i}^{(1)} \left[ \prod_{j=1}^2 (\lambda_j^2 - \lambda_i^2) \right] = 0, \\ \sum_{i=4}^8 r_{1i}^{(1)} \left[ \prod_{j=1}^3 (\lambda_j^2 - \lambda_i^2) \right] &= 0, \sum_{i=5}^8 r_{1i}^{(1)} \left[ \prod_{j=1}^4 (\lambda_j^2 - \lambda_i^2) \right] = 0, \\ \sum_{i=6}^8 r_{1i}^{(1)} \left[ \prod_{j=1}^5 (\lambda_j^2 - \lambda_i^2) \right] &= 0, \sum_{i=7}^8 r_{1i}^{(1)} \left[ \prod_{j=1}^6 (\lambda_j^2 - \lambda_i^2) \right] = 0, \prod_{j=1}^7 r_{18}^{(1)}(\lambda_j^2 - \lambda_8^2) = 1. \end{aligned} \quad (4.36)$$

Also,

$$(\Delta + \lambda_p^2)\varsigma_g(\mathbf{x}) = \delta(\mathbf{x}) + (\lambda_p^2 - \lambda_g^2)\varsigma_g(\mathbf{x}) \quad p, g = 1, \dots, 10. \quad (4.37)$$

Now consider

$$\begin{aligned} \Gamma^{(1)}(\Delta)\Lambda^{(1)}(\Delta)Y_{11}^{(1)}(\mathbf{x}) &= \prod_{i=1}^8 (\Delta + \lambda_i^2) \sum_{g=1}^8 r_{1g}^{(1)} \varsigma_g(\mathbf{x}) \\ &= \prod_{i=2}^8 (\Delta + \lambda_i^2) \sum_{g=1}^8 r_{1g}^{(1)} \left[ \delta(\mathbf{x}) + (\lambda_1^2 - \lambda_g^2)\varsigma_g(\mathbf{x}) \right] \\ &= \prod_{i=2}^8 (\Delta + \lambda_i^2) \left[ \delta(\mathbf{x}) \sum_{g=1}^8 r_{1g}^{(1)} + \sum_{g=2}^8 r_{1g}^{(1)} (\lambda_1^2 - \lambda_g^2)\varsigma_g(\mathbf{x}) \right]. \end{aligned}$$

Using equations (4.35)-(4.37) in the above relation, we obtain

$$\begin{aligned} \Gamma^{(1)}(\Delta)\Lambda^{(1)}(\Delta)Y_{11}^{(1)}(\mathbf{x}) &= \prod_{i=2}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=2}^8 r_{1g}^{(1)} (\lambda_1^2 - \lambda_g^2)\varsigma_g(\mathbf{x}) \right] \\ &= \prod_{i=3}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=2}^8 r_{1g}^{(1)} (\lambda_1^2 - \lambda_g^2) \left[ \delta(\mathbf{x}) + (\lambda_2^2 - \lambda_g^2)\varsigma_g(\mathbf{x}) \right] \right] \end{aligned}$$

$$\begin{aligned}
&= \prod_{i=3}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=3}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^2 (\lambda_j^2 - \lambda_g^2) \right] \varsigma_g(\mathbf{x}) \right] \\
&= \prod_{i=4}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=3}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^2 (\lambda_j^2 - \lambda_g^2) \right] \left[ \delta(\mathbf{x}) + (\lambda_3^2 - \lambda_g^2) \varsigma_g(\mathbf{x}) \right] \right] \\
&= \prod_{i=4}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=4}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^3 (\lambda_j^2 - \lambda_g^2) \right] \varsigma_g(\mathbf{x}) \right] \\
&= \prod_{i=5}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=4}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^3 (\lambda_j^2 - \lambda_g^2) \right] \left[ \delta(\mathbf{x}) + (\lambda_4^2 - \lambda_g^2) \varsigma_g(\mathbf{x}) \right] \right] \\
&= \prod_{i=5}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=5}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^4 (\lambda_j^2 - \lambda_g^2) \right] \varsigma_g(\mathbf{x}) \right] \\
&= \prod_{i=6}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=5}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^4 (\lambda_j^2 - \lambda_g^2) \right] \left[ \delta(\mathbf{x}) + (\lambda_5^2 - \lambda_g^2) \varsigma_g(\mathbf{x}) \right] \right] \\
&= \prod_{i=6}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=6}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^5 (\lambda_j^2 - \lambda_g^2) \right] \varsigma_g(\mathbf{x}) \right] \\
&= \prod_{i=7}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=6}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^5 (\lambda_j^2 - \lambda_g^2) \right] \left[ \delta(\mathbf{x}) + (\lambda_6^2 - \lambda_g^2) \varsigma_g(\mathbf{x}) \right] \right] \\
&= \prod_{i=7}^8 (\Delta + \lambda_i^2) \left[ \sum_{g=7}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^6 (\lambda_j^2 - \lambda_g^2) \right] \varsigma_g(\mathbf{x}) \right] \\
&= (\Delta + \lambda_8^2) \left[ \sum_{g=7}^8 r_{1g}^{(1)} \left[ \prod_{j=1}^6 (\lambda_j^2 - \lambda_g^2) \right] \left[ \delta(\mathbf{x}) + (\lambda_7^2 - \lambda_g^2) \varsigma_g(\mathbf{x}) \right] \right] \\
&= (\Delta + \lambda_8^2) \varsigma_8(\mathbf{x}) = \delta(\mathbf{x}).
\end{aligned}$$

Equations (4.31)-(4.33) can be proved in the similar way.

We introduce the matrix

$$\mathbf{G}^{(1)}(\mathbf{x}) = \mathbf{R}(\mathbf{D}_\mathbf{x}) \mathbf{Y}^{(1)}(\mathbf{x}). \quad (4.38)$$

From equations (4.27), (4.29) and (4.38), we obtain

$$\mathbf{F}^{(1)}(\mathbf{D}_\mathbf{x}) \mathbf{G}^{(1)}(\mathbf{x}) = \mathbf{F}^{(1)}(\mathbf{D}_\mathbf{x}) \mathbf{R}(\mathbf{D}_\mathbf{x}) \mathbf{Y}^{(1)}(\mathbf{x}) = \boldsymbol{\Theta}^{(1)}(\Delta) \mathbf{Y}^{(1)}(\mathbf{x}) = \delta(\mathbf{x}) \mathbf{I}(\mathbf{x}).$$

Hence,  $\mathbf{G}^{(1)}(\mathbf{x})$  is a solution to equation (3.8) for  $i = 1$ .

**Theorem 1:** If the condition (3.7) is satisfied, then the matrix  $\mathbf{G}^{(1)}(\mathbf{x})$  defined by the equation (4.38) is the fundamental solution of the system of equations (3.2) and the matrix  $\mathbf{G}^{(1)}(\mathbf{x})$  is represented in the following form:

$$\mathbf{G}^{(1)}(\mathbf{x}) = \left( H_{pq}(\mathbf{x}) \right)_{13 \times 13} = \begin{pmatrix} \mathbf{H}^{(1)} & \mathbf{H}^{(2)} & \mathbf{H}^{(5)} & \mathbf{H}^{(10)} \\ \mathbf{H}^{(3)} & \mathbf{H}^{(4)} & \mathbf{H}^{(6)} & \mathbf{H}^{(11)} \\ \mathbf{H}^{(7)} & \mathbf{H}^{(8)} & \mathbf{H}^{(9)} & \mathbf{H}^{(15)} \\ \mathbf{H}^{(12)} & \mathbf{H}^{(13)} & \mathbf{H}^{(14)} & \mathbf{H}^{(16)} \end{pmatrix}_{13 \times 13}, \quad (4.39)$$

where  $\mathbf{H}^{(p)}(\mathbf{x})$ ,  $p = 1, \dots, 16$  are given in Appendix D.

## 5. CONSTRUCTION OF MATRICES $\mathbf{G}^{(i)}(\mathbf{x})$ , $i = 2, 3, 4$

**5.1. Pseudo-oscillations.** We introduce the matrix

$$\mathbf{G}^{(2)}(\mathbf{x}) = \mathbf{T}(\mathbf{D}_\mathbf{x}) \mathbf{Y}^{(2)}(\mathbf{x}), \quad (5.1)$$

where, the matrices  $\mathbf{T}(\mathbf{D}_\mathbf{x})$  and  $\mathbf{Y}^{(2)}(\mathbf{x})$  can be obtained from matrices  $\mathbf{R}(\mathbf{D}_\mathbf{x})$  and  $\mathbf{Y}^{(1)}(\mathbf{x})$  respectively by taking  $\omega = -\iota\tau$  and repeating the above procedure after equation (3.8).

**Theorem 2:** If the condition (3.7) is satisfied, then the matrix  $\mathbf{G}^{(2)}(\mathbf{x})$  defined by the equation (5.1) is the fundamental solution of the system of equations (3.3).

**5.2. Quasi-static oscillations.** In this case, the matrix  $\mathbf{N}^{(3)}(\Delta)$ , operators  $\Gamma^{(3)}(\Delta)$ ,  $\Lambda^{(3)}(\Delta)$  and matrix operators  $\Theta^{(3)}(\Delta)$ ,  $\mathbf{M}(\mathbf{D}_\mathbf{x})$ ,  $\mathbf{Y}^{(3)}(\mathbf{x})$  and  $\mathbf{G}^{(3)}(\mathbf{x})$  are obtained as

$$(i) \quad \hat{\mathbf{N}}^{(3)}(\Delta) = \left( \hat{N}_{gh}^{(3)}(\Delta) \right)_{6 \times 6} = \begin{pmatrix} \tilde{\lambda} & -\Re_1 & -\Re_2 & -\Re_3 & \iota\omega\vartheta T_0 & 0 \\ \Re_1 & A_1\Delta - \alpha_1 & A_4\Delta - \alpha_4 & A_6\Delta - \alpha_6 & \iota\omega\ell_1 T_0 & \iota\omega r_1 \\ \Re_2 & A_4\Delta - \alpha_4 & A_2\Delta - \alpha_2 & A_5\Delta - \alpha_5 & \iota\omega\ell_2 T_0 & \iota\omega r_2 \\ \Re_3 & A_6\Delta - \alpha_6 & A_5\Delta - \alpha_5 & A_3\Delta - \alpha_3 & \iota\omega\ell_3 T_0 & \iota\omega r_3 \\ -\vartheta & \ell_1 & \ell_2 & \ell_3 & k\Delta + \iota\omega a & -\kappa_3 \\ 0 & -r_1\Delta & -r_2\Delta & -r_3\Delta & \kappa_1\Delta & \kappa_7\Delta + \kappa_8 \end{pmatrix}_{6 \times 6}$$

$$\mathbf{N}^{(3)}(\Delta) = \left( N_{gh}^{(3)}(\Delta) \right)_{6 \times 6} = \Delta \left( \hat{N}_{gh}^{(3)}(\Delta) \right)_{6 \times 6},$$

$$(ii) \quad \Gamma^{(3)}(\Delta) = \Delta \prod_{i=1}^5 (\Delta + \tilde{\mu}_i^2), \Lambda^{(3)}(\Delta) = \Delta (\Delta + \tilde{\mu}_6^2) =$$

$$\frac{1}{\tilde{N}} \begin{vmatrix} \tilde{\mu}\Delta & K^*\Delta \\ -K^* & \gamma\Delta - 2K^* \end{vmatrix}, \tilde{\mu}_7^2 = -\frac{2K^*}{\tilde{\alpha}},$$

where  $\tilde{\mu}_i^2$ ,  $i = 1, \dots, 5$  are the roots of the equation  $|\hat{\mathbf{N}}^{(3)}(-m)| = 0$  (with respect to  $m$ ).

$$(iii) \quad \Theta^{(3)}(\Delta) = \left( \Theta_{gh}^{(3)}(\Delta) \right)_{13 \times 13},$$

$$\begin{aligned}
\Theta_{pp}^{(3)}(\Delta) &= \Gamma^{(3)}(\Delta)\Lambda^{(3)}(\Delta) = \Delta^2 \prod_{i=1}^6 (\Delta + \tilde{\mu}_i^2), \\
\Theta_{p+3;p+3}^{(3)}(\Delta) &= \Lambda^{(3)}(\Delta)(\Delta + \tilde{\mu}_7^2) = \Delta \prod_{i=6}^7 (\Delta + \tilde{\mu}_i^2), \\
\Theta_{ll}^{(3)}(\Delta) &= \Gamma^{(3)}(\Delta) = \Delta \prod_{i=1}^5 (\Delta + \tilde{\mu}_i^2), \\
\Theta_{p+10;p+10}^{(3)}(\Delta) &= \Gamma^{(3)}(\Delta)(\Delta + \tilde{\mu}_8^2) = \Delta \prod_{i=1}^{5,8} (\Delta + \tilde{\mu}_i^2), \quad \tilde{\mu}_8^2 = \lambda_{10}^2, \\
\Theta_{gh}^{(3)}(\Delta) &= 0; \quad p = 1, 2, 3; \quad g, h = 1, \dots, 13; \quad l = 7, \dots, 10; \quad g \neq h \\
(iv) \quad w_{11}^{(3)}(\Delta) &= -\frac{1}{\tilde{M}\tilde{N}} \left\{ \left[ (\lambda + \mu)(\gamma\Delta - 2K^*) - K^{*2} \right] \tilde{N}_{11}^{(3)}(\Delta) + (\gamma\Delta - 2K^*) \times \right. \\
&\quad \left. \left[ -\Re_i \tilde{N}_{1;i+1}^{(3)}(\Delta) + \iota\omega\vartheta T_0 \tilde{N}_{15}^{(3)}(\Delta) \right] \right\}, \\
w_{p+1;1}^{(3)}(\Delta) &= -\frac{1}{\tilde{M}\tilde{N}} \left\{ \left[ (\lambda + \mu)(\gamma\Delta - 2K^*) - K^{*2} \right] \tilde{N}_{p1}^{(3)}(\Delta) + (\gamma\Delta - 2K^*) \times \right. \\
&\quad \left. \left[ -\Re_i \tilde{N}_{p;i+1}^{(3)}(\Delta) + \iota\omega\vartheta T_0 \tilde{N}_{p5}^{(3)}(\Delta) \right] \right\}, \\
w_{21}^{(3)}(\Delta) &= -\frac{K^* \Gamma^{(3)}(\Delta)}{\tilde{N}}, \quad w_{12}^{(3)}(\Delta) = -\frac{K^* (\Delta + \tilde{\mu}_7^2)}{\tilde{N}}, \\
w_{22}^{(3)}(\Delta) &= -\frac{(\alpha + \beta)\tilde{\mu}\Delta - K^{*2}}{\tilde{N}\tilde{\alpha}}, \\
w_{1;l+1}^{(3)}(\Delta) &= \frac{\tilde{N}_{1l}^{(3)}(\Delta)}{\tilde{M}}, \quad w_{p+1;l+1}^{(3)}(\Delta) = \frac{\tilde{N}_{pl}^{(3)}(\Delta)}{\tilde{M}}, \quad w_{p+1;2}^{(3)}(\Delta) = w_{2;p+1}^{(3)}(\Delta) = 0, \\
w_{17}^{(3)}(\Delta) &= -\frac{1}{\tilde{M}\kappa_6} \left[ (\kappa_4 + \kappa_5) \tilde{N}_{16}^{(3)}(\Delta) - r_i \tilde{N}_{1;i+1}^{(3)}(\Delta) + \kappa_1 \tilde{N}_{15}^{(3)}(\Delta) \right], \\
w_{p+1;7}^{(3)}(\Delta) &= -\frac{1}{\tilde{M}\kappa_6} \left[ (\kappa_4 + \kappa_5) \tilde{N}_{p6}^{(3)}(\Delta) - r_i \tilde{N}_{p;i+1}^{(3)}(\Delta) + \kappa_1 \tilde{N}_{p5}^{(3)}(\Delta) \right] \\
&\quad p = 2, \dots, 6; \quad l = 2, \dots, 5
\end{aligned}$$

where  $\tilde{N}_{ij}^{(3)}$  is the cofactor of the element  $N_{ij}^{(3)}$  of the matrix  $\mathbf{N}^{(3)}$ .

$$\begin{aligned}
(v) \mathbf{M}(\mathbf{D}_{\mathbf{x}}) &= \left( M_{gh}(\mathbf{D}_{\mathbf{x}}) \right)_{13 \times 13} = \begin{pmatrix} \mathbf{M}^{(1)} & \mathbf{M}^{(2)} & \mathbf{M}^{(5)} & \mathbf{M}^{(10)} \\ \mathbf{M}^{(3)} & \mathbf{M}^{(4)} & \mathbf{M}^{(6)} & \mathbf{M}^{(11)} \\ \mathbf{M}^{(7)} & \mathbf{M}^{(8)} & \mathbf{M}^{(9)} & \mathbf{M}^{(15)} \\ \mathbf{M}^{(12)} & \mathbf{M}^{(13)} & \mathbf{M}^{(14)} & \mathbf{M}^{(16)} \end{pmatrix}_{13 \times 13}, \\
\mathbf{M}^{(i)}(\mathbf{D}_{\mathbf{x}}) &= \left( M_{gh}^{(i)}(\mathbf{D}_{\mathbf{x}}) \right)_{3 \times 3}, \quad \mathbf{M}^{(j)}(\mathbf{D}_{\mathbf{x}}) = \left( M_{gh}^{(j)}(\mathbf{D}_{\mathbf{x}}) \right)_{3 \times 4},
\end{aligned}$$

$$\begin{aligned}
\mathbf{M}^{(l)}(\mathbf{D}_{\mathbf{x}}) &= \left( M_{gh}^{(l)}(\mathbf{D}_{\mathbf{x}}) \right)_{4 \times 3}, \mathbf{M}^{(9)}(\mathbf{D}_{\mathbf{x}}) = \left( M_{gh}^{(9)}(\mathbf{D}_{\mathbf{x}}) \right)_{4 \times 4}, \\
M_{gh}^{(1)}(\mathbf{D}_{\mathbf{x}}) &= \frac{1}{\tilde{N}}(\gamma\Delta - 2K^*)\Gamma^{(3)}(\Delta)\delta_{gh} + w_{11}^{(3)}(\Delta)\frac{\partial^2}{\partial x_g \partial x_h}, \\
M_{gh}^{(2)}(\mathbf{D}_{\mathbf{x}}) &= w_{12}^{(3)}(\Delta)\sum_{p=1}^3 \varepsilon_{gph} \frac{\partial}{\partial x_p}, M_{gh}^{(3)}(\mathbf{D}_{\mathbf{x}}) = w_{21}^{(3)}(\Delta)\sum_{p=1}^3 \varepsilon_{gph} \frac{\partial}{\partial x_p}, \\
M_{gh}^{(4)}(\mathbf{D}_{\mathbf{x}}) &= \frac{1}{\tilde{N}}(\Delta + \tilde{\mu}_7^2)\tilde{\mu}\Delta\delta_{gh} + w_{22}^{(3)}(\Delta)\frac{\partial^2}{\partial x_g \partial x_h}, \\
M_{gh}^{(5)}(\mathbf{D}_{\mathbf{x}}) &= w_{1;h+2}^{(3)}(\Delta)\frac{\partial}{\partial x_g}, M_{gh}^{(q)}(\mathbf{D}_{\mathbf{x}}) = 0, \\
M_{gh}^{(7)}(\mathbf{D}_{\mathbf{x}}) &= w_{g+2;1}^{(3)}(\Delta)\frac{\partial}{\partial x_h}, M_{gh}^{(9)}(\mathbf{D}_{\mathbf{x}}) = w_{g+2;h+2}^{(3)}(\Delta), \\
M_{gh}^{(10)}(\mathbf{D}_{\mathbf{x}}) &= w_{17}^{(3)}(\Delta)\frac{\partial^2}{\partial x_g \partial x_h}, M_{gh}^{(12)}(\mathbf{D}_{\mathbf{x}}) = w_{71}^{(3)}(\Delta)\frac{\partial^2}{\partial x_g \partial x_h}, \\
M_{gh}^{(14)}(\mathbf{D}_{\mathbf{x}}) &= w_{7;h+2}^{(3)}(\Delta)\frac{\partial}{\partial x_g}, M_{gh}^{(15)}(\mathbf{D}_{\mathbf{x}}) = w_{g+2;7}^{(3)}(\Delta)\frac{\partial}{\partial x_h}, \\
M_{gh}^{(16)}(\mathbf{D}_{\mathbf{x}}) &= \frac{1}{\kappa_6}\Gamma^{(3)}(\Delta)\delta_{gh} + w_{77}^{(3)}(\Delta)\frac{\partial^2}{\partial x_g \partial x_h} \\
i &= 1, 2, 3, 4, 10, 11, 12, 13, 16; \quad j = 5, 6, 14; \quad l = 7, 8, 15; \quad q = 6, 8, 11, 13. \\
(vi) \quad \mathbf{Y}^{(3)}(\mathbf{x}) &= \left( Y_{ij}^{(3)}(\mathbf{x}) \right)_{13 \times 13}, \quad Y_{pp}^{(3)}(\mathbf{x}) = r_{11}^{(3)}\varsigma_1^*(\mathbf{x}) + r_{12}^{(3)}\varsigma_2^*(\mathbf{x}) + \sum_{g=1}^6 r_{1;g+2}^{(3)}\tilde{\zeta}_g(\mathbf{x}), \\
Y_{p+3;p+3}^{(3)}(\mathbf{x}) &= r_{21}^{(3)}\varsigma_1^*(\mathbf{x}) + \sum_{g=6}^7 r_{2;g-4}^{(3)}\tilde{\zeta}_g(\mathbf{x}), Y_{ll}^{(3)}(\mathbf{x}) = r_{31}^{(3)}\varsigma_1^*(\mathbf{x}) + \sum_{g=1}^5 r_{3;g+1}^{(3)}\tilde{\zeta}_g(\mathbf{x}), \\
Y_{p+10;p+10}^{(3)}(\mathbf{x}) &= r_{41}^{(3)}\varsigma_1^*(\mathbf{x}) + \sum_{g=1}^{5,8} r_{4;g+1}^{(3)}\tilde{\zeta}_g(\mathbf{x}), Y_{ij}^{(3)}(\mathbf{x}) = 0 \\
p &= 1, 2, 3; \quad l = 7, \dots, 10; \quad i, j = 1, \dots, 13; \quad i \neq j,
\end{aligned}$$

where

$$\begin{aligned}
\varsigma_1^*(\mathbf{x}) &= -\frac{1}{4\pi|\mathbf{x}|}, \varsigma_2^*(\mathbf{x}) = -\frac{|\mathbf{x}|}{8\pi}, \tilde{\zeta}_g(\mathbf{x}) = -\frac{e^{i\tilde{\mu}_g|\mathbf{x}|}}{4\pi|\mathbf{x}|}; \quad g = 1, \dots, 8, \\
r_{11}^{(3)} &= -\sum_{p=1}^6 \left( \prod_{j=1, j \neq p}^6 \tilde{\mu}_j^2 \right) \prod_{i=1}^6 \tilde{\mu}_i^{-4}, r_{12}^{(3)} = \prod_{i=1}^6 \tilde{\mu}_i^{-2}, r_{1;l+2}^{(3)} = \tilde{\mu}_l^{-4} \prod_{i=1, i \neq l}^6 (\tilde{\mu}_i^2 - \tilde{\mu}_l^2)^{-1}, \\
r_{21}^{(3)} &= \prod_{i=6}^7 \tilde{\mu}_i^{-2}, r_{2;q-4}^{(3)} = -\tilde{\mu}_q^{-2} \prod_{i=6, i \neq q}^7 (\tilde{\mu}_i^2 - \tilde{\mu}_q^2)^{-1}, r_{31}^{(3)} = \prod_{i=1}^5 \tilde{\mu}_i^{-2}, \\
r_{3;p+1}^{(3)} &= -\tilde{\mu}_p^{-2} \prod_{i=1, i \neq p}^5 (\tilde{\mu}_i^2 - \tilde{\mu}_p^2)^{-1},
\end{aligned}$$

$$r_{41}^{(3)} = \prod_{i=1}^{5,8} \tilde{\mu}_i^{-2}, r_{4;y+1}^{(3)} = -\tilde{\mu}_y^{-2} \prod_{i=1, i \neq y}^{5,8} (\tilde{\mu}_i^2 - \tilde{\mu}_y^2)^{-1},$$

$$Y_{ij}^{(3)}(\mathbf{x}) = 0; \quad l = 1, \dots, 6; \quad q = 6, 7; \quad p = 1, \dots, 5; \quad y = 1, \dots, 5, 8.$$

By introducing the matrix

$$\mathbf{G}^{(3)}(\mathbf{x}) = \mathbf{M}(\mathbf{D}_\mathbf{x}) \mathbf{Y}^{(3)}(\mathbf{x}), \quad (5.2)$$

we obtain

$$\mathbf{F}^{(3)}(\mathbf{D}_\mathbf{x}) \mathbf{G}^{(3)}(\mathbf{x}) = \mathbf{F}^{(3)}(\mathbf{D}_\mathbf{x}) \mathbf{M}(\mathbf{D}_\mathbf{x}) \mathbf{Y}^{(3)}(\mathbf{x}) = \boldsymbol{\Theta}^{(3)}(\Delta) \mathbf{Y}^{(3)}(\mathbf{x}) = \delta(\mathbf{x}) \mathbf{I}(\mathbf{x}).$$

Hence,  $\mathbf{G}^{(3)}(\mathbf{x})$  is a fundamental solution to equation (3.8) for  $i = 3$ .

**Theorem 3:** If the condition (3.7) is satisfied, then the matrix  $\mathbf{G}^{(3)}(\mathbf{x})$  defined by the equation (5.2) is the fundamental solution of the system of equations (3.4).

**5.3. Equilibrium Theory.** In this case, the matrix  $\mathbf{N}^{(4)}(\Delta)$ , the operators  $\Gamma^{(4)}(\Delta)$ ,  $\Lambda^{(4)}(\Delta)$  and the matrix operators  $\boldsymbol{\Theta}^{(4)}(\Delta)$ ,  $\mathbf{Z}(\mathbf{D}_\mathbf{x})$ ,  $\mathbf{Y}^{(4)}(\mathbf{x})$  and  $\mathbf{G}^{(4)}(\mathbf{x})$  are obtained as

$$(i) \hat{\mathbf{N}}^{(4)}(\Delta) = \left( \hat{N}_{gh}^{(4)}(\Delta) \right)_{4 \times 4} = \begin{pmatrix} \tilde{\lambda} & -\Re_1 & -\Re_2 & -\Re_3 \\ \Re_1 & A_1 \Delta - \alpha_1 & A_4 \Delta - \alpha_4 & A_6 \Delta - \alpha_6 \\ \Re_2 & A_4 \Delta - \alpha_4 & A_2 \Delta - \alpha_2 & A_5 \Delta - \alpha_5 \\ \Re_3 & A_6 \Delta - \alpha_6 & A_5 \Delta - \alpha_5 & A_3 \Delta - \alpha_3 \end{pmatrix}_{4 \times 4},$$

$$\mathbf{N}^{(4)}(\Delta) = \left( N_{gh}^{(4)}(\Delta) \right)_{4 \times 4} = \Delta \left( \hat{N}_{gh}^{(4)}(\Delta) \right)_{4 \times 4},$$

$$(ii) \Gamma^{(4)}(\Delta) = \Delta \prod_{i=1}^3 (\Delta + \omega_i^2), \Lambda^{(4)}(\Delta) = \Delta (\Delta + \omega_4^2), \omega_4^2 = \tilde{\mu}_6^2, \omega_5^2 = \tilde{\mu}_7^2, \omega_6^2 = \frac{\kappa_1 \kappa_3 - \kappa_2 \kappa_7}{k \kappa_7}, \omega_7^2 = -\frac{\kappa_2}{\kappa_6},$$

where  $\omega_i^2$ ,  $i = 1, 2, 3$  are the roots of the equation  $|\hat{\mathbf{N}}^{(4)}(-m)| = 0$  (with respect to  $m$ ).

$$(iii) \boldsymbol{\Theta}^{(4)}(\Delta) = \left( \Theta_{gh}^{(4)}(\Delta) \right)_{13 \times 13},$$

$$\Theta_{pp}^{(4)}(\Delta) = \Gamma^{(4)}(\Delta) \Lambda^{(4)}(\Delta) = \Delta^2 \prod_{i=1}^4 (\Delta + \omega_i^2),$$

$$\Theta_{p+3;p+3}^{(4)}(\Delta) = \Lambda^{(4)}(\Delta) (\Delta + \omega_5^2) = \Delta \prod_{i=4}^5 (\Delta + \omega_i^2),$$

$$\Theta_{p+6;p+6}^{(4)}(\Delta) = \Gamma^{(4)}(\Delta) = \Delta \prod_{i=1}^3 (\Delta + \omega_i^2),$$

$$\begin{aligned}
\Theta_{10;10}^{(4)}(\Delta) &= \Gamma^{(4)}(\Delta)\Delta(\Delta + \omega_6^2) = \Delta^2 \prod_{i=1}^{3,6} (\Delta + \omega_i^2), \\
\Theta_{p+10;p+10}^{(4)}(\Delta) &= \Gamma^{(4)}(\Delta)\Delta(\Delta + \omega_6^2)(\Delta + \omega_7^2) = \Delta^2 \prod_{i=1}^{3,6,7} (\Delta + \omega_i^2), \\
\Theta_{gh}^{(4)}(\Delta) &= 0; \quad p = 1, 2, 3; \quad g, h = 1, \dots, 13; \quad g \neq h. \\
(iv) \quad w_{11}^{(4)}(\Delta) &= -\frac{1}{\tilde{\lambda}\tilde{N}_\varrho} \left\{ \left[ (\lambda + \mu)(\gamma\Delta - 2K^*) - K^{*2} \right] \tilde{N}_{11}^{(4)}(\Delta) - (\gamma\Delta - 2K^*) \Re_i \tilde{N}_{1;i+1}^{(4)}(\Delta) \right\}, \\
w_{l+1;1}^{(4)}(\Delta) &= -\frac{1}{\tilde{\lambda}\tilde{N}_\varrho} \left\{ \left[ (\lambda + \mu)(\gamma\Delta - 2K^*) - K^{*2} \right] \tilde{N}_{l1}^{(4)}(\Delta) - (\gamma\Delta - 2K^*) \Re_i \tilde{N}_{l;i+1}^{(4)}(\Delta) \right\}, \\
w_{21}^{(4)}(\Delta) &= -\frac{K^*\Gamma^{(4)}(\Delta)}{\tilde{N}}, \quad w_{12}^{(4)}(\Delta) = -\frac{K^*(\Delta + \omega_5^2)}{\tilde{N}}, \quad w_{22}^{(4)}(\Delta) = w_{22}^{(3)}(\Delta), \\
w_{1;l+1}^{(4)}(\Delta) &= \frac{\tilde{N}_{1l}^{(4)}(\Delta)}{\varrho\tilde{\lambda}}, \quad w_{p+1;l+1}^{(4)}(\Delta) = \frac{\tilde{N}_{pl}^{(4)}(\Delta)}{\varrho\tilde{\lambda}}, \\
w_{16}^{(4)}(\Delta) &= \frac{1}{k\kappa_7\tilde{\lambda}\varrho} \left[ \kappa_3\Delta r_i \tilde{N}_{1;i+1}^{(4)}(\Delta) + (\kappa_7\Delta - \kappa_2) \left[ \vartheta \tilde{N}_{11}^{(4)}(\Delta) - \ell_i \tilde{N}_{1;i+1}^{(4)}(\Delta) \right] \right], \\
w_{l+1;6}^{(4)}(\Delta) &= \frac{1}{k\kappa_7\tilde{\lambda}\varrho} \left[ \kappa_3\Delta r_i \tilde{N}_{l;i+1}^{(4)}(\Delta) + (\kappa_7\Delta - \kappa_2) \left[ \vartheta \tilde{N}_{l1}^{(4)}(\Delta) - \ell_i \tilde{N}_{l;i+1}^{(4)}(\Delta) \right] \right], \\
w_{17}^{(4)}(\Delta) &= \frac{(\Delta + \omega_7^2)}{k\kappa_7\tilde{\lambda}\varrho} \left[ k\Delta r_i \tilde{N}_{1;i+1}^{(4)}(\Delta) - \kappa_1 \left[ \vartheta \tilde{N}_{11}^{(4)}(\Delta) - \ell_i \tilde{N}_{1;i+1}^{(4)}(\Delta) \right] \right], \\
w_{l+1;7}^{(4)}(\Delta) &= \frac{(\Delta + \omega_7^2)}{k\kappa_7\tilde{\lambda}\varrho} \left[ k\Delta r_i \tilde{N}_{l;i+1}^{(4)}(\Delta) - \kappa_1 \left[ \vartheta \tilde{N}_{l1}^{(4)}(\Delta) - \ell_i \tilde{N}_{l;i+1}^{(4)}(\Delta) \right] \right], \\
w_{67}^{(4)}(\Delta) &= -\frac{\kappa_1\Gamma^{(4)}(\Delta)(\Delta + \omega_7^2)}{k\kappa_7}, \quad w_{76}^{(4)}(\Delta) = \frac{\kappa_3\Gamma^{(4)}(\Delta)}{k\kappa_7}, \\
w_{66}^{(4)}(\Delta) &= \frac{(\kappa_7\Delta - \kappa_2)\Gamma^{(4)}(\Delta)}{k\kappa_7}, \quad w_{77}^{(4)}(\Delta) = -\frac{\Gamma^{(4)}(\Delta)[\kappa_1\kappa_3 + \Delta k(\kappa_4 + \kappa_5)]}{k\kappa_6\kappa_7}, \\
w_{q+1;2}^{(4)}(\Delta) &= w_{2;q+1}^{(4)}(\Delta) = w_{6j}^{(4)}(\Delta) = w_{7j}^{(4)}(\Delta) = 0, \\
p, l &= 2, 3, 4; \quad j = 1, 3, 4, 5; \quad q = 2, \dots, 6
\end{aligned}$$

where  $\tilde{N}_{ij}^{(4)}$  is the cofactor of the element  $N_{ij}^{(4)}$  of the matrix  $\mathbf{N}^{(4)}$ .

$$\begin{aligned}
(v) \mathbf{Z}(\mathbf{D}_\mathbf{x}) &= \left( Z_{gh}(\mathbf{D}_\mathbf{x}) \right)_{13 \times 13} = \begin{pmatrix} \mathbf{Z}^{(1)} & \mathbf{Z}^{(2)} & \mathbf{Z}^{(5)} & \mathbf{Z}^{(10)} \\ \mathbf{Z}^{(3)} & \mathbf{Z}^{(4)} & \mathbf{Z}^{(6)} & \mathbf{Z}^{(11)} \\ \mathbf{Z}^{(7)} & \mathbf{Z}^{(8)} & \mathbf{Z}^{(9)} & \mathbf{Z}^{(15)} \\ \mathbf{Z}^{(12)} & \mathbf{Z}^{(13)} & \mathbf{Z}^{(14)} & \mathbf{Z}^{(16)} \end{pmatrix}_{13 \times 13}, \\
\mathbf{Z}^{(i)}(\mathbf{D}_\mathbf{x}) &= \left( Z_{gh}^{(i)}(\mathbf{D}_\mathbf{x}) \right)_{3 \times 3}, \quad \mathbf{Z}^{(j)}(\mathbf{D}_\mathbf{x}) = \left( Z_{gh}^{(j)}(\mathbf{D}_\mathbf{x}) \right)_{3 \times 4}, \\
\mathbf{Z}^{(l)}(\mathbf{D}_\mathbf{x}) &= \left( Z_{gh}^{(l)}(\mathbf{D}_\mathbf{x}) \right)_{4 \times 3}, \quad \mathbf{Z}^{(9)}(\mathbf{D}_\mathbf{x}) = \left( Z_{gh}^{(9)}(\mathbf{D}_\mathbf{x}) \right)_{4 \times 4},
\end{aligned}$$

$$\begin{aligned}
Z_{gh}^{(1)}(\mathbf{D}_\mathbf{x}) &= \frac{1}{\tilde{N}}(\gamma\Delta - 2K^*)\Gamma^{(4)}(\Delta)\delta_{gh} + w_{11}^{(4)}(\Delta)\frac{\partial^2}{\partial x_g\partial x_h}, \\
Z_{gh}^{(2)}(\mathbf{D}_\mathbf{x}) &= w_{12}^{(4)}(\Delta)\sum_{p=1}^3\varepsilon_{gph}\frac{\partial}{\partial x_p}, Z_{gh}^{(3)}(\mathbf{D}_\mathbf{x}) = w_{21}^{(4)}(\Delta)\sum_{p=1}^3\varepsilon_{gph}\frac{\partial}{\partial x_p}, \\
Z_{gh}^{(4)}(\mathbf{D}_\mathbf{x}) &= \frac{1}{\tilde{N}}(\Delta + \omega_5^2)\tilde{\mu}\Delta\delta_{gh} + w_{22}^{(4)}(\Delta)\frac{\partial^2}{\partial x_g\partial x_h}, \\
Z_{gh}^{(5)}(\mathbf{D}_\mathbf{x}) &= w_{1;h+2}^{(4)}(\Delta)\frac{\partial}{\partial x_g}, Z_{gh}^{(q)}(\mathbf{D}_\mathbf{x}) = 0, \\
Z_{gh}^{(7)}(\mathbf{D}_\mathbf{x}) &= w_{g+2;1}^{(4)}(\Delta)\frac{\partial}{\partial x_h}, Z_{gh}^{(9)}(\mathbf{D}_\mathbf{x}) = w_{g+2;h+2}^{(4)}(\Delta), \\
Z_{gh}^{(10)}(\mathbf{D}_\mathbf{x}) &= w_{17}^{(4)}(\Delta)\frac{\partial^2}{\partial x_g\partial x_h}, \\
Z_{gh}^{(14)}(\mathbf{D}_\mathbf{x}) &= w_{7;h+2}^{(4)}(\Delta)\frac{\partial}{\partial x_g}, Z_{gh}^{(15)}(\mathbf{D}_\mathbf{x}) = w_{g+2;7}^{(4)}(\Delta)\frac{\partial}{\partial x_h}, \\
Z_{gh}^{(16)}(\mathbf{D}_\mathbf{x}) &= \frac{1}{\kappa_6}\Delta(\Delta + \omega_6^2)\Gamma^{(4)}(\Delta)\delta_{gh} + w_{77}^{(4)}(\Delta)\frac{\partial^2}{\partial x_g\partial x_h} \\
i &= 1, 2, 3, 4, 10, 11, 12, 13, 16; \quad j = 5, 6, 14; \quad l = 7, 8, 15; \quad q = 6, 8, 11, 12, 13. \\
(vi) \quad \mathbf{Y}^{(4)}(\mathbf{x}) &= \left( Y_{ij}^{(4)}(\mathbf{x}) \right)_{13 \times 13}, \quad Y_{pp}^{(4)}(\mathbf{x}) = r_{11}^{(4)}\varsigma_1^*(\mathbf{x}) + r_{12}^{(4)}\varsigma_2^*(\mathbf{x}) + \sum_{g=1}^4 r_{1;g+2}^{(4)}\hat{\varsigma}_g(\mathbf{x}), \\
Y_{p+3;p+3}^{(4)}(\mathbf{x}) &= r_{21}^{(4)}\varsigma_1^*(\mathbf{x}) + \sum_{g=4}^5 r_{2;g-2}^{(4)}\hat{\varsigma}_g(\mathbf{x}), Y_{p+6;p+6}^{(4)}(\mathbf{x}) = r_{31}^{(4)}\varsigma_1^*(\mathbf{x}) + \sum_{g=1}^3 r_{3;g+1}^{(4)}\hat{\varsigma}_g(\mathbf{x}), \\
Y_{10;10}^{(4)}(\mathbf{x}) &= r_{41}^{(4)}\varsigma_1^*(\mathbf{x}) + r_{42}^{(4)}\varsigma_2^*(\mathbf{x}) + \sum_{g=1}^{3,6} r_{4;g+2}^{(4)}\hat{\varsigma}_g(\mathbf{x}), \\
Y_{p+10;p+10}^{(4)}(\mathbf{x}) &= r_{51}^{(4)}\varsigma_1^*(\mathbf{x}) + r_{52}^{(4)}\varsigma_2^*(\mathbf{x}) + \sum_{g=1}^{3,6,7} r_{5;g+2}^{(4)}\hat{\varsigma}_g(\mathbf{x}), \\
Y_{ij}^{(4)}(\mathbf{x}) &= 0; \quad p = 1, 2, 3; \quad i, j = 1, \dots, 13; \quad i \neq j,
\end{aligned}$$

where

$$\begin{aligned}
\hat{\varsigma}_g(\mathbf{x}) &= -\frac{e^{\iota\omega_g|\mathbf{x}|}}{4\pi|\mathbf{x}|}; \quad g = 1, \dots, 7, \\
r_{11}^{(4)} &= -\sum_{p=1}^4 \left( \prod_{j=1, j \neq p}^4 \omega_j^2 \right) \prod_{i=1}^4 \omega_i^{-4}, \\
r_{12}^{(4)} &= \prod_{i=1}^4 \omega_i^{-2}, r_{1;l+2}^{(4)} = \omega_l^{-4} \prod_{i=1, i \neq l}^4 (\omega_i^2 - \omega_l^2)^{-1}, \\
r_{21}^{(4)} &= \prod_{i=4}^5 \omega_i^{-2}, r_{2;q-2}^{(4)} = -\omega_q^{-2} \prod_{i=4, i \neq q}^5 (\omega_i^2 - \omega_q^2)^{-1}, r_{31}^{(4)} = \prod_{i=1}^3 \omega_i^{-2},
\end{aligned}$$



$$\begin{aligned}
 r_{3;e+1}^{(4)} &= -\omega_e^{-2} \prod_{i=1, i \neq e}^3 (\omega_i^2 - \omega_e^2)^{-1}, \\
 r_{41}^{(4)} &= -\sum_{p=1}^{3,6} \left( \prod_{j=1, j \neq p}^{3,6} \omega_j^2 \right) \prod_{i=1}^{3,6} \omega_i^{-4}, r_{42}^{(4)} = \prod_{i=1}^{3,6} \omega_i^{-2}, \\
 r_{4;z+2}^{(4)} &= \omega_z^{-4} \prod_{i=1, i \neq z}^{3,6} (\omega_i^2 - \omega_z^2)^{-1}, r_{51}^{(4)} = -\sum_{p=1}^{3,6,7} \left( \prod_{j=1, j \neq p}^{3,6,7} \omega_j^2 \right) \prod_{i=1}^{3,6,7} \omega_i^{-4}, \\
 r_{52}^{(4)} &= \prod_{i=1}^{3,6,7} \omega_i^{-2}, r_{5;y+2}^{(4)} = \omega_y^{-4} \prod_{i=1, i \neq y}^{3,6,7} (\omega_i^2 - \omega_y^2)^{-1}, \\
 l &= 1, \dots, 4; \quad q = 4, 5; \quad e = 1, 2, 3; \quad z = 1, 2, 3, 6; \quad y = 1, 2, 3, 6, 7.
 \end{aligned}$$

If we introduce the matrix

$$\mathbf{G}^{(4)}(\mathbf{x}) = \mathbf{R}^{(4)}(\mathbf{D}_\mathbf{x})\mathbf{Y}^{(4)}(\mathbf{x}). \quad (5.3)$$

then, we obtain

$$\mathbf{F}^{(4)}(\mathbf{D}_\mathbf{x})\mathbf{G}^{(4)}(\mathbf{x}) = \mathbf{F}^{(4)}(\mathbf{D}_\mathbf{x})\mathbf{Z}(\mathbf{D}_\mathbf{x})\mathbf{Y}^{(4)}(\mathbf{x}) = \mathbf{\Theta}^{(4)}(\Delta)\mathbf{Y}^{(4)}(\mathbf{x}) = \delta(\mathbf{x})\mathbf{I}(\mathbf{x}).$$

Hence,  $\mathbf{G}^{(4)}(\mathbf{x})$  is a solution to equation (3.8) for  $i = 4$ .

**Theorem 4:** If the condition (3.7) is satisfied, then the matrix  $\mathbf{G}^{(4)}(\mathbf{x})$  defined by the equation (5.3) is the fundamental solution of the system of equations (3.5).

## 6. BASIC PROPERTIES OF $\mathbf{G}^{(1)}(\mathbf{x})$

**Theorem 5:** Each column of the matrix  $\mathbf{G}^{(1)}(\mathbf{x})$  is a solution of the system of equations (3.2) at every point  $\mathbf{x} \in E^3$  except the origin.

**Theorem 6:** If the condition (3.7) is satisfied, then the fundamental solution of the system of equations  $\tilde{\mathbf{F}}(\mathbf{D}_\mathbf{x})\mathbf{U}(\mathbf{x}) = \mathbf{0}$  is the matrix

$$\mathbf{W}(\mathbf{x}) = \left( W_{gh}(\mathbf{x}) \right)_{13 \times 13} = \begin{pmatrix} \mathbf{W}^{(1)} & \mathbf{W}^{(2)} & \mathbf{W}^{(5)} & \mathbf{W}^{(10)} \\ \mathbf{W}^{(3)} & \mathbf{W}^{(4)} & \mathbf{W}^{(6)} & \mathbf{W}^{(11)} \\ \mathbf{W}^{(7)} & \mathbf{W}^{(8)} & \mathbf{W}^{(9)} & \mathbf{W}^{(15)} \\ \mathbf{W}^{(12)} & \mathbf{W}^{(13)} & \mathbf{W}^{(14)} & \mathbf{W}^{(16)} \end{pmatrix}_{13 \times 13}, \quad (6.1)$$

where  $\mathbf{W}^{(p)}(\mathbf{x})$ ,  $p = 1, \dots, 16$  are defined in Appendix E.

**Lemma 2:** If condition (3.7) is satisfied, then

$$\Delta w_{11}^{(1)}(\Delta) = \frac{1}{\tilde{M}}\Lambda^{(1)}(\Delta)\tilde{N}_{11}^{(1)}(\Delta) - \frac{1}{\tilde{N}}\Gamma^{(1)}(\Delta)(\gamma\Delta + \tilde{K}), \quad (6.2)$$

$$\Delta w_{22}^{(1)}(\Delta) = \frac{1}{\tilde{\alpha}} \left[ \Lambda^{(1)}(\Delta) - \frac{1}{\tilde{N}}(\tilde{\alpha}\Delta + \tilde{K})(\tilde{\mu}\Delta + \rho\omega^2) \right], \quad (6.3)$$

$$\Delta w_{77}^{(1)}(\Delta) = \frac{1}{\tilde{M}}(\Delta + \lambda_{10}^2)\tilde{N}_{66}^{(1)}(\Delta) - \frac{1}{\kappa_6}\Gamma^{(1)}(\Delta). \quad (6.4)$$

**Proof:** Consider

$$w_{11}^{(1)}(\Delta) = -\frac{1}{\tilde{M}\tilde{N}} \left\{ \left[ (\lambda + \mu)(\gamma\Delta + \tilde{K}) - K^{*2} \right] \tilde{N}_{11}^{(1)}(\Delta) + (\gamma\Delta + \tilde{K}) \times \right. \\ \left. \left[ -\Re_i \tilde{N}_{1;i+1}^{(1)}(\Delta) + \iota\omega\vartheta T_0 \tilde{N}_{15}^{(1)}(\Delta) \right] \right\}.$$

Now

$$\Gamma^{(1)}(\Delta) = \frac{1}{\tilde{M}} |\mathbf{N}^{(1)}(\Delta)| = \\ \frac{1}{\tilde{M}} \left\{ [\tilde{\lambda}\Delta + \rho\omega^2] \tilde{N}_{11}^{(1)} - \Re_i \Delta \tilde{N}_{1;i+1}^{(1)} + \iota\omega\vartheta T_0 \Delta \tilde{N}_{15}^{(1)}(\Delta) \right\}.$$

Therefore,

$$\Delta w_{11}^{(1)}(\Delta) = -\frac{1}{\tilde{M}\tilde{N}} \left\{ \left[ (\lambda + \mu)(\gamma\Delta + \tilde{K}) - K^{*2} \right] \Delta \tilde{N}_{11}^{(1)}(\Delta) + (\gamma\Delta + \tilde{K}) \times \right. \\ \left. \left[ -\Re_i \Delta \tilde{N}_{1;i+1}^{(1)}(\Delta) + \iota\omega\vartheta T_0 \Delta \tilde{N}_{15}^{(1)}(\Delta) \right] \right\} \\ = -\frac{1}{\tilde{M}\tilde{N}} \left\{ \left[ \tilde{M}\Gamma^{(1)}(\Delta) - (\tilde{\lambda}\Delta + \rho\omega^2) \tilde{N}_{11}^{(1)} \right] (\gamma\Delta + \tilde{K}) \right. \\ \left. + \left[ (\lambda + \mu)(\gamma\Delta + \tilde{K}) - K^{*2} \right] \Delta \tilde{N}_{11}^{(1)} \right\} \\ = \frac{1}{\tilde{M}} \Lambda^{(1)}(\Delta) \tilde{N}_{11}^{(1)}(\Delta) - \frac{1}{\tilde{N}} \Gamma^{(1)}(\Delta) (\gamma\Delta + \tilde{K}).$$

Also taking the R.H.S. of equation (6.3),

$$\frac{1}{\tilde{N}\tilde{\alpha}} \left\{ \left[ (\tilde{\mu}\Delta + \rho\omega^2)(\gamma\Delta + \tilde{K}) + K^{*2} \Delta \right] - (\tilde{\alpha}\Delta + \tilde{K})(\tilde{\mu}\Delta + \rho\omega^2) \right\} \\ = -\frac{1}{\tilde{N}\tilde{\alpha}} \Delta \left[ (\alpha + \beta)(\tilde{\mu}\Delta + \rho\omega^2) - K^{*2} \right] = \Delta w_{22}^{(1)}(\Delta).$$

Equation (6.4) can be proved in similar way.

**Theorem 7:** If condition (3.7) is satisfied and  $\mathbf{x} \in \mathbb{E}^3 - \{\mathbf{0}\}$ , then

$$\mathbf{H}^{(1)}(\mathbf{x}) = \nabla \operatorname{div} \sum_{j=1}^6 x_{1j} \varsigma_j(\mathbf{x}) - \operatorname{curl} \operatorname{curl} \sum_{e=6}^8 x_{1e} \varsigma_e(\mathbf{x}),$$

$$\mathbf{H}^{(2)}(\mathbf{x}) = \mathbf{H}^{(3)}(\mathbf{x}) = \operatorname{curl} \sum_{e=7}^8 x_{2e} \varsigma_e(\mathbf{x}),$$

$$\mathbf{H}^{(4)}(\mathbf{x}) = \nabla \operatorname{div} [x_{49} \varsigma_9(\mathbf{x})] - \operatorname{curl} \operatorname{curl} \sum_{e=7}^8 x_{4e} \varsigma_e(\mathbf{x}),$$

$$H_{iq}^{(5)}(\mathbf{x}) = \frac{\partial}{\partial x_i} \sum_{j=1}^6 x_{5qj} \varsigma_j(\mathbf{x}), \mathbf{H}^{(p)}(\mathbf{x}) = \mathbf{0},$$

$$\begin{aligned}
 H_{qi}^{(7)}(\mathbf{x}) &= \frac{\partial}{\partial x_i} \sum_{j=1}^6 x_{7qj} \varsigma_j(\mathbf{x}), H_{ql}^{(9)}(\mathbf{x}) = \sum_{j=1}^6 x_{9qlj} \varsigma_j(\mathbf{x}), \\
 \mathbf{H}^{(10)}(\mathbf{x}) &= \nabla \operatorname{div} \sum_{j=1}^6 x_{10j} \varsigma_j(\mathbf{x}), \mathbf{H}^{(12)}(\mathbf{x}) = \nabla \operatorname{div} \sum_{j=1}^6 x_{12j} \varsigma_j(\mathbf{x}), \\
 H_{iq}^{(14)}(\mathbf{x}) &= \frac{\partial}{\partial x_i} \sum_{j=1}^6 x_{14qj} \varsigma_j(\mathbf{x}), H_{qi}^{(15)}(\mathbf{x}) = \frac{\partial}{\partial x_i} \sum_{j=1}^6 x_{15qj} \varsigma_j(\mathbf{x}), \\
 \mathbf{H}^{(16)}(\mathbf{x}) &= \nabla \operatorname{div} \sum_{j=1}^6 x_{16j} \varsigma_j(\mathbf{x}) + \operatorname{curl} \operatorname{curl} [x_{167} \varsigma_{10}(\mathbf{x})] \\
 i &= 1, 2, 3; \quad q, l = 1, \dots, 4; \quad p = 6, 8, 11, 13
 \end{aligned}$$

where

$$\begin{aligned}
 x_{1j} &= -\frac{r_{3j}^{(1)}}{\tilde{M}\lambda_j^2} \tilde{N}_{11}^{(1)}(-\lambda_j^2), x_{1e} = \frac{(-1)^{e+1}(\gamma\lambda_e^2 - \tilde{K})}{\tilde{N}\lambda_e^2(\lambda_8^2 - \lambda_7^2)}, x_{2e} = \frac{(-1)^e K^*}{\tilde{N}(\lambda_8^2 - \lambda_7^2)}, \\
 x_{4e} &= \frac{(-1)^{e+1}(\tilde{\mu}\lambda_e^2 - \rho\omega^2)}{\tilde{N}\lambda_e^2(\lambda_8^2 - \lambda_7^2)}, x_{49} = -\frac{1}{\tilde{\alpha}\lambda_9^2}, x_{5qj} = \frac{r_{3j}^{(1)}}{\tilde{M}} \tilde{N}_{1;q+1}^{(1)}(-\lambda_j^2), \\
 x_{7qj} &= -\frac{r_{3j}^{(1)}}{\tilde{M}\lambda_j^2} \tilde{N}_{q+1;1}^{(1)}(-\lambda_j^2), x_{9qlj} = \frac{r_{3j}^{(1)}}{\tilde{M}} \tilde{N}_{q+1;l+1}^{(1)}(-\lambda_j^2), \\
 x_{10j} &= \frac{r_{3j}^{(1)}}{\tilde{M}} \tilde{N}_{16}^{(1)}(-\lambda_j^2), x_{12j} = -\frac{r_{3j}^{(1)}}{\tilde{M}\lambda_j^2} \tilde{N}_{61}^{(1)}(-\lambda_j^2), \\
 x_{14qj} &= \frac{r_{3j}^{(1)}}{\tilde{M}} \tilde{N}_{6;q+1}^{(1)}(-\lambda_j^2), x_{15qj} = -\frac{r_{3j}^{(1)}}{\tilde{M}\lambda_j^2} \tilde{N}_{q+1;6}^{(1)}(-\lambda_j^2), \\
 x_{16j} &= -\frac{r_{3j}^{(1)}}{\tilde{M}\lambda_j^2} \tilde{N}_{66}^{(1)}(-\lambda_j^2), \quad x_{167} = \frac{1}{\kappa_6\lambda_{10}^2} \\
 j &= 1, \dots, 6; \quad q, l = 1, \dots, 4; \quad e = 7, 8.
 \end{aligned} \tag{6.5}$$

**Proof:** It follows from equation (4.37) that

$$\Delta \varsigma_j(\mathbf{x}) = -\lambda_j^2 \varsigma_j(\mathbf{x}); \quad j = 1, \dots, 10.$$

Thus, we have

$$-\frac{1}{\lambda_j^2}(\nabla \operatorname{div} - \operatorname{curl} \operatorname{curl})\varsigma_j(\mathbf{x}) = \mathbf{J} \varsigma_j(\mathbf{x}), \quad \mathbf{x} \neq \mathbf{0}.$$

Consider

$$\begin{aligned}
 \mathbf{H}^{(1)}(\mathbf{x}) &= \mathbf{R}^{(1)}(\mathbf{D}_{\mathbf{x}})Y_{11}^{(1)}(\mathbf{x}) \\
 &= \left\{ \frac{1}{\tilde{N}}(\gamma\Delta + \tilde{K})\mathbf{J}\Gamma^{(1)}(\Delta) + w_{11}^{(1)}(\Delta)\nabla \operatorname{div} \right\} \sum_{j=1}^8 r_{1j}^{(1)} \varsigma_j(\mathbf{x})
 \end{aligned}$$

$$\begin{aligned}
&= \sum_{j=1}^8 r_{1j}^{(1)} \left\{ \left[ -\frac{1}{\tilde{N}\lambda_j^2} (-\gamma\lambda_j^2 + \tilde{K}) \Gamma^{(1)}(-\lambda_j^2) + w_{11}^{(1)}(-\lambda_j^2) \right] \nabla \operatorname{div} + \right. \\
&\quad \left. \frac{1}{\tilde{N}\lambda_j^2} (-\gamma\lambda_j^2 + \tilde{K}) \Gamma^{(1)}(-\lambda_j^2) \operatorname{curl} \operatorname{curl} \right\} \varsigma_j(\mathbf{x}). \tag{6.6}
\end{aligned}$$

From equation (6.2), we have

$$w_{11}^{(1)}(-\lambda_j^2) = -\frac{1}{\tilde{M}\lambda_j^2} \Lambda^{(1)}(-\lambda_j^2) \tilde{N}_{11}^{(1)}(-\lambda_j^2) + \frac{1}{\tilde{N}\lambda_j^2} \Gamma^{(1)}(-\lambda_j^2) (-\gamma\lambda_j^2 + \tilde{K}).$$

Using above equation in equation (6.6), we get

$$\begin{aligned}
\mathbf{H}^{(1)}(\mathbf{x}) &= \sum_{j=1}^8 r_{1j}^{(1)} \left\{ \left[ -\frac{1}{\tilde{M}\lambda_j^2} \Lambda^{(1)}(-\lambda_j^2) \tilde{N}_{11}^{(1)}(-\lambda_j^2) \right] \nabla \operatorname{div} + \right. \\
&\quad \left. \frac{1}{\tilde{N}\lambda_j^2} (-\gamma\lambda_j^2 + \tilde{K}) \Gamma^{(1)}(-\lambda_j^2) \operatorname{curl} \operatorname{curl} \right\} \varsigma_j(\mathbf{x}). \tag{6.7}
\end{aligned}$$

Now,

$$\begin{aligned}
\Gamma^{(1)}(-\lambda_j^2) r_{1j}^{(1)} &= 0; \quad j = 1, \dots, 6 \\
\Gamma^{(1)}(-\lambda_j^2) r_{1j}^{(1)} &= \frac{(-1)^{j+1}}{\lambda_8^2 - \lambda_7^2}; \quad j = 7, 8
\end{aligned}$$

and

$$\begin{aligned}
\Lambda^{(1)}(-\lambda_j^2) r_{1j}^{(1)} &= r_{3j}^{(1)}; \quad j = 1, \dots, 6 \\
\Lambda^{(1)}(-\lambda_j^2) r_{1j}^{(1)} &= 0; \quad j = 7, 8. \tag{6.8}
\end{aligned}$$

By virtue of equation (6.8), equation (6.7) becomes

$$\begin{aligned}
\mathbf{H}^{(1)}(\mathbf{x}) &= \nabla \operatorname{div} \sum_{j=1}^6 \left[ -\frac{1}{\tilde{M}\lambda_j^2} r_{3j}^{(1)} \tilde{N}_{11}^{(1)}(-\lambda_j^2) \right] \varsigma_j(\mathbf{x}) + \\
&\quad \operatorname{curl} \operatorname{curl} \sum_{e=7}^8 \frac{(-1)^{e+1} (-\gamma\lambda_e^2 + \tilde{K})}{\tilde{N}\lambda_e^2 (\lambda_8^2 - \lambda_7^2)} \varsigma_e(\mathbf{x}) \\
&= \nabla \operatorname{div} \sum_{j=1}^6 x_{1j} \varsigma_j(\mathbf{x}) - \operatorname{curl} \operatorname{curl} \sum_{e=7}^8 x_{1e} \varsigma_e(\mathbf{x}).
\end{aligned}$$

The remaining formulae of above theorem can be proved in the similar way.

**Lemma 3:** If the condition (3.7) is satisfied, then

$$\begin{aligned}
\sum_{j=1}^6 r_{3j}^{(1)} &= \sum_{j=1}^6 r_{3j}^{(1)} \lambda_j^2 = \sum_{j=1}^6 r_{3j}^{(1)} \lambda_j^4 = \sum_{j=1}^6 r_{3j}^{(1)} \lambda_j^6 = \sum_{j=1}^6 r_{3j}^{(1)} \lambda_j^8 = 0, \\
\sum_{j=1}^6 r_{3j}^{(1)} \lambda_j^{10} &= -1, \quad \sum_{j=1}^6 \frac{r_{3j}^{(1)}}{\lambda_j^2} = \prod_{i=1}^6 \lambda_i^{-2} = \frac{\tilde{M}}{\rho \omega^2 \tilde{N}_{11}^{(1)}(0)} = \frac{\tilde{M}}{\kappa_8 \tilde{N}_{66}^{(1)}(0)}, \tag{6.9}
\end{aligned}$$

and

$$\begin{aligned}
\sum_{j=1}^6 x_{1j} &= -(\rho\omega^2)^{-1}, \sum_{j=1}^6 x_{1j}\lambda_j^2 = -\tilde{\lambda}^{-1}, \sum_{e=7}^8 x_{1e}\lambda_e^2 = -\tilde{\mu}^{-1}, \\
\sum_{j=1}^6 x_{16j} &= -\kappa_8^{-1}, \sum_{j=1}^6 x_{16j}\lambda_j^2 = -\kappa_7^{-1}, \sum_{j=1}^6 x_{911j} = \frac{A_2 A_3 - A_5^2}{\varrho}, \\
\sum_{j=1}^6 x_{922j} &= \frac{A_1 A_3 - A_6^2}{\varrho}, \sum_{j=1}^6 x_{933j} = \frac{A_1 A_2 - A_4^2}{\varrho}, \sum_{j=1}^6 x_{944j} = k^{-1}.
\end{aligned} \tag{6.10}$$

**Proof:** Consider

$$\tilde{N}_{11}^{(1)}(-\lambda_j^2) = -k\kappa_7\varrho\lambda_j^{10} + B_1\lambda_j^8 + B_2\lambda_j^6 + B_3\lambda_j^4 + B_4\lambda_j^2 + \tilde{N}_{11}^{(1)}(0), \tag{6.11}$$

where  $B_p$ ,  $p = 1, \dots, 4$  are coefficients, independent of  $\lambda_j$  and skipped due to lengthy calculations.

Using equation (4.28), relations (6.9) can be proved by direct calculations.

From equations (6.9) and (6.11), we get

$$\begin{aligned}
\sum_{j=1}^6 \frac{r_{3j}^{(1)}}{\lambda_j^2} \tilde{N}_{11}^{(1)}(-\lambda_j^2) &= \sum_{j=1}^6 r_{3j}^{(1)} [-k\kappa_7\varrho\lambda_j^8 + B_1\lambda_j^6 + B_2\lambda_j^4 + B_3\lambda_j^2 + B_4 + \tilde{N}_{11}^{(1)}(0)\lambda_j^{-2}] \\
&= \tilde{N}_{11}^{(1)}(0) \sum_{j=1}^6 \frac{r_{3j}^{(1)}}{\lambda_j^2} = \frac{\tilde{M}}{\rho\omega^2},
\end{aligned}$$

and

$$\sum_{j=1}^6 r_{3j}^{(1)} \tilde{N}_{11}^{(1)}(-\lambda_j^2) = \sum_{j=1}^6 r_{3j}^{(1)} [-k\kappa_7\varrho\lambda_j^{10} + B_1\lambda_j^8 + B_2\lambda_j^6 + B_3\lambda_j^4 + B_4\lambda_j^2 + \tilde{N}_{11}^{(1)}(0)] = k\kappa_7\varrho.$$

Therefore, from equation (6.5), we have

$$\begin{aligned}
\sum_{j=1}^6 x_{1j} &= -\sum_{j=1}^6 \frac{r_{3j}^{(1)}}{\tilde{M}\lambda_j^2} \tilde{N}_{11}^{(1)}(-\lambda_j^2) = -(\rho\omega^2)^{-1}, \\
\sum_{j=1}^6 x_{1j}\lambda_j^2 &= -\sum_{j=1}^6 \frac{r_{3j}^{(1)}}{\tilde{M}} \tilde{N}_{11}^{(1)}(-\lambda_j^2) = -\frac{k\kappa_7\varrho}{\tilde{M}} = -\tilde{\lambda}^{-1}.
\end{aligned}$$

Also, we obtain

$$\sum_{e=7}^8 x_{1e}\lambda_e^2 = -\frac{\gamma}{\tilde{N}} = -\tilde{\mu}^{-1}.$$

Similarly, we can prove remaining results of equation (6.10).

**Theorem 8:** The relations

$$G_{pq}^{(1)}(\mathbf{x}) - W_{pq}(\mathbf{x}) = \text{constant} + O(|\mathbf{x}|); \quad p, q = 1, \dots, 13. \quad (6.12)$$

hold in the neighborhood of the origin.

**Proof:** Consider

$$\mathbf{H}^{(1)}(\mathbf{x}) - \mathbf{W}^{(1)}(\mathbf{x}) = \nabla \operatorname{div} \tilde{Y}_{11}(\mathbf{x}) - \operatorname{curl} \operatorname{curl} \tilde{Y}_{22}(\mathbf{x}), \quad (6.13)$$

where

$$\begin{aligned} \tilde{Y}_{11}(\mathbf{x}) &= \sum_{j=1}^6 x_{1j} \varsigma_j(\mathbf{x}) - \frac{\varsigma_2^*(\mathbf{x})}{\tilde{\lambda}}, \\ \tilde{Y}_{22}(\mathbf{x}) &= \sum_{e=7}^8 x_{1e} \varsigma_e(\mathbf{x}) - \frac{\varsigma_2^*(\mathbf{x})}{\tilde{\mu}}. \end{aligned} \quad (6.14)$$

From equation (6.14), we have

$$\begin{aligned} \tilde{Y}_{11}(\mathbf{x}) &= \sum_{j=1}^6 \frac{-x_{1j}}{4\pi} \sum_{g=0}^{\infty} \frac{\iota^g \lambda_j^g}{g!} |\mathbf{x}|^{g-1} + \frac{|\mathbf{x}|}{8\pi \tilde{\lambda}} \\ &= -\frac{1}{8\pi} \left[ 2 \sum_{j=1}^6 x_{1j} \sum_{g=0}^{\infty} \frac{\iota^g \lambda_j^g}{g!} |\mathbf{x}|^{g-1} - \frac{|\mathbf{x}|}{\tilde{\lambda}} \right] \\ &= -\frac{1}{8\pi} \left[ \frac{2}{|\mathbf{x}|} \sum_{j=1}^6 x_{1j} - |\mathbf{x}| \left( \sum_{j=1}^6 x_{1j} \lambda_j^2 + \frac{1}{\tilde{\lambda}} \right) \right] - \frac{\iota}{4\pi} \sum_{j=1}^6 x_{1j} \lambda_j + \tilde{Y}_{33}(\mathbf{x}). \end{aligned} \quad (6.15)$$

Similarly,

$$\tilde{Y}_{22}(\mathbf{x}) = -\frac{1}{8\pi} \left[ \frac{2}{|\mathbf{x}|} \sum_{e=7}^8 x_{1e} - |\mathbf{x}| \left( \sum_{e=7}^8 x_{1e} \lambda_e^2 + \frac{1}{\tilde{\mu}} \right) \right] - \frac{\iota}{4\pi} \sum_{e=7}^8 x_{1e} \lambda_e + \tilde{Y}_{44}(\mathbf{x}), \quad (6.16)$$

where

$$\begin{aligned} \tilde{Y}_{33}(\mathbf{x}) &= -\frac{1}{4\pi} \sum_{j=1}^6 x_{1j} \sum_{g=3}^{\infty} \frac{\iota^g \lambda_j^g}{g!} |\mathbf{x}|^{g-1}, \\ \tilde{Y}_{44}(\mathbf{x}) &= -\frac{1}{4\pi} \sum_{e=7}^8 x_{1e} \sum_{g=3}^{\infty} \frac{\iota^g \lambda_e^g}{g!} |\mathbf{x}|^{g-1}. \end{aligned} \quad (6.17)$$

Clearly

$$\tilde{Y}_{qq}(\mathbf{x}) = O(|\mathbf{x}|^2), \quad \frac{\partial}{\partial x_e} \tilde{Y}_{qq}(\mathbf{x}) = O(|\mathbf{x}|),$$

$$\frac{\partial^2}{\partial x_e \partial x_i} \tilde{Y}_{qq}(\mathbf{x}) = \text{constant} + O(|\mathbf{x}|); \quad e, i = 1, 2, 3; \quad q = 3, 4. \quad (6.18)$$

Consider

$$\frac{\partial}{\partial x_i} \left( \frac{1}{|\mathbf{x}|} \right) = -\frac{x_i}{|\mathbf{x}|^3}, \quad \frac{\partial^2}{\partial x_i^2} \left( \frac{1}{|\mathbf{x}|} \right) = \left[ \frac{3x_i^2}{|\mathbf{x}|^5} - \frac{1}{|\mathbf{x}|^3} \right]$$

Hence,

$$\Delta \frac{1}{|\mathbf{x}|} = \sum_{i=1}^3 \frac{\partial^2}{\partial x_i^2} \left( \frac{1}{|\mathbf{x}|} \right) = 0.$$

Therefore,

$$(\nabla \operatorname{div} - \operatorname{curl} \operatorname{curl}) \frac{1}{|\mathbf{x}|} = \mathbf{J} \Delta \frac{1}{|\mathbf{x}|} = \mathbf{0}. \quad (6.19)$$

Equation (6.13) with the aid of equations (6.10) and (6.15)-(6.19) becomes

$$\mathbf{H}^{(1)}(\mathbf{x}) - \mathbf{W}^{(1)}(\mathbf{x}) = \nabla \operatorname{div} \tilde{Y}_{33}(\mathbf{x}) - \operatorname{curl} \operatorname{curl} \tilde{Y}_{44}(\mathbf{x}) = \text{constant} + O(|\mathbf{x}|).$$

Similarly other formulae of equation (6.12) can be proved.

Therefore, matrix  $\mathbf{W}(\mathbf{x})$  is the singular part of the fundamental matrix  $\mathbf{G}^{(1)}(\mathbf{x})$  in the neighborhood of the origin.

## 7. CONCLUSIONS:

This paper successfully focuses on deriving the linear theory of micropolar thermoelasticity with triple porosity and microtemperatures, without relying on Darcy's law. The main achievements and conclusions of the study can be summarized as follows:

1. The governing equations for micropolar thermoelasticity with triple porosity and microtemperatures are reduced in an isotropic medium. This reduction simplifies the analysis and allows for a more accessible understanding of the material behavior.
2. The fundamental solution, denoted as  $\mathbf{G}^{(1)}(\mathbf{x})$ , is derived for the system of equations (3.2) describing steady oscillations. This solution, expressed in terms of elementary functions, provides insights into the material's response under steady-state conditions.
3. Additionally, the fundamental solutions  $\mathbf{G}^{(i)}(\mathbf{x})$ ,  $i = 2, 3, 4$  for the system of equations (3.3)-(3.5) in the cases of pseudo-static, quasi-static oscillations, and equilibrium are also obtained.
4. The derived fundamental solution  $\mathbf{G}^{(1)}(\mathbf{x})$  enables the investigation of three-dimensional boundary value problems in the theory of triple porosity micropolar thermoelastic solids with microtemperatures using the potential method. This method provides a valuable approach for analyzing and solving boundary value problems within the linear theory of micropolar thermoelasticity with triple porosity and microtemperatures.

In summary, this paper's achievements in deriving the fundamental solutions for the linear theory of micropolar thermoelasticity with triple porosity and microtemperatures contribute to the understanding and analysis of these materials' behavior. The results obtained provide a foundation for further research and practical applications in the field of micropolar thermoelasticity with triple porosity and microtemperatures.

## APPENDIX A. COEFFICIENTS FOR THE DIFFERENTIAL OPERATOR (3.6)

$$\begin{aligned}
F_{pq}^{(1)}(\mathbf{D}_\mathbf{x}) &= [\tilde{\mu}\Delta + \rho\omega^2]\delta_{pq} + (\lambda + \mu)\frac{\partial^2}{\partial x_p \partial x_q}, F_{p;q+3}^{(1)}(\mathbf{D}_\mathbf{x}) = F_{p+3;q}^{(1)}(\mathbf{D}_\mathbf{x}) = \\
&K^* \sum_{j=1}^3 \varepsilon_{pj q} \frac{\partial}{\partial x_j}, F_{p;q+6}^{(1)}(\mathbf{D}_\mathbf{x}) = -F_{q+6;p}^{(1)}(\mathbf{D}_\mathbf{x}) = \Re_q \frac{\partial}{\partial x_p}, \\
F_{p;10}^{(1)}(\mathbf{D}_\mathbf{x}) &= -\vartheta \frac{\partial}{\partial x_p}, F_{p;q+10}^{(1)}(\mathbf{D}_\mathbf{x}) = 0, \\
F_{p+3;q+3}^{(1)}(\mathbf{D}_\mathbf{x}) &= (\gamma\Delta + \tilde{K})\delta_{pq} + (\alpha + \beta)\frac{\partial^2}{\partial x_p \partial x_q}, F_{p+3;l}^{(1)}(\mathbf{D}_\mathbf{x}) = F_{l;p+3}^{(1)}(\mathbf{D}_\mathbf{x}) = 0, \\
F_{p+6;p+6}^{(1)}(\mathbf{D}_\mathbf{x}) &= A_p\Delta - \beta_p, F_{78}^{(1)}(\mathbf{D}_\mathbf{x}) = F_{87}^{(1)}(\mathbf{D}_\mathbf{x}) = A_4\Delta - \alpha_4, \\
F_{79}^{(1)}(\mathbf{D}_\mathbf{x}) &= F_{97}^{(1)}(\mathbf{D}_\mathbf{x}) = A_6\Delta - \alpha_6, F_{89}^{(1)}(\mathbf{D}_\mathbf{x}) = F_{98}^{(1)}(\mathbf{D}_\mathbf{x}) = A_5\Delta - \alpha_5, \\
F_{p+6;10}^{(1)}(\mathbf{D}_\mathbf{x}) &= \ell_p, F_{p+6;q+10}^{(1)}(\mathbf{D}_\mathbf{x}) = -r_p \frac{\partial}{\partial x_q}, F_{10;q}^{(1)}(\mathbf{D}_\mathbf{x}) = \iota\omega\vartheta T_0 \frac{\partial}{\partial x_q}, \\
F_{10;q+6}^{(1)}(\mathbf{D}_\mathbf{x}) &= \iota\omega\ell_q T_0, F_{10;10}^{(1)}(\mathbf{D}_\mathbf{x}) = k\Delta + \iota\omega a, \\
F_{10;q+10}^{(1)}(\mathbf{D}_\mathbf{x}) &= \kappa_1 \frac{\partial}{\partial x_q}, F_{p+10;q}^{(1)}(\mathbf{D}_\mathbf{x}) = 0, F_{p+10;q+6}^{(1)}(\mathbf{D}_\mathbf{x}) = \iota\omega r_q \frac{\partial}{\partial x_p}, \\
F_{p+10;10}^{(1)}(\mathbf{D}_\mathbf{x}) &= -\kappa_3 \frac{\partial}{\partial x_p}, F_{p+10;q+10}^{(1)}(\mathbf{D}_\mathbf{x}) = (\kappa_6\Delta + \kappa_8)\delta_{pq} + (\kappa_4 + \kappa_5)\frac{\partial^2}{\partial x_p \partial x_q}, \\
\tilde{\mu} &= \mu + K^*, \quad \tilde{K} = -2K^* + \rho J\omega^2, \quad \kappa_8 = -\kappa_2 + \iota\omega\chi \\
p, q &= 1, 2, 3; \quad l = 7, \dots, 13. \\
\tilde{F}_{pq}(\mathbf{D}_\mathbf{x}) &= \tilde{\mu}\Delta\delta_{pq} + (\lambda + \mu)\frac{\partial^2}{\partial x_p \partial x_q}, \tilde{F}_{p+3;q+3}(\mathbf{D}_\mathbf{x}) = \gamma\Delta\delta_{pq} + (\alpha + \beta)\frac{\partial^2}{\partial x_p \partial x_q}, \\
\tilde{F}_{p+6;p+6}(\mathbf{D}_\mathbf{x}) &= A_p\Delta, \tilde{F}_{78}(\mathbf{D}_\mathbf{x}) = \tilde{F}_{87}(\mathbf{D}_\mathbf{x}) = A_4\Delta, \tilde{F}_{79}(\mathbf{D}_\mathbf{x}) = \tilde{F}_{97}(\mathbf{D}_\mathbf{x}) = A_6\Delta, \\
\tilde{F}_{89}(\mathbf{D}_\mathbf{x}) &= \tilde{F}_{98}(\mathbf{D}_\mathbf{x}) = A_5\Delta, \tilde{F}_{10;10}(\mathbf{D}_\mathbf{x}) = k\Delta, \\
\tilde{F}_{p+10;q+10}(\mathbf{D}_\mathbf{x}) &= \kappa_6\Delta\delta_{pq} + (\kappa_4 + \kappa_5)\frac{\partial^2}{\partial x_p \partial x_q}, \\
\tilde{F}_{pi}(\mathbf{D}_\mathbf{x}) &= \tilde{F}_{ip}(\mathbf{D}_\mathbf{x}) = \tilde{F}_{p+3;j}(\mathbf{D}_\mathbf{x}) = \tilde{F}_{j;p+3}(\mathbf{D}_\mathbf{x}) = 0, \\
\tilde{F}_{p+6;l}(\mathbf{D}_\mathbf{x}) &= \tilde{F}_{l;p+6}(\mathbf{D}_\mathbf{x}) = \tilde{F}_{10;q+10}(\mathbf{D}_\mathbf{x}) = \tilde{F}_{q+10;10}(\mathbf{D}_\mathbf{x}) = 0, \\
p, q &= 1, 2, 3; \quad j = 7, \dots, 13; \quad i = 4, \dots, 13; \quad l = 10, 11, 12, 13.
\end{aligned}$$



## APPENDIX B. SOME QUANTITIES IN EQUATIONS (4.12), (4.13), (4.17), (4.22) AND (4.23)

$\mathbf{S} = (\text{div } \mathbf{u}, \phi, \theta, \text{div } \mathbf{w})$ ,  $\tilde{\mathbf{Q}} = (w_1, \dots, w_6) = (\text{div } \mathbf{H}, L_i, Z, \text{div } \mathbf{X})$  and

$$\mathbf{N}^{(1)}(\Delta) = \left( N_{gh}^{(1)}(\Delta) \right)_{6 \times 6} =$$

$$= \begin{pmatrix} \tilde{\lambda}\Delta + \rho\omega^2 & -\Re_1\Delta & -\Re_2\Delta & -\Re_3\Delta & \iota\omega\vartheta T_0\Delta & 0 \\ \Re_1 & A_1\Delta - \beta_1 & A_4\Delta - \alpha_4 & A_6\Delta - \alpha_6 & \iota\omega\ell_1 T_0 & \iota\omega r_1 \\ \Re_2 & A_4\Delta - \alpha_4 & A_2\Delta - \beta_2 & A_5\Delta - \alpha_5 & \iota\omega\ell_2 T_0 & \iota\omega r_2 \\ \Re_3 & A_6\Delta - \alpha_6 & A_5\Delta - \alpha_5 & A_3\Delta - \beta_3 & \iota\omega\ell_3 T_0 & \iota\omega r_3 \\ -\vartheta & \ell_1 & \ell_2 & \ell_3 & k\Delta + \iota\omega a & -\kappa_3 \\ 0 & -r_1\Delta & -r_2\Delta & -r_3\Delta & \kappa_1\Delta & \kappa_7\Delta + \kappa_8 \end{pmatrix}_{6 \times 6},$$

$$\Psi = (\Psi_1, \dots, \Psi_6), \Psi_p = \frac{1}{\tilde{M}} \sum_{i=1}^6 \tilde{N}_{ip}^{(1)}(\Delta) w_i,$$

$$\Gamma^{(1)}(\Delta) = \frac{1}{\tilde{M}} |\mathbf{N}^{(1)}(\Delta)|, \tilde{M} = \tilde{\lambda} k \kappa_7 \varrho \quad p = 1, \dots, 6$$

and  $\tilde{N}_{ip}^{(1)}$  is the cofactor of the element  $N_{ip}^{(1)}$  of the matrix  $\mathbf{N}^{(1)}$ .

$$\Lambda^{(1)}(\Delta) = \frac{1}{\tilde{N}} \begin{vmatrix} \tilde{\mu}\Delta + \rho\omega^2 & K^*\Delta \\ -K^* & \gamma\Delta + \tilde{K} \end{vmatrix}, \tilde{N} = \gamma\tilde{\mu},$$

$$\Psi' = \frac{1}{\tilde{N}} \left\{ - \left[ (\gamma\Delta + \tilde{K})(\lambda + \mu) - K^{*2} \right] \nabla \Psi_1 + (\gamma\Delta + \tilde{K}) \times \right.$$

$$\left. \left[ \Gamma^{(1)}(\Delta) \mathbf{H} + \Re_i \nabla \Psi_{i+1} - \iota\omega\vartheta T_0 \nabla \Psi_5 \right] - K^* \Gamma^{(1)}(\Delta) \text{curl } \mathbf{V} \right\}.$$

$$\Psi'' = \frac{1}{\tilde{N}} \left\{ - \left[ (\alpha + \beta)(\tilde{\mu}\Delta + \rho\omega^2) - K^{*2} \right] \nabla \Psi_7 + \right.$$

$$\left. (\tilde{\mu}\Delta + \rho\omega^2)(\Delta + \lambda_9^2) \mathbf{V} - K^*(\Delta + \lambda_9^2) \text{curl } \mathbf{H} \right\}.$$

$$\lambda_{10}^2 = \frac{\kappa_8}{\kappa_6}, \quad \Psi''' = \frac{1}{\kappa_6} \left\{ \Gamma^{(1)}(\Delta) \mathbf{X} - \nabla \left[ (\kappa_4 + \kappa_5) \Psi_6 - r_i \Psi_{i+1} + \kappa_1 \Psi_5 \right] \right\}.$$

## APPENDIX C. SOME QUANTITIES IN EQUATIONS (4.24), (4.25) AND (4.26)

$$\hat{\Psi} = (\Psi', \Psi'', \Psi_2, \dots, \Psi_5, \Psi'''),$$

$$\Theta^{(1)}(\Delta) = \left( \Theta_{gh}^{(1)}(\Delta) \right)_{13 \times 13},$$

$$\Theta_{pp}^{(1)}(\Delta) = \Gamma^{(1)}(\Delta) \Lambda^{(1)}(\Delta) = \prod_{i=1}^8 (\Delta + \lambda_i^2),$$

$$\begin{aligned}
\Theta_{p+3;p+3}^{(1)}(\Delta) &= \Lambda^{(1)}(\Delta)(\Delta + \lambda_9^2) = \prod_{i=7}^9 (\Delta + \lambda_i^2), \\
\Theta_l^{(1)}(\Delta) &= \Gamma^{(1)}(\Delta) = \prod_{i=1}^6 (\Delta + \lambda_i^2), \\
\Theta_{p+10;p+10}^{(1)}(\Delta) &= \Gamma^{(1)}(\Delta)(\Delta + \lambda_{10}^2) = \prod_{i=1}^{6,10} (\Delta + \lambda_i^2), \Theta_{gh}^{(1)}(\Delta) = 0, \\
p &= 1, 2, 3 \quad g, h = 1, \dots, 13 \quad l = 7, \dots, 10 \quad g \neq h. \\
w_{11}^{(1)}(\Delta) &= -\frac{1}{\tilde{M}\tilde{N}} \left\{ \left[ (\lambda + \mu)(\gamma\Delta + \tilde{K}) - K^{*2} \right] \tilde{N}_{11}^{(1)}(\Delta) + (\gamma\Delta + \tilde{K}) \times \right. \\
&\quad \left. \left[ -\Re_i \tilde{N}_{1;i+1}^{(1)}(\Delta) + i\omega\vartheta T_0 \tilde{N}_{15}^{(1)}(\Delta) \right] \right\}, \\
w_{p+1;1}^{(1)}(\Delta) &= -\frac{1}{\tilde{M}\tilde{N}} \left\{ \left[ (\lambda + \mu)(\gamma\Delta + \tilde{K}) - K^{*2} \right] \tilde{N}_{p1}^{(1)}(\Delta) + (\gamma\Delta + \tilde{K}) \times \right. \\
&\quad \left. \left[ -\Re_i \tilde{N}_{p;i+1}^{(1)}(\Delta) + i\omega\vartheta T_0 \tilde{N}_{p5}^{(1)}(\Delta) \right] \right\}, \\
w_{21}^{(1)}(\Delta) &= -\frac{K^* \Gamma^{(1)}(\Delta)}{\tilde{N}}, w_{12}^{(1)}(\Delta) = -\frac{K^* (\Delta + \lambda_9^2)}{\tilde{N}}, \\
w_{22}^{(1)}(\Delta) &= -\frac{(\alpha + \beta)(\tilde{\mu}\Delta + \rho\omega^2) - K^{*2}}{\tilde{N}\tilde{\alpha}}, w_{1;l+1}^{(1)}(\Delta) = \frac{\tilde{N}_{1l}^{(1)}(\Delta)}{\tilde{M}}, \\
w_{p+1;l+1}^{(1)}(\Delta) &= \frac{\tilde{N}_{pl}^{(1)}(\Delta)}{\tilde{M}}, w_{2;p+1}^{(1)}(\Delta) = w_{p+1;2}^{(1)}(\Delta) = 0, \\
w_{17}^{(1)}(\Delta) &= -\frac{1}{\tilde{M}\kappa_6} \left[ (\kappa_4 + \kappa_5) \tilde{N}_{16}^{(1)}(\Delta) - r_i \tilde{N}_{1;i+1}^{(1)}(\Delta) + \kappa_1 \tilde{N}_{15}^{(1)}(\Delta) \right], \\
w_{p+1;7}^{(1)}(\Delta) &= -\frac{1}{\tilde{M}\kappa_6} \left[ (\kappa_4 + \kappa_5) \tilde{N}_{p6}^{(1)}(\Delta) - r_i \tilde{N}_{p;i+1}^{(1)}(\Delta) + \kappa_1 \tilde{N}_{p5}^{(1)}(\Delta) \right], \\
p &= 2, \dots, 6; \quad l = 2, \dots, 5. \\
\mathbf{R}(\mathbf{D}_\mathbf{x}) &= \left( R_{gh}(\mathbf{D}_\mathbf{x}) \right)_{13 \times 13} = \begin{pmatrix} \mathbf{R}^{(1)} & \mathbf{R}^{(2)} & \mathbf{R}^{(5)} & \mathbf{R}^{(10)} \\ \mathbf{R}^{(3)} & \mathbf{R}^{(4)} & \mathbf{R}^{(6)} & \mathbf{R}^{(11)} \\ \mathbf{R}^{(7)} & \mathbf{R}^{(8)} & \mathbf{R}^{(9)} & \mathbf{R}^{(15)} \\ \mathbf{R}^{(12)} & \mathbf{R}^{(13)} & \mathbf{R}^{(14)} & \mathbf{R}^{(16)} \end{pmatrix}_{13 \times 13}, \\
\mathbf{R}^{(i)}(\mathbf{D}_\mathbf{x}) &= \left( R_{gh}^{(i)}(\mathbf{D}_\mathbf{x}) \right)_{3 \times 3}, \mathbf{R}^{(j)}(\mathbf{D}_\mathbf{x}) = \left( R_{gh}^{(j)}(\mathbf{D}_\mathbf{x}) \right)_{3 \times 4}, \\
\mathbf{R}^{(l)}(\mathbf{D}_\mathbf{x}) &= \left( R_{gh}^{(l)}(\mathbf{D}_\mathbf{x}) \right)_{4 \times 3}, \mathbf{R}^{(9)}(\mathbf{D}_\mathbf{x}) = \left( R_{gh}^{(9)}(\mathbf{D}_\mathbf{x}) \right)_{4 \times 4}, \\
R_{gh}^{(1)}(\mathbf{D}_\mathbf{x}) &= \frac{1}{\tilde{N}} (\gamma\Delta + \tilde{K}) \Gamma^{(1)}(\Delta) \delta_{gh} + w_{11}^{(1)}(\Delta) \frac{\partial^2}{\partial x_g \partial x_h},
\end{aligned}$$

$$\begin{aligned}
R_{gh}^{(2)}(\mathbf{D}_\mathbf{x}) &= w_{12}^{(1)}(\Delta) \sum_{p=1}^3 \varepsilon_{gph} \frac{\partial}{\partial x_p}, R_{gh}^{(3)}(\mathbf{D}_\mathbf{x}) = w_{21}^{(1)}(\Delta) \sum_{p=1}^3 \varepsilon_{gph} \frac{\partial}{\partial x_p}, \\
R_{gh}^{(4)}(\mathbf{D}_\mathbf{x}) &= \frac{1}{\tilde{N}}(\Delta + \lambda_9^2)(\tilde{\mu}\Delta + \rho\omega^2)\delta_{gh} + w_{22}^{(1)}(\Delta) \frac{\partial^2}{\partial x_g \partial x_h}, \\
R_{gh}^{(5)}(\mathbf{D}_\mathbf{x}) &= w_{1;h+2}^{(1)}(\Delta) \frac{\partial}{\partial x_g}, R_{gh}^{(q)}(\mathbf{D}_\mathbf{x}) = 0, \\
R_{gh}^{(7)}(\mathbf{D}_\mathbf{x}) &= w_{g+2;1}^{(1)}(\Delta) \frac{\partial}{\partial x_h}, R_{gh}^{(9)}(\mathbf{D}_\mathbf{x}) = w_{g+2;h+2}^{(1)}(\Delta), \\
R_{gh}^{(10)}(\mathbf{D}_\mathbf{x}) &= w_{17}^{(1)}(\Delta) \frac{\partial^2}{\partial x_g \partial x_h}, R_{gh}^{(12)}(\mathbf{D}_\mathbf{x}) = w_{71}^{(1)}(\Delta) \frac{\partial^2}{\partial x_g \partial x_h}, \\
R_{gh}^{(14)}(\mathbf{D}_\mathbf{x}) &= w_{7;h+2}^{(1)}(\Delta) \frac{\partial}{\partial x_g}, R_{gh}^{(15)}(\mathbf{D}_\mathbf{x}) = w_{g+2;7}^{(1)}(\Delta) \frac{\partial}{\partial x_h}, \\
R_{gh}^{(16)}(\mathbf{D}_\mathbf{x}) &= \frac{1}{\kappa_6} \Gamma^{(1)}(\Delta) \delta_{gh} + w_{77}^{(1)}(\Delta) \frac{\partial^2}{\partial x_g \partial x_h}, \\
i &= 1, 2, 3, 4, 10, 11, 12, 13, 16; \quad j = 5, 6, 14; \quad l = 7, 8, 15; \quad q = 6, 8, 11, 13.
\end{aligned}$$

## APPENDIX D. SOME QUANTITIES IN RELATIONS (4.34) AND (4.39)

$$\begin{aligned}
z_1 &= \prod_{i=3}^8 (\lambda_2^2 - \lambda_i^2) \prod_{j=4}^8 (\lambda_3^2 - \lambda_j^2) \prod_{l=5}^8 (\lambda_4^2 - \lambda_l^2) \prod_{p=6}^8 (\lambda_5^2 - \lambda_p^2) \prod_{q=7}^8 (\lambda_6^2 - \lambda_q^2) (\lambda_7^2 - \lambda_8^2), \\
z_2 &= \prod_{i=3}^8 (\lambda_1^2 - \lambda_i^2) \prod_{j=4}^8 (\lambda_3^2 - \lambda_j^2) \prod_{l=5}^8 (\lambda_4^2 - \lambda_l^2) \prod_{p=6}^8 (\lambda_5^2 - \lambda_p^2) \prod_{q=7}^8 (\lambda_6^2 - \lambda_q^2) (\lambda_7^2 - \lambda_8^2), \\
z_3 &= \prod_{i=2, i \neq 3}^8 (\lambda_1^2 - \lambda_i^2) \prod_{j=4}^8 (\lambda_2^2 - \lambda_j^2) \prod_{l=5}^8 (\lambda_4^2 - \lambda_l^2) \prod_{p=6}^8 (\lambda_5^2 - \lambda_p^2) \prod_{q=7}^8 (\lambda_6^2 - \lambda_q^2) (\lambda_7^2 - \lambda_8^2), \\
z_4 &= \prod_{i=2, i \neq 4}^8 (\lambda_1^2 - \lambda_i^2) \prod_{j=3, j \neq 4}^8 (\lambda_2^2 - \lambda_j^2) \prod_{l=5}^8 (\lambda_3^2 - \lambda_l^2) \prod_{p=6}^8 (\lambda_5^2 - \lambda_p^2) \prod_{q=7}^8 (\lambda_6^2 - \lambda_q^2) (\lambda_7^2 - \lambda_8^2), \\
z_5 &= \prod_{i=2, i \neq 5}^8 (\lambda_1^2 - \lambda_i^2) \prod_{j=3, j \neq 5}^8 (\lambda_2^2 - \lambda_j^2) \prod_{l=4, l \neq 5}^8 (\lambda_3^2 - \lambda_l^2) \prod_{p=6}^8 (\lambda_4^2 - \lambda_p^2) \prod_{q=7}^8 (\lambda_6^2 - \lambda_q^2) (\lambda_7^2 - \lambda_8^2), \\
z_6 &= \prod_{i=2, i \neq 6}^8 (\lambda_1^2 - \lambda_i^2) \prod_{j=3, j \neq 6}^8 (\lambda_2^2 - \lambda_j^2) \prod_{l=4, l \neq 6}^8 (\lambda_3^2 - \lambda_l^2) \prod_{p=5, p \neq 6}^8 (\lambda_4^2 - \lambda_p^2) \prod_{q=7}^8 (\lambda_5^2 - \lambda_q^2) (\lambda_7^2 - \lambda_8^2), \\
z_7 &= \prod_{i=2, i \neq 7}^8 (\lambda_1^2 - \lambda_i^2) \prod_{j=3, j \neq 7}^8 (\lambda_2^2 - \lambda_j^2) \prod_{l=4, l \neq 7}^8 (\lambda_3^2 - \lambda_l^2) \prod_{p=5, p \neq 7}^8 (\lambda_4^2 - \lambda_p^2) \prod_{q=6, q \neq 7}^8 (\lambda_5^2 - \lambda_q^2) (\lambda_6^2 - \lambda_8^2), \\
z_8 &= \prod_{i=2}^7 (\lambda_1^2 - \lambda_i^2) \prod_{j=3}^7 (\lambda_2^2 - \lambda_j^2) \prod_{l=4}^7 (\lambda_3^2 - \lambda_l^2) \prod_{p=5}^7 (\lambda_4^2 - \lambda_p^2) \prod_{q=6}^7 (\lambda_5^2 - \lambda_q^2) (\lambda_6^2 - \lambda_7^2),
\end{aligned}$$

$$z_9 = \prod_{i=2}^8 (\lambda_1^2 - \lambda_i^2) \prod_{j=3}^8 (\lambda_2^2 - \lambda_j^2) \prod_{l=4}^8 (\lambda_3^2 - \lambda_l^2) \prod_{p=5}^8 (\lambda_4^2 - \lambda_p^2) \prod_{q=6}^8 (\lambda_5^2 - \lambda_q^2) \prod_{z=7}^8 (\lambda_6^2 - \lambda_z^2) (\lambda_7^2 - \lambda_8^2).$$

$$\mathbf{H}^{(i)}(\mathbf{x}) = \left( H_{gh}^{(i)}(\mathbf{x}) \right)_{3 \times 3}, \mathbf{H}^{(j)}(\mathbf{x}) = \left( H_{gh}^{(j)}(\mathbf{x}) \right)_{3 \times 4},$$

$$\mathbf{H}^{(l)}(\mathbf{x}) = \left( H_{gh}^{(l)}(\mathbf{x}) \right)_{4 \times 3}, \mathbf{H}^{(9)}(\mathbf{x}) = \left( H_{gh}^{(9)}(\mathbf{x}) \right)_{4 \times 4},$$

$$\mathbf{H}^{(z)}(\mathbf{x}) = \mathbf{R}^{(z)}(\mathbf{D}_\mathbf{x}) Y_{11}^{(1)}(\mathbf{x}), \mathbf{H}^{(y)}(\mathbf{x}) = \mathbf{R}^{(y)}(\mathbf{D}_\mathbf{x}) Y_{44}^{(1)}(\mathbf{x}), \mathbf{H}^{(e)}(\mathbf{x}) = \mathbf{R}^{(e)}(\mathbf{D}_\mathbf{x}) Y_{77}^{(1)}(\mathbf{x}),$$

$$\mathbf{H}^{(n)}(\mathbf{x}) = \mathbf{R}^{(n)}(\mathbf{D}_\mathbf{x}) Y_{11;11}^{(1)}(\mathbf{x}), \mathbf{H}^{(p)}(\mathbf{x}) = \mathbf{0}$$

$$i = 1, 2, 3, 4, 10, 11, 12, 13, 16; \quad j = 5, 6, 14; \quad l = 7, 8, 15; \\ z = 1, 3, 7, 12; \quad y = 2, 4; \quad e = 5, 9, 14; \quad n = 10, 15, 16; \quad p = 6, 8, 11, 13.$$

APPENDIX E. ELEMENTS OF THE MATRIX IN EQUATION (6.1)

$$\mathbf{W}^{(i)}(\mathbf{x}) = \left( W_{gh}^{(i)}(\mathbf{x}) \right)_{3 \times 3}, \mathbf{W}^{(j)}(\mathbf{x}) = \left( W_{gh}^{(j)}(\mathbf{x}) \right)_{3 \times 4}, \mathbf{W}^{(l)}(\mathbf{x}) = \left( W_{gh}^{(l)}(\mathbf{x}) \right)_{4 \times 3},$$

$$\mathbf{W}^{(9)}(\mathbf{x}) = \left( W_{gh}^{(9)}(\mathbf{x}) \right)_{4 \times 4}, W_{gh}^{(1)}(\mathbf{x}) = \left[ \frac{1}{\bar{\lambda}} \nabla \operatorname{div} - \frac{1}{\bar{\mu}} \operatorname{curl} \operatorname{curl} \right] \varsigma_2^*(\mathbf{x}),$$

$$W_{gh}^{(p)}(\mathbf{x}) = 0, W_{gh}^{(4)}(\mathbf{x}) = \left[ \frac{1}{\bar{\alpha}} \nabla \operatorname{div} - \frac{1}{\gamma} \operatorname{curl} \operatorname{curl} \right] \varsigma_2^*(\mathbf{x}),$$

$$W_{11}^{(9)}(\mathbf{x}) = \frac{A_2 A_3 - A_5^2}{\varrho} \varsigma_1^*(\mathbf{x}), W_{12}^{(9)}(\mathbf{x}) = W_{21}^{(9)}(\mathbf{x}) = \frac{A_5 A_6 - A_4 A_3}{\varrho} \varsigma_1^*(\mathbf{x}),$$

$$W_{22}^{(9)}(\mathbf{x}) = \frac{A_1 A_3 - A_6^2}{\varrho} \varsigma_1^*(\mathbf{x}), W_{33}^{(9)}(\mathbf{x}) = \frac{A_1 A_2 - A_4^2}{\varrho} \varsigma_1^*(\mathbf{x}),$$

$$W_{13}^{(9)}(\mathbf{x}) = W_{31}^{(9)}(\mathbf{x}) = \frac{A_4 A_5 - A_2 A_6}{\varrho} \varsigma_1^*(\mathbf{x}),$$

$$W_{23}^{(9)}(\mathbf{x}) = W_{32}^{(9)}(\mathbf{x}) = \frac{A_4 A_6 - A_1 A_5}{\varrho} \varsigma_1^*(\mathbf{x}),$$

$$W_{e4}^{(9)}(\mathbf{x}) = W_{4e}^{(9)}(\mathbf{x}) = 0, W_{44}^{(9)}(\mathbf{x}) = \frac{1}{k} \varsigma_1^*(\mathbf{x}),$$

$$W_{gh}^{(16)}(\mathbf{x}) = \left[ \frac{1}{\kappa_7} \nabla \operatorname{div} - \frac{1}{\kappa_6} \operatorname{curl} \operatorname{curl} \right] \varsigma_2^*(\mathbf{x}),$$

$$i = 1, \dots, 4, 10, \dots, 13, 16; \quad j = 5, 6, 14; \quad l = 7, 8, 15; \\ e = 1, 2, 3; \quad p = 2, 3, 5, \dots, 8, 10, \dots, 15.$$

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## **A Short History of the Publications of the University of Miskolc**

The University of Miskolc (Hungary) is an important center of research in Central Europe. Its parent university was founded by the Empress Maria Teresia in Selmezbánya (today Banská Štiavnica, Slovakia) in 1735. After the first World War the legal predecessor of the University of Miskolc moved to Sopron (Hungary) where, in 1929, it started the series of university publications with the title *Publications of the Mining and Metallurgical Division of the Hungarian Academy of Mining and Forestry Engineering* (Volumes I.–VI.). From 1934 to 1947 the Institution had the name Faculty of Mining, Metallurgical and Forestry Engineering of the József Nádor University of Technology and Economic Sciences at Sopron. Accordingly, the publications were given the title *Publications of the Mining and Metallurgical Engineering Division* (Volumes VII.–XVI.). For the last volume before 1950 – due to a further change in the name of the Institution – *Technical University, Faculties of Mining, Metallurgical and Forestry Engineering, Publications of the Mining and Metallurgical Divisions* was the title.

For some years after 1950 the Publications were temporarily suspended.

After the foundation of the Mechanical Engineering Faculty in Miskolc in 1949 and the movement of the Sopron Mining and Metallurgical Faculties to Miskolc, the Publications restarted with the general title *Publications of the Technical University of Heavy Industry* in 1955. Four new series – Series A (Mining), Series B (Metallurgy), Series C (Machinery) and Series D (Natural Sciences) – were founded in 1976. These came out both in foreign languages (English, German and Russian) and in Hungarian. In 1990, right after the foundation of some new faculties, the university was renamed to University of Miskolc. At the same time the structure of the Publications was reorganized so that it could follow the faculty structure. Accordingly three new series were established: Series E (Legal Sciences), Series F (Economic Sciences) and Series G (Humanities and Social Sciences). The latest series, i.e., the series H (European Integration Studies) was founded in 2001. The eight series are formed by some periodicals and such publications which come out with various frequencies.

Papers on computational and applied mechanics were published in the

### **Publications of the University of Miskolc, Series D, Natural Sciences.**

This series was given the name Natural Sciences, Mathematics in 1995. The name change reflects the fact that most of the papers published in the journal are of mathematical nature though papers on mechanics also come out.

The series

### **Publications of the University of Miskolc, Series C, Fundamental Engineering Sciences**

founded in 1995 also published papers on mechanical issues. The present journal, which is published with the support of the Faculty of Mechanical Engineering and Informatics as a member of the Series C (Machinery), is the legal successor of the above journal.



## **Contents Contributed Papers**

- Tamás FÜLÖP, Mátyás SZÜCS and Donát TAKÁCS: Generic-motivated  
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