SUPPRESSING THE RAYLEIGH-TAYLOR INSTABILITY WITH AN ALTERNATING MAGNETIC FIELD

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Abstract

The model is to learn the impact of alternating magnetic field on the interface of two superposed magnetic fluids with the normal rotation through a nonlinear perturbation analysis. A nonlinear instability due to streaming superposed magnetic fluids with rotation and an alternating magnetic field studied by the technique of multiple scales. Making use of boundary conditions, the solutions of the linearized equations of motion culminates to the linear dispersion relation.

Keywords: Magnetic fluids, Linear Dispersion Relation, Schrodinger Equation, Alternating Magnetic field, Technique of Multiple Scales.

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1. Introduction

Rayleigh-Taylor instability (RTI) is caused at the interface between two different density fluids in the presence of a constant acceleration pointing from the heavy fluid to the light fluid .The instability of a dense fluid above a lower density fluid in a gravitational field is known as the Rayleigh-Taylor instability in honor of Lord Rayleigh who first expressed it mathematically in 1883.In 1950 Sir.G.Taylor demonstrated that the instability can also transpire in accelerated fluids.

Cowley and Rosensweig(1967) observed the linear stability of two superposed magnetic nanofluids in the existence of an externally applied magnetic field.An inviscid,incompressible magnetic fluid with the influence of magnetic field, gravity and surface tension was analyzed by Malik and Singh(1984).
Lizuka and Wadati(1990) considered the nonlinear RTI under the cause of surface tension between two superposed fluids in the absence of a magnetic field. Elhefnawy (1993) investigated the nonlinear stage of the two dimensional RTI for two magnetic nanofluids , with the effect of surface tension between two fluids with tangential magnetic field.Nonlinear wave propagation on the surface between two superposed magnetic fluids emphasized by a tangential periodic magnetic field was insisted by El-Dib(1993).
Rosensweig experimented the heating magnetic fluid with an alternating magnetic field(2002).
Chengsen et al.,(2004) have studied the combination of the RTI and the Kelvin- Helmholtz instability (KHI) of compressible fluids.
The RTI of two superposed incompressible fluids of distinct densities in the existence of small rotation,surface tension and suspended dust particles has been investigated by Sharma et al.,(2010).Hoshoudy et al.,(2014) analyzed the effect of general rotation on RTI of two superposed fluids with suspended particles.RTI of a two fluid layer subjected to rotation and a periodic tangential magnetic field was researched by Hemamalini and Anjalidevi(2014).The effect of the magnetic field on the RTI in a couple-stress fluid has been done by Chavaraddi(2018).Analytical and Numerical investigation of RTI in nanofluids was studied by Ahuja et al.,(2021).Thus, this study will help to draw the fair conclusion about the effect of rotation parameter on RTI in ferrofluids.

2. Mathematical Modeling

This model is considered with two infinite horizontal layers of homogeneous magnetic fluids with the region $z < 0$ as a lower layer of magnetic fluid with density ρ_1 , permeability μ_1 and $z > 0$ as an upper layer of magnetic fluid with density ρ_2 and permeability μ_2 .These layers are superimposed on each other with the hypothesis that lighter fluid is overlapping on heavier fluid and are detached at the interface $z = 0$ where the surface tension is influential. The fluids are taken to be inviscid and incompressible ferrofluids.The system is accelerated due to gravity $\boldsymbol{g}$ (0,0,-g) and rotation parameter is supposed to act in normal direction as $\boldsymbol{\Omega}(0,0,\Omega)$.
The system is highlighted by an alternating magnetic field $\boldsymbol{H} = H_0 \cos\omega t\,\vec{i}$ in the x direction, H_0 represents the amplitude of the magnetic field, ω shows the field frequency and along the x direction the unit vector is used as $\vec{i}$. $z = \eta(x, t)$ elucidates the interface between the two fluids. When the interface is completely flat then it is constituted as $\eta = 0$.

Investigation begins with the basic equations:

$$\nabla.\boldsymbol{q} = 0 \tag{1}$$

$$\rho\frac{d\boldsymbol{q}}{dt} + 2\rho(\boldsymbol{\Omega}\times\boldsymbol{q}) = -\nabla p + (\rho+\delta\rho)\boldsymbol{g} + \left(\frac{\mu-\mu_0}{2}\right)\nabla\left(\boldsymbol{H_0}+\boldsymbol{h}\right)^2 \tag{2}$$

$$\frac{d}{dt}(\rho+\delta\rho) = 0 \tag{3}$$

$$\nabla.\boldsymbol{B} = 0 \tag{4}$$

$$\nabla\times\boldsymbol{H} = 0 \tag{5}$$

where $\boldsymbol{q} = (u,v,w),$ p denotes the total pressure , μ_0 takes the value 1 and $\boldsymbol{\Omega}(0,0,\Omega)$.

As a consequence of the interface, an additional magnetic field $\boldsymbol{h}$ is attained, which is acquired from the potential function. i.e., ψ exists such that $\boldsymbol{h} = -\nabla\psi$.

The magnetic potential ψ execute the equations,

$$\nabla^2\psi^{(1)}=0, \quad -\infty < z < \eta(x,t)$$
$$\nabla^2\psi^{(2)}=0, \quad \eta(x,t) < z < \infty \tag{6}$$

where $z = \eta\,(x, t)$ is the elevation of the interface calculated from the unperturbed level.

The kinematic boundary condition at the interface $z = \eta\,(x, t)$,

$$\frac{\partial\eta}{\partial t}+u^i\,\frac{\partial\eta}{\partial x}-w^i=0 \qquad i = 1, 2 \tag{7}$$

where u and w indicates the tangential and normal velocity respectively.

In inviscid fluid, normal component of the velocity is continuous at $z = \eta\,(x, t)$ is

$$\hat{n}.\boldsymbol{q}^{(1)} = \hat{n}.\boldsymbol{q}^{(2)} \tag{8}$$

The continuity of the normal and tangential components of the magnetic field across the interface $z = \eta\,(x, t)$ involves,

$$\mu H_{1n} = H_{2n} \quad \text{where} \quad \mu = \frac{\mu_1}{\mu_2} \tag{9}$$

$$H_{1t} = H_{2t} \tag{10}$$

Normal stress condition at the perturbed interface $z = \eta\,(x, t)$ yields the constraint,

$$[[-p+\frac{\mu}{2}(H_n^{\ 2}-H_t^{\ 2})]] = \frac{-T\eta_{xx}}{(1+\eta_x^{\ 2})^{\frac{3}{2}}} \tag{11}$$

where $\hat{n} = \dfrac{(-\eta_x,0,1)}{\sqrt{1+\eta_x^{\ 2}}}$, p stands for the magnetostrictive pressure, T intimates the coefficient of the surface tension and [[ ]] characterizing the jump in the quantity across the interface.

3. Perturbation Analysis

The perturbed equations are solved by registering the mode of multiple scales by considering the steepness ratio of the wave ε .

Introducing the spatial and temporal scales $x_n = \dfrac{1}{\varepsilon^{-n}x^{-1}}, t_n = \dfrac{1}{\varepsilon^{-n}t^{-1}} \quad (n = 0\, to\, 2)$

The nonlinear interactions in a highly unstable region is marked out by developing the various physical quantities as,

$$\eta(x,t) = \sum_{n=1}^{3}\varepsilon^n\,\eta_n\,(x_0,x_1,x_2\,;\,t_0,t_1,t_2) + O(\varepsilon^4) \tag{12}$$

$$\boldsymbol{q}(x,z,t) = \sum_{n=1}^{3}\varepsilon^n\,\boldsymbol{q}_n\,(x_0,x_1,x_2,z\,;\,t_0,t_1,t_2) + O(\varepsilon^4) \tag{13}$$

$$\psi(x,z,t) = \sum_{n=1}^{3}\varepsilon^n\,\psi_n\,(x_0,x_1,x_2,z\,;\,t_0,t_1,t_2) + O(\varepsilon^4) \tag{14}$$

and $$\eta_1 = A(x_1,x_2\,;t_1,t_2)\exp i\,(kx_0-\omega_0 t_0) + c.c \tag{15}$$

where *c.c* denotes the complex conjugate of all earlier terms, *A* shows an amplitude of the propagating wave, *k* represents the wave number and ω_0 shows the frequency of the disturbance. The short scale x_0 denotes the wavelength, the fast scale t_0 indicates the frequency of the wave. The scales of the phase and the amplitude are marked respectively as t_1 and t_2 whereas the spatial modulation of the phase is noted by x_1 and the amplitude is marked by x_2.

Effectiveness of the Maclaurin series at $z = 0$ for the quantities, the boundary conditions are appraised. Then on replacing the above expansions (12) - (15) into the set of equations (1) - (11) and comparing the terms of same powers of $\varepsilon, \varepsilon^2, \varepsilon^3$ etc., to gain three set of equations.

4. Linear Dispersion Relation

By utilizing first order equations, the linear dispersion relation has been occurred.

$$\left(1-\frac{4\Omega^2}{\omega_0{}^2}\right)^{\frac{1}{2}} \omega_0{}^2 (\rho_1+\rho_2) = (\rho_1-\rho_2)gk - \frac{H_0{}^2 \cos^2 \omega t (1-\mu)^2 \mu_2}{(1+\mu)} k^2 + Tk^3 \qquad (16)$$

where $\mu = \dfrac{\mu_1}{\mu_2}$.

Non existence of rotation produces the linear dispersion relation as

$$\omega_0{}^2 = k \frac{(k^2 T + (\rho_2 - \rho_1) g}{\rho_2 + \rho_1}$$

The condition concurs with the result of a linear perturbation of Chandrasekhar (1961) in the nonappearance of magnetic field.

5. Second- Order Problem

Deputing the solution of the linear order problem into the second order equations and solve them by presuming,

$$\eta_2 = \Lambda A^2 \exp(2i\theta) + c.c \qquad (17)$$

where $\wedge = \dfrac{Nr}{Dr}$,

$$Nr = -H_0^2 \cos^2 \omega t\, k^2 \frac{(\mu_2-\mu_1)^3}{(\mu_1+\mu_2)^2} + \frac{(\rho_2-\rho_1)}{k^2}\left[\beta\omega_0{}^2 (2\gamma-\beta) + 2\Omega^2\beta(2\beta-\gamma)\right] \qquad (18)$$

$$Dr = 2kH_0^2 \cos^2 \omega t \frac{(\mu_2-\mu_1)^2 \mu_2}{(\mu_1+\mu_2)} + \frac{2\gamma}{k^2} \left(\Omega^2 - \omega_0{}^2\right)(\rho_1+\rho_2) - (\rho_2-\rho_1)g + 4k^2 T \qquad (19)$$

where

$$\theta = kx_0 - \omega_0 t_0 , \quad \beta = k\left(1-\frac{4\Omega^2}{\omega_0{}^2}\right)^{\frac{1}{2}} , \quad \gamma = k\left(1-\frac{\Omega^2}{\omega_0{}^2}\right)^{\frac{1}{2}}$$

6. Third Order Problem and Nonlinear Evolution Equation

Surrogating the solution of the first and the second order problem into the third-order problem, in order to derive the third-order **dispersion relation.**

$$\frac{\partial^2 A}{\partial x_1^2}\left\{\frac{2\omega_0}{k^3}\left(\frac{\beta\omega_0}{k}+\frac{s_1}{2\beta}\right)(\rho_1+\rho_2)-\frac{8\Omega^2}{k^3\omega_0}\left(\frac{\beta\omega_0}{k}+\frac{s_1}{2\beta}\right)(\rho_1+\rho_2)+\frac{\beta}{k^4}\left({\omega_0}^2-4\Omega^2\right)(\rho_1+\rho_2)\right\}$$

$$+\frac{\partial^2 A}{\partial x_1\partial t_1}\left\{\frac{\omega_0\beta}{k^3}(\rho_1+\rho_2)+\frac{2\omega_0}{k^3}\left(\beta+\frac{s_2}{2\beta}\right)(\rho_1+\rho_2)-\frac{2\Omega^2 s_2}{k^3\beta\omega_0}(\rho_1+\rho_2)+\frac{1}{k^2}\left(\frac{\beta\omega_0}{k}+\frac{s_1}{2\beta}\right)(\rho_1+\rho_2)\right.$$

$$\left.-\frac{4\Omega^2}{k^3\omega_0}\left(\beta+\frac{s_2}{2\beta}\right)(\rho_1+\rho_2)+\frac{4\Omega^2}{k^2{\omega_0}^2}\left(\frac{\beta\omega_0}{k}+\frac{s_1}{2\beta}\right)(\rho_1+\rho_2)\right\}+$$

$$\frac{\partial A}{\partial x_2}\left\{-H_0^2\cos^2\omega t i\frac{(\mu_1-\mu_2)^2}{(\mu_1+\mu_2)}\right. +$$

$$\left.\frac{8\Omega^2 i\beta}{k^3}(\rho_1+\rho_2)-\frac{{\omega_0}^2\beta i}{k^3}(\rho_1+\rho_2)-\frac{{\omega_0}^2\beta}{k^2}(\rho_1+\rho_2)-2Tik\right\}$$

$$+\frac{\partial^2 A}{\partial t_1^2}\left\{\frac{1}{k^2}\left(\beta+\frac{s_2}{2\beta}\right)(\rho_1+\rho_2)+\frac{2\Omega^2 s_2}{k^2{\omega_0}^2\beta}(\rho_1+\rho_2)\right\}-\frac{\partial A}{\partial t_2}\left\{\frac{\beta\omega_0 i}{k^2}(\rho_1+\rho_2)\right\}$$

$$+A^2\bar{A}\left\{\frac{H_0^2\cos^2\omega t k^2(1-\mu)}{2(1+\mu)^2}(\mu_2-1)[k(\mu+3)+(1-\mu)6\Lambda+4\Lambda\mu]-\frac{H_0^2\cos^2\omega t k^2(1-\mu)}{2(1+\mu)^2}(\mu_1-1)[k(\mu+3)+(1-\mu)6\Lambda-4\Lambda]\right.$$

$$+4k^2(\mu_2-1)H_0^2\cos^2\omega t\left(\frac{1-\mu}{1+\mu}\right)^2(\Lambda+k)-4k^2(\mu_1-1)H_0^2\cos^2\omega t\left(\frac{1-\mu}{1+\mu}\right)^2(\Lambda-k)-\frac{2\rho_2\beta\gamma}{k^2}{\omega_0}^2(\beta+\Lambda)$$

$$-\frac{2\rho_1\beta\gamma}{k^2}{\omega_0}^2(\beta-\Lambda)-\frac{4\rho_2\gamma^2}{k^2}{\omega_0}^2(\beta+\Lambda)-\frac{4\rho_1\gamma^2}{k^2}{\omega_0}^2(\beta-\Lambda)$$

$$+\frac{2\rho_2\beta^2}{k^2}{\omega_0}^2(\Lambda+\beta)-\frac{2\rho_1\beta^2}{k^2}{\omega_0}^2(\Lambda-\beta)+\frac{4\omega_0}{k^2}\left(\rho_2\gamma^2\omega_0(\Lambda+\beta)+\rho_1\gamma^2\omega_0(\beta-\Lambda)\right)$$

$$-\frac{4\Omega^2}{k^2}\left(\rho_2\gamma^2(\beta+\Lambda)-\rho_1\gamma^2(\beta-\Lambda)\right)-4H_0^2\cos^2\omega t k^2\left(\frac{1-\mu}{1+\mu}\right)\left((\mu_2-1)(\Lambda+k)+(1-\mu_1)(k-\Lambda)\right)+$$

$$(\mu_2-1)H_0^2\cos^2\omega t k^3\left(\frac{1-\mu}{1+\mu}\right)-(\mu_1-1)H_0^2\cos^2\omega t k^3\left(\frac{1-\mu}{1+\mu}\right)+\frac{4\Omega^2\beta^3}{k^2}(\rho_2-\rho_1)$$

$$-\frac{\beta^3{\omega_0}^2}{k^2}(\rho_2-\rho_1)-4H_0^2\cos^2\omega t k^3\left(\frac{1-\mu}{1+\mu}\right)(\mu_2-\mu_1)+H_0^2\cos^2\omega t k^3\left(\frac{1-\mu}{1+\mu}\right)^2(2\mu_1+2\mu_2-1)$$

$$4H_0^2\cos^2\omega t k^2\Lambda\left(\frac{1-\mu}{1+\mu}\right)(\mu_1+\mu_2)-4H_0^2\cos^2\omega t k^2\left(\frac{1-\mu}{1+\mu}\right)\left(2\Lambda-\mu_2(\Lambda+k)+\mu_1(\Lambda-k)\right)$$

$$+(\mu_1-1)H_0^2\cos^2\omega t i\left(\frac{1-\mu}{1+\mu}\right)+\frac{4\rho_2\Omega^2 i}{k^3}\beta-\frac{{\omega_0}^2 i\beta}{k^3}(\rho_1+\rho_2)$$

$$+4H_0^2\cos^2\omega t k^2\Lambda\left(\frac{1-\mu}{1+\mu}\right)(\mu_1+\mu_2)-4H_0^2\cos^2\omega t k^2\left(\frac{1-\mu}{1+\mu}\right)^2\left(\mu_2(k+\Lambda)+\mu_1(k-\Lambda)-k\right)$$

$$-4H_0^2\cos^2\omega t\,k^2\Lambda(\mu_2-\mu_1)+4H_0^2\cos^2\omega t\,k^3\left(\frac{1-\mu}{1+\mu}\right)^2(\mu_1+\mu_2-1)$$

$$\left.-2H_0^2\cos^2\omega t\,k^3\left(\frac{1-\mu}{1+\mu}\right)^2(\mu_2-\mu_1)-\frac{3}{2}k^4T\right\}=0 \qquad (20)$$

where $s_1=\frac{2\beta^2}{k\omega_0}\left(4\Omega^2-\omega_0{}^2\right)$, $s_2=k^2-\beta^2-\frac{4\Omega^2\beta^2}{\omega_0{}^2}$

7. Nonlinear Schrodinger Equation and Stability Analysis

Presuming the coefficients of the terms $\frac{\partial^2 A}{\partial x_1^2},\frac{\partial^2 A}{\partial x_1\partial t_1},\frac{\partial^2 A}{\partial t_1^2},\frac{\partial A}{\partial x_2}$ and $\frac{\partial A}{\partial t_2}$ in equation (20) by N_{1k}^*, N_{2k}^*, N_{3k}^*, N_{4k}^* *and* N_{5k}^* respectively.

Then the third order dispersion relation expects the second order nonlinear Schrödinger equation:

$$i\frac{\partial A}{\partial\tau}+\beta_{1k}^*\frac{\partial^2 A}{\partial\xi^2}+\beta_k^*\frac{\partial A}{\partial\xi}+Q_k|A|^2A=0 \qquad (21)$$

where

$$\beta_{1k}^*=\frac{i}{N_{5k}}[C_{gk}^2N_{3k}-C_{gk}N_{2k}+N_{1k}],\ \beta_k^*=-i\left[C_{gk}-\frac{N_{4k}}{N_{5k}}\right],\ Q_k=\frac{i}{N_{5k}}\left[\frac{\partial D}{\partial|A|^2}\right]$$

and $C_{gk}=-\frac{Dk}{D\omega_0}$.

$$Dk=(\rho_2-\rho_1)g+2kH_0^2\cos^2\omega t\frac{(\mu_2-\mu_1)^2}{(\mu_1+\mu_2)}\mu_2\ \text{-}3Tk^2$$

$$D\omega_0=\frac{(4\Omega^2-2\omega_0^2)}{(\omega_0^2-4\Omega^2)^{\frac{1}{2}}}(\rho_1+\rho_2)$$

Dk and $D\omega_0$ are acquired from the linear dispersion relation.

The stability norms is scrutinized by concluding the time varying solution,

$A=m\exp\left(iQ_km^2\tau\right)$, m is a constant. (22)

Equation (22) is perturbed by considering,

$$A=[m+D_{1k}(\xi,\tau)+iE_{1k}(\xi,\tau)]\exp\left(iQ_km^2\tau\right) \qquad (23)$$

where real functions are marked as D_{1k} and E_{1k}.

Using equation (23) in nonlinear Schrödinger equation (21) and avoiding the nonlinear terms in D_{1k} and E_{1k}.

$$-\frac{\partial E_{1k}}{\partial \tau}+\beta_{1k}^{*}\frac{\partial^{2} D_{1k}}{\partial \xi^{2}}+\beta_{k}^{*}\frac{\partial D_{1k}}{\partial \xi}=0 \quad \text{and} \quad (24)$$

$$\frac{\partial D_{1k}}{\partial \tau}+\beta_{1k}^{*}\frac{\partial^{2} E_{1k}}{\partial \xi^{2}}+\beta_{k}^{*}\frac{\partial E_{1k}}{\partial \xi}=0 \quad (25)$$

Indicating

$$D_{1k}(\xi,\tau)=D^{*}\exp\left(ik_{2}\,\xi+\omega_{2k}\tau\right)+C.C \quad (26)$$

and

$$E_{1k}(\xi,\tau)=E^{*}\exp\left(ik_{2}\,\xi+\omega_{2k}\tau\right)+C.C \quad (27)$$

where D^{*} and E^{*} are constant values.

By employing (26) and (27), the disturbance frequency ω_{2k} and the wave number k_2 impulse the **dispersion relation**,

$$\omega_{2k}^{2}+\left[\beta_{1k}^{*2}k_{2}^{4}-2ik_{2}^{3}\beta_{k}^{*}\beta_{1k}^{*}-k_{2}^{2}\beta_{k}^{*2}\right]=0 \quad (28)$$

i.e., $\omega_{2k}^{2}=-\left[\beta_{k}^{*}\,i\,k_{2}-\beta_{1k}^{*}k_{2}^{2}\right]^{2}$

8. Discussion and Conclusion

- The linear dispersion relation in the case of alternating magnetic field correlates with the linear dispersion on condition of tangential magnetic field and the field frequency $\omega=0$.
- It is constituted that, the system is unstable when the effects of rotation and tangential magnetic field are coupled (Anjalidevi and Jothimani , 2001).
- The linear dispersion relation harmonized with Rosensweig(1967) in the absence of rotation and tangential magnetic field. It is also similar with the linear perturbation by Chandrasekar(1961) in the absence of magnetic field and rotation.
- The instability commences when $H^{2}\geq H_{c}^{2}$ where

  $$H_{c}^{2}=\frac{2(\mu_{1}+\mu_{2})\,\mu_{2}}{(\mu_{2}-\mu_{1})^{2}}\left[(\rho_{1}-\rho_{2})\,gT\right]^{\frac{1}{2}}.$$

  This value is confirmed with the value of the critical magnetic field investigated by Cowley and Rosensweig(1967).
- Further in non-appearance of rotation, the neutral stability takes place at $\omega_{0}=0$ in linear dispersion relation and the neutral stability curve H_{0}^{2} Vs k has a minimum H_{c}^{2} for a finite

  $K_{c}=\left(\frac{(\rho_{1}-\rho_{2})\,g}{T}\right)^{\frac{1}{2}}$ where

  $$H_{c}^{2}=\frac{2(\mu_{1}+\mu_{2})\,\mu_{2}}{(\mu_{2}-\mu_{1})^{2}}\left[(\rho_{1}-\rho_{2})\,gT\right]^{\frac{1}{2}}.$$
- By assuming the wave number k_{2} real and positive values in the dispersion relation and from the preceding discussions the following culmination is arrived. We perceive that ω_{2k} is purely imaginary and that being the case, the system is found to be stable.

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