Rozchodzenie się fal Love'a w falowodach sprężystych obciążonych na powierzchni cieczą lepkosprężystą

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OUTLINE

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   (State of the art)
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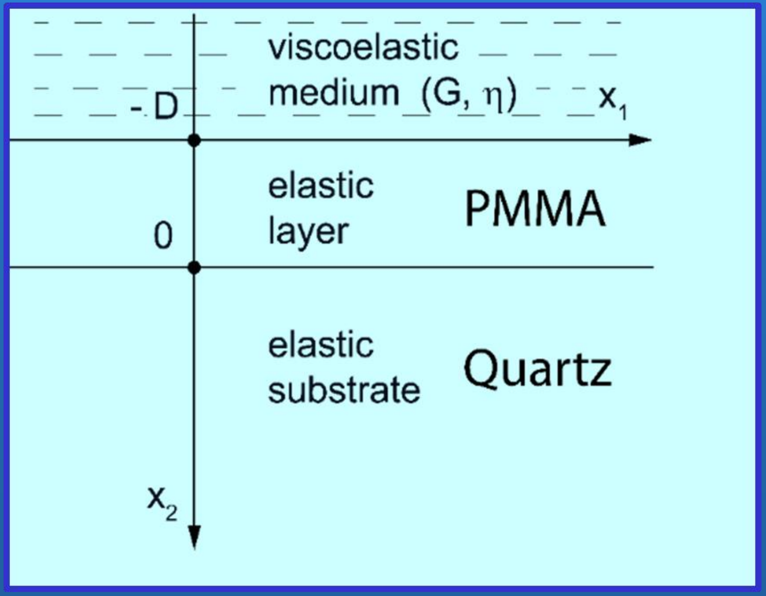
Objectives of the study

A. Scientific objective of the Study is to develop theoretical foundations and creating a mathematical model of the phenomenon of propagation of transverse surface Love waves in a layered viscoelastic media

B. In future, establishing on this basis a new non-destructive method for the identification of rheological parameters (elasticity, viscosity, density) of viscoelastic media. New method that uses surface Love waves will be non-destructive, rapid, accurate and computerized without drawbacks of classical mechanical methods.



This problem has not been solved yet in the worldwide literature

Fig.1. Lossless (elastic) Love wave waveguide (surface layer plus substrate) loaded at the surface x_2 = - D with a lossy viscoelastic medium of the shear modulus G and viscosity η.

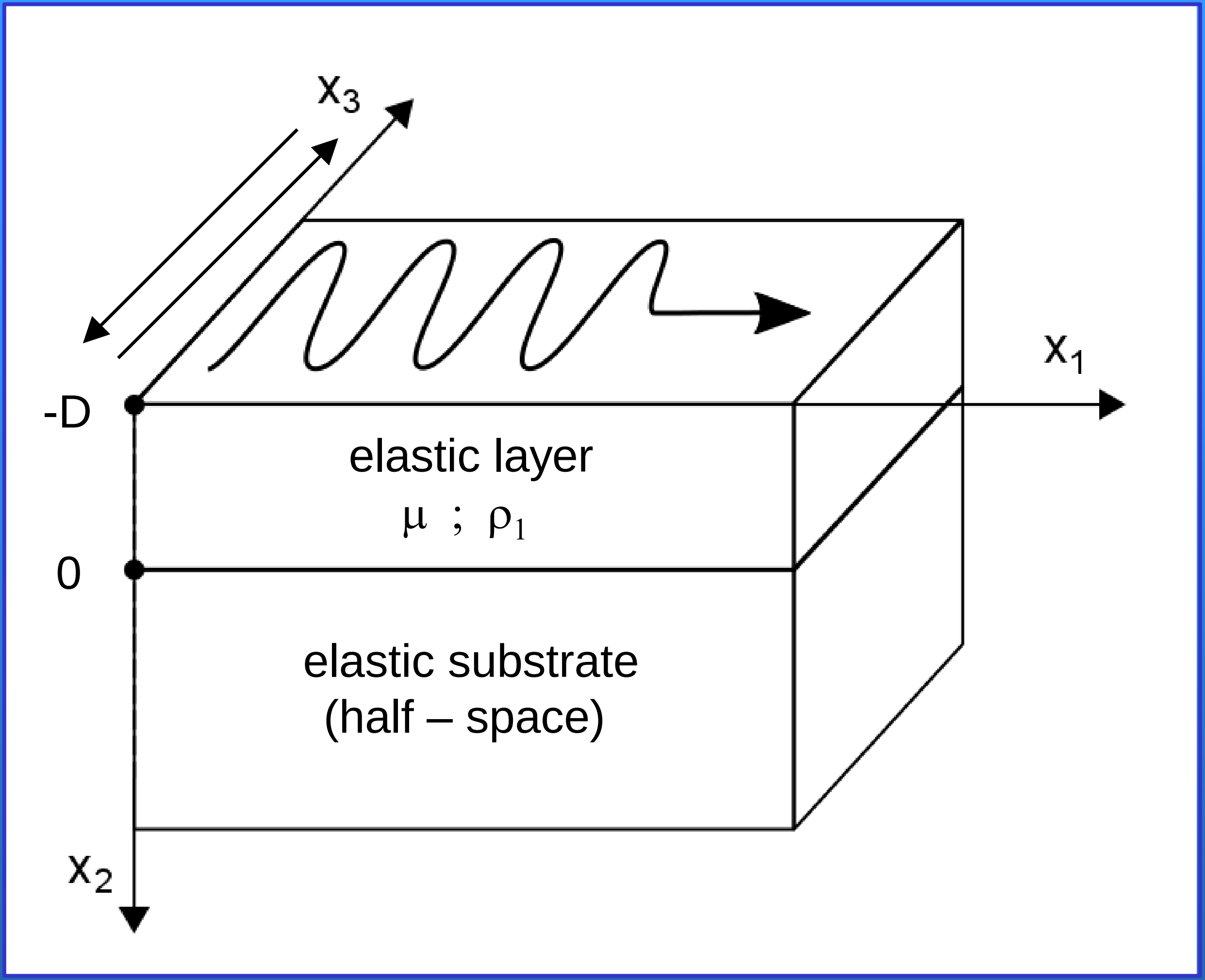


Fig.2. SH (Shear Horizontal) surface Love wave waveguide.
Love wave propagates along x_1 axis.
Love wave has only one shear component of mechanical displacement along x_3 axis.

Importance of the problem

A. Large quantity of processed plastics and polymers (milion tons a year).

Trial and Error method is still often used in the plastic industry

B. Theory of sensors (bio and chemosensors).

Presented in this study model can serve as a mathematical model of sensors.

To date, there is no mathematical model of sensors based on the SH waves.

D. In geophysics and seismology. Exploration of natural resources. Love waves propagating in layered geological structures coverd with a liquid (e.g., Ocean). Lack of the theory.

E. In microelectronics (MEMS – Micro Electro Mechanical Systems).

Examination of the quality of thin layers.

Twisted Railroad Tracks

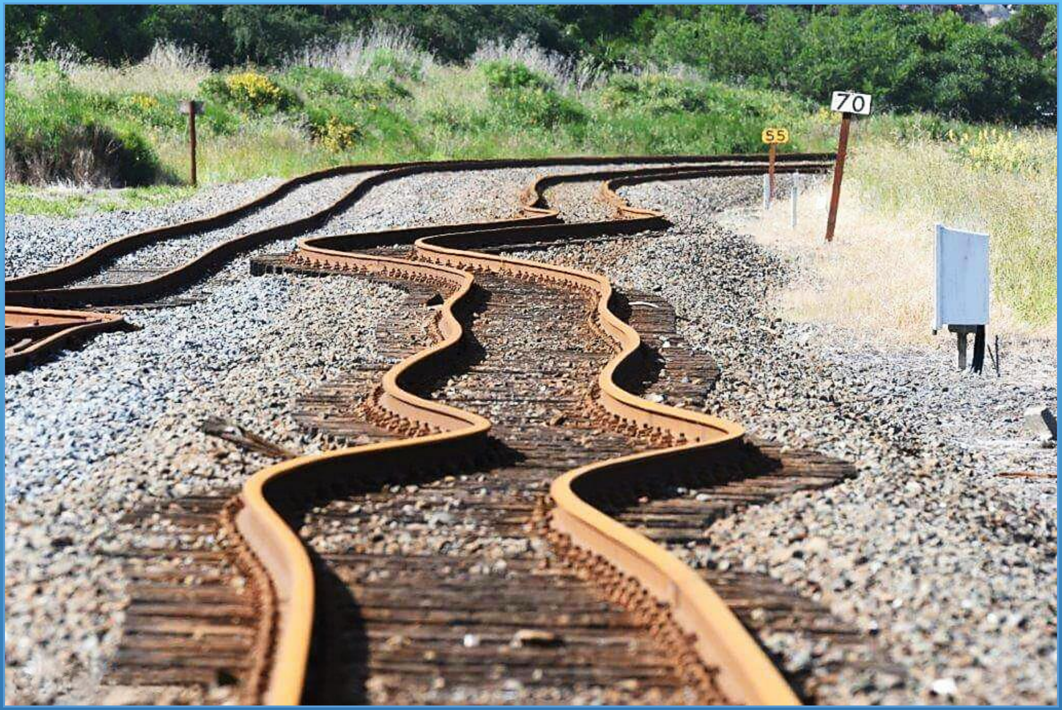
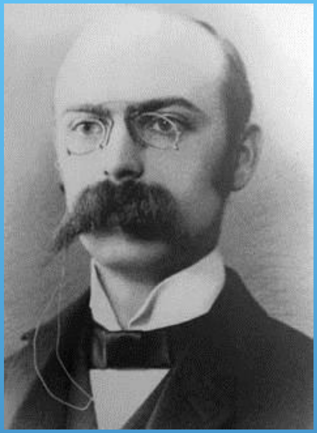


Fig.3. Example of structural damages due to SH displacement of Love surface waves



Augustus, Edward, Hough Love - 1911

Mechanical methods for determining the rheological properties of viscoelastic media

A. Couette (rotating cylinders) – 1890

B. Falling ball (Hoppler - 1932)

C. Falling sinker (e.g., needle, cone, cylinder)

D. Cone-plate

E. Capillary tube viscometer (Poiseuille)

Disadvantages:

a) Presence of moving parts
b) Require special sophisticated equipment
c) Measurements are tedious and time consuming
d) Large dimensions
e) Difficult to computerize
f) Cannot operate in real-time
g) Only laboratory methods (cannot be employed on-line)

Application of bulk ultrasonic waves for the determination of the rheological parameters of viscoelastic media

For example: Plate SH (Shear Horizontal) ultrasonic waves, Torsional waves, Lamb waves.

1. Standing waves (resonators)
   e.g., torsionally oscillating piezoelectric quartz rod, vibrating fork, vibrating cantilever (2008) – complicated setup, optical readoud

2. Travelling waves (waveguides)

The acoustic energy is distributed in the entire volume of resonator or waveguide. The contact with an investigated viscoelastic liquid takes place on their surface.

3. Low sensitivity of sensors that use bulk ultrasonic waves.

Application of surface ultrasonic waves (i.e., Love and B-G waves) for the determination of the rheological parameters of viscoelastic media

- Love waves (1911), Bleustein-Gulyaev (B-G) waves (1968)
- The energy of SH-SAW is concentrated in the vicinity of the waveguide surface. Thus the SH-SAW velocity and attenuation strongly depend on the boundary conditions on the waveguide surface.
- In consequence, the sensitivity of the viscosity sensors using SH-SAW (e.g., Love waves) can be several orders larger than the sensitivity of the sensors employing bulk shear acoustic waves.

Properties of Love waves

- One component of the mechanical displacement. (Waves undergo dispersion). (Frequency range from 0.001 Hz to 500 MHz)
- Transverse (shear horizontal) surface wave does not exist in a homogeneous elastic half-space

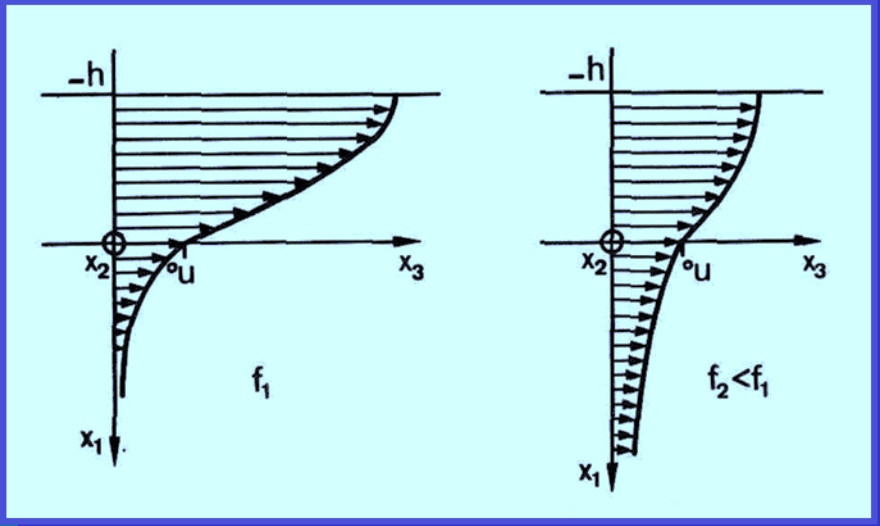


Fig.4. Distribution of the mechanical displacement with depth. $f_1 > f_2$.

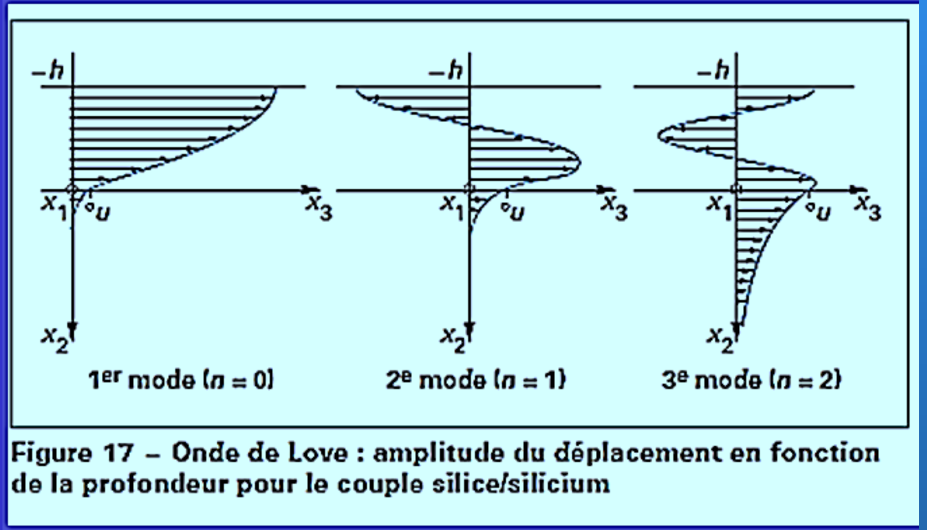
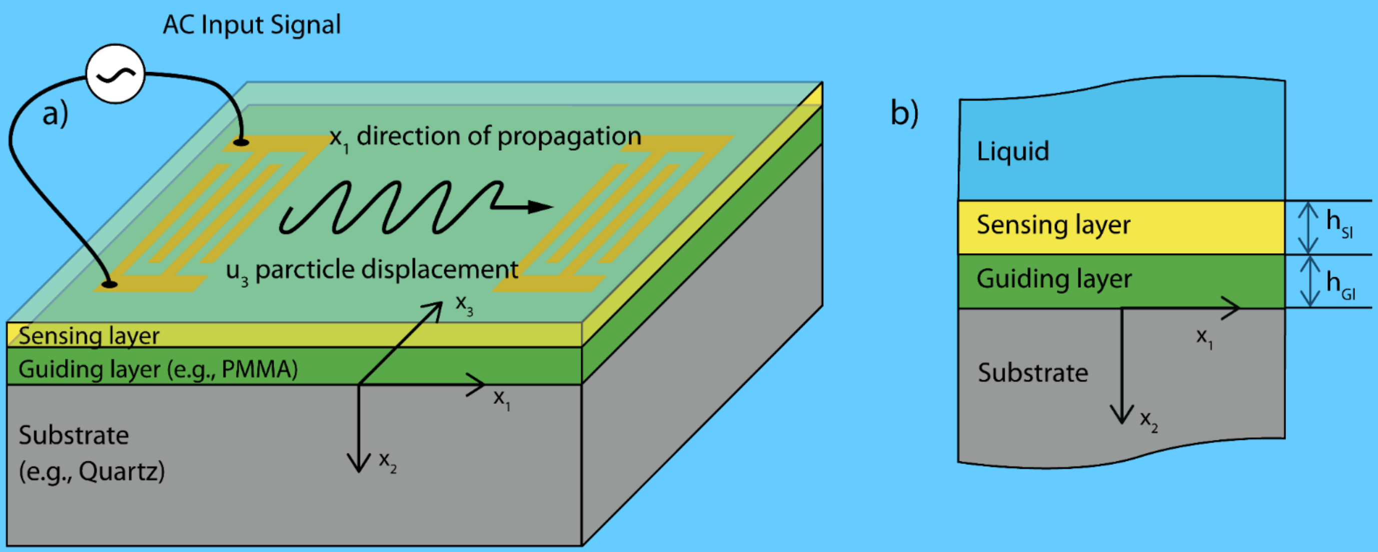


Fig.5. Distribution of the mechanical displacement with depth for subsequent modes.

Advantages of Love waves sensors

1. Absence of moving parts
2. Operation in real time
3. Short measuring time
4. High sensitivity
5. Can operate at high-pressure (up to 1 GPa), and elevated temperatures (up to 400 ºC)
6. Low power consumption
7. Small dimensions, simple and robust construction of the sensor
8. Possibility of computerization
9. Output signal is electrical

Physical Model of Love Wave Sensor



a) Typical dimensions - 1 x 5 x 20 mm
b) Circuit configuration - resonator or delay line
c) Frequency range - 50 - 500 MHz
d) Wavelength range - 10 - 100 μm

Theory of Love waves propagating in viscoelastic layered media. (State of the art)

The problem of Love wave propagation in viscoelastic media is still not solved.

1) K. Sezawa, K. Kanai, Damping of periodic visco-elastic waves with increase in focal distance, Bulletin of the Earthquake Research Institute (Tokyo), 16 (1938) 491-503.

2) T. K. Das, P. R. Sengupta,L. Debnath, Effect of gravity on viscoelastic surface waves in solids involving time rate of strain and stress of higher order, International Journal of Mathematics and Mathematical Sciences, 18 (1995) 71-76.

3) M. Goto, H. Yatsuda and J. Kondoh, Effect of viscoelastic film for shear horizontal surface acoustic wave on quartz, Japanese Journal of Applied Physics, Volume 54, Number 7S1 (2015).

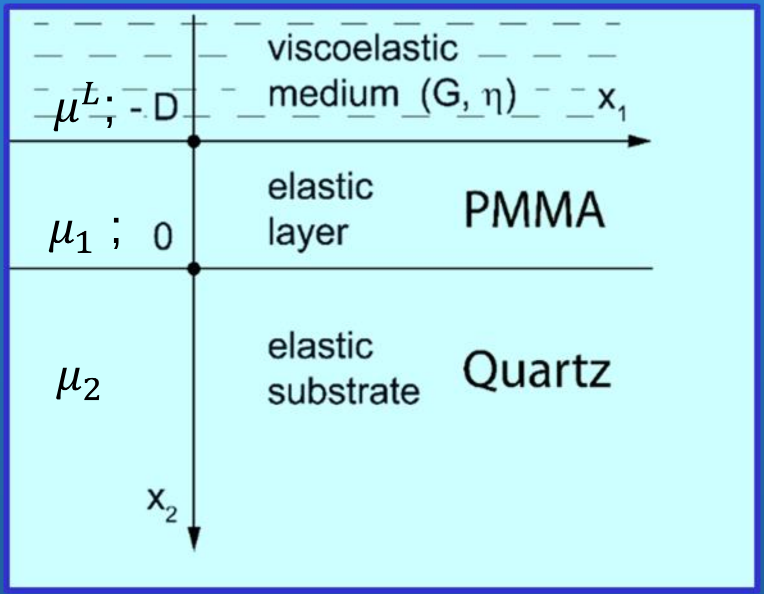
4) G. McHale, M.I. Newton, and F. Martin, Theoretical mass, liquid, and polymer sensitivity of acoustic wave sensors with viscoelastic guiding layers, Journal of Applied Physics, 93 (2003) 675-690.

Mathematical Model: Direct Sturm-Liouville Problem

Direct Sturm-Liouville Problem for Love's wave propagating in the layered viscoelastic waveguide consists in determining the phase velocity and attenuation of Love wave, knowing all the material parameters of the waveguide and viscoelastic medium for a fixed frequency.

$\mu = G' + jG''$ - complex shear modulus; $tan\delta = G''/G'$ - loss tangent;
δ is a phase shift between stress and strain; $j = (-1)^{1/2}$.

$k = k_0 + j\alpha$ - complex wave number of the Love wave



$$\begin{cases} L\, y(x) = \lambda y(x) \\ \lambda = \text{eigenvalue} \\ y(x) = \text{eigenvector} \end{cases} \Rightarrow \{\lambda,\, y(x)\}$$

Material parameters

↓

Wave velocity and attenuation

Fig.6. Love wave waveguide loaded with a viscoelastic medium (liquid).

Assumptions

1. We consider (fundamental) first mode (a kind of vibration) of Love waves

2. The substrate and surface layer are elastic, isotropic, homogeneous and lossless media

3. The surface layer is loaded by a viscoelastic medium

4. There is no variation along the axis (x_3)

5. Losses are introduces only by the presence of a viscoelastic medium

6. Mechanical displacement of the Love wave:

$$u_3(x_1, x_2, t) = f(x_2) \cdot exp[j(k \cdot x_1 - \omega t)]$$

Mathematical model: Differential equations of motion

1) In viscoelastic medium: $(x_2 < -D)$:

$$\frac{1}{v_L^2}\frac{\partial^2 u_3}{\partial t^2} = \left(\frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2}\right)u_3 \qquad (1)$$

where: $v_L = (\mu^L/\rho_L)^{1/2}$ is the complex bulk shear wave velocity in the viscoelastic medium

2) In elastic surface layer: $(0 > x_2 > -D)$:

$$\frac{1}{v_1^2}\frac{\partial^2 u_3}{\partial t^2} = \left(\frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2}\right)u_3 \qquad (2)$$

where: $v_1 = (\mu_1/\rho_1)^{1/2}$ is the bulk shear wave velocity in the layer

3) In elastic substrate: $(x_2 > 0)$:

$$\frac{1}{v_2^2}\frac{\partial^2 u_3}{\partial t^2} = \left(\frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2}\right)u_3 \qquad (3)$$

where: $v_2 = (\mu_2/\rho_2)^{1/2}$ is the bulk shear wave velocity in the substrate.

Propagation wave solution

In elastic surface layer: $(0 > x_2 > -D)$

Mechanical displacement:

$$u_3^{(1)} = W(x_2) \cdot exp[j(k \cdot x_1 - \omega t)] \quad (4)$$

$$W''(x_2) - (k_1^2 - k_0^2) \cdot W(x_2) = 0 \quad (5)$$

We postulate the solution in the form q_B:

$$W(x_2) = C_1 \cdot \sin(q_B \cdot x_2) + C_2 \cdot \cos(q_B \cdot x_2) \quad (6)$$

where: $q_B = (k_1^2 - k^2)^{1/2}$ $k_1 = \frac{\omega}{v_1}$; C_1 and C_2 are arbitrary constants

q_B is a complex quantity

Shear stress component:

$$\tau_{23}^{(1)} = \mu_1 \frac{\partial u_3^{(1)}}{\partial x_2} = [C_1 \cdot \mu_1 \cdot q_B \cdot \cos(q_B \cdot x_2) - C_2 \cdot \mu_1 . q_B \cdot \sin(q_B \cdot x_2)] \cdot exp[j(kx_1 - \omega t)]$$

(7)

In elastic substrate:

$(x_2 > 0)$

Mechanical displacement:

$$u_3^{(2)} = U(x_2) \cdot exp[j(k \cdot x_1 - \omega t)] \quad (8)$$

$$U''(x_2) - (k^2 - k_2^2) \cdot U(x_2) = 0 \quad (9)$$

$$U(x_2) = C_3 \cdot exp(-b \cdot x_2) \quad (10)$$

where: $b = (k^2 - k_2^2)^{1/2}$ $k_2 = \frac{\omega}{v_2}$ $Re(b) > 0$

b is a complex quantity

C_3 is an arbitrary constant

Shear stress component:

$$\tau_{23}^{(2)} = \mu_2 \frac{\partial u_3^{(2)}}{\partial x_2} = C_3 \cdot \mu_2 \,(-b) \cdot exp(-b \cdot x_2) \cdot exp[j(kx_1 - \omega t)] \quad (11)$$

In viscoelastic medium: $(x_2 < -D)$

Mechanical displacement: $$u_3^L = V(x_2) \cdot exp[j(k \cdot x_1 - \omega t)]$$ (12)

$$V''(x_2) - \left(k^2 - \frac{\rho_L \omega^2}{\mu^L}\right) \cdot V(x_2) = 0$$ (13)

$$V(x_2) = C_4 \cdot exp(\lambda_1 \cdot x_2)$$ (14)

where: $\lambda_1 = \sqrt{k^2 - \frac{\rho_L \omega^2}{\mu^L}}$ $Re(\lambda_1) > 0$

λ_1 is a complex quantity

C_4 is an arbitrary constant

Shear stress component :

$$\tau_{23}^{(L)} = \mu^L \frac{\partial u_3^L}{\partial x_2} = C_4 \cdot \mu^L \cdot \lambda_1 \cdot exp(\lambda_1 \cdot x_2) \cdot exp[j(kx_1 - \omega t)]$$ (15)

Boundary conditions

1. On the viscoelastically loaded waveguide surface ($x_2 = -D$), continuity of the displacement field u_3 and stress τ_{23}:

$$u_3^{(L)}\Big|_{x_2=-D} = u_3^{(1)}\Big|_{x_2=-D} \qquad (16)$$

$$\tau_{23}^{(L)}\Big|_{x_2=-D} = \tau_{23}^{(1)}\Big|_{x_2=-D} \qquad (17)$$

2. Continuity of the displacement field u_3 and stress τ_{23} at the interface between the elastic layer and the substrate ($x_2 = 0$):

$$u_3^{(1)}\Big|_{x_2=0} = u_3^{(2)}\Big|_{x_2=0} \qquad (18)$$

$$\tau_{23}^{(1)}\Big|_{x_2=0} = \tau_{23}^{(2)}\Big|_{x_2=0} \qquad (19)$$

3. $u_3 = 0$ when $x_2 \to \pm\infty$.

Complex dispersion equation

After substitution of Eqs. (6), (10), (14) and (7), (11), (15) into boundary conditions (16 -19), the set of four linear and homogeneous equations for unknown coefficients C_1, C_2, C_3 and C_4 is obtained.

[M] = 4x4 Matrix

$$[M]\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = 0 \qquad (20)$$

Necessary condition for nontrivial solution is that the determinant of this matrix M equals zero.

$$\det\,[M] = 0 \qquad (21)$$

This leads to the following complex dispersion relation:

Complex dispersion equation Analytical form

$$F(k,\omega) = \sin(q_B D)\cdot\{(\mu_1)^2 \cdot q_B^2 - \mu_2 \cdot b \cdot \lambda_1 \cdot \mu^L\} - \cos(q_B D)\cdot \mu_1 \cdot q_B \cdot \{\mu_2 \cdot b + \lambda_1 \cdot \mu^L\} = 0 \qquad (22)$$

$F(k,\omega)$ is an implicit function of (k,ω)

In Eq.22 the quantities: $\mu^L, \lambda_1, b\ and\ q_B$ are complex:

$$\lambda_1 = \sqrt{(k_0^2 - \alpha^2) + j\cdot 2\cdot k_0 \cdot \alpha - \frac{\rho_L \omega^2}{\mu^L}} \qquad (23)$$

$$q_B = \sqrt{(k_1^2 - k_0^2 + \alpha^2) + j\cdot(k_1^2\ -\ 2\cdot k_0\cdot\alpha)} \qquad (24)$$

$$b = \sqrt{(k_0^2 - \alpha^2 - k_2^2) + j\cdot 2\cdot k_0\cdot\alpha} \qquad (25)$$

$$\mu^L = (G - j\omega\eta) = G(1 - j tan\delta) \quad ; \quad \text{(for K-V model)} \qquad (26)$$

where: $k_1 = \omega/v_1$; $k_2 = \frac{\omega}{v_2}$; $k_0 = \frac{\omega}{v_p}$; α and $tan\delta = \left(\frac{\omega\eta}{G}\right)$ are real variables.

Separating real and imaginary parts of the complex dispersion equation (22), we obtain:

$$Re(F) = A(\mu_1,\ \rho_1, \mu_2,\ \rho_2, \rho_L, G, \eta,\ D,\ \omega;\ k_0, \alpha) = 0 \qquad (27)$$

$$Im(F) = B(\mu_1,\ \rho_1, \mu_2,\ \rho_2, \rho_L, G, \eta, D,\ \omega;\ k_0, \alpha) = 0 \qquad (28)$$

This is a system (27-28) of two real nonlinear algebraic equations.
The unknowns are: (k_0 and α).
The parameters are: $\mu_1,\ \rho_1, \mu_2, \rho_2, \rho_L, G, \eta,\ D$ and ω.

$k = k_0 + j\alpha$ - complex wave number of the Love wave

$v_p = \omega / k_0$ - Love wave phase velocity

α - Love wave attenuation in Np/m

Modified Powell hybrid method: Program MATHCAD and SCILAB

Numerical calculations

Material parameters: (typical for biosensors)

For (Polymethylmethacrylate) PMMA

$\mu_1 = 1.43 \cdot 10^9 \; N/m^2$

$\rho_1 = 1.18 \cdot 10^3 \; kg/m^3$

$v_1 = (\mu_1/\rho_1)^{1/2} = 1100 \; m/s$

For ST-90° X Quartz

$\mu_2 = 67.85 \cdot 10^{10} \; N/m^2$

$\rho_2 = 2.56 \cdot 10^3 \; kg/m^3$

$v_2 = (\mu_2/\rho_2)^{1/2} = 5060 m/s$

Thickness: $D = 400 \; \mu m$

Program Mathcad and Scilab

Viscoelastic material: $\eta = 1 \; mPas$,
$G = 5 \times 10^4$
$\rho_L = 1 \times 10^3 \; kg/m^3$

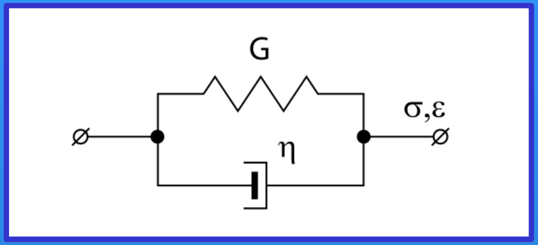
Numerical calculations were performed in the range: f = from 0 to 1000 MHz

Rheological models of viscoelastic materials considered in this study

1) Kelvin-Voigt model

$$\mu^L = G - j\omega\eta = G(1 - j tan\delta)$$

$$tan\delta = \omega\eta/G$$

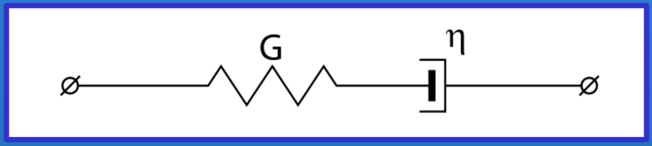


(31)

2) Maxwell model

$$\mu^L = G\frac{(\omega\tau)^2}{1+(\omega\tau)^2} - jG\frac{\omega\tau}{1+(\omega\tau)^2}$$

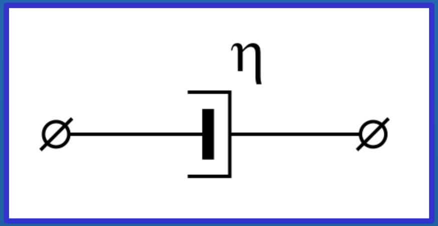
$$\omega\tau = \omega\eta/G \quad ; \quad tan\delta = 1/\omega\tau$$



(32)

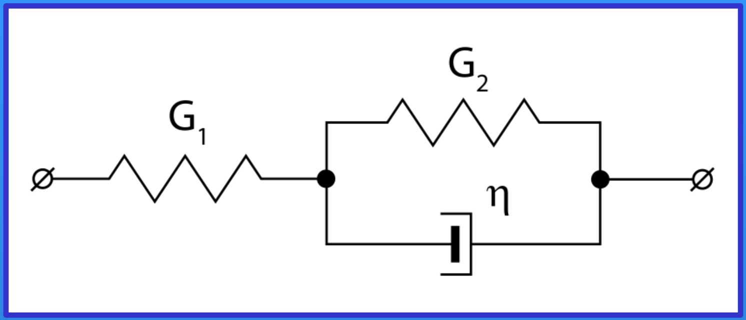
3) Newton model

$$\mu^L = -j\omega\eta$$



(33)

Standard rheological models of viscoelastic materials



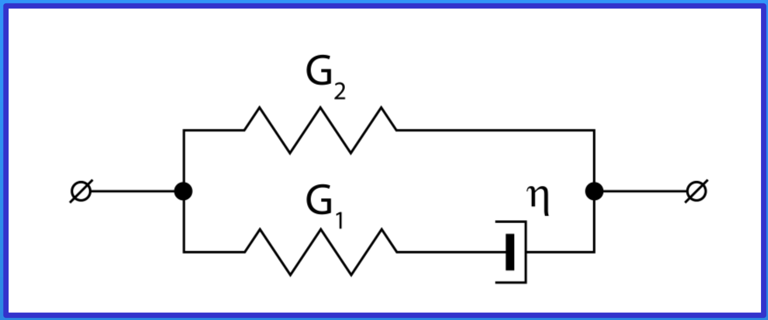
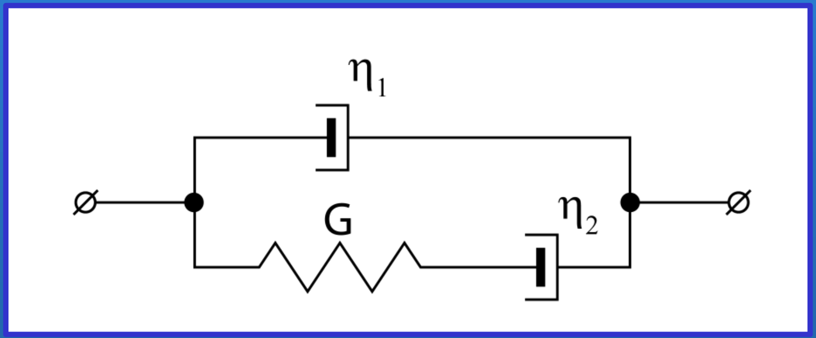


Fig.7. a) Solid I b) Solid II



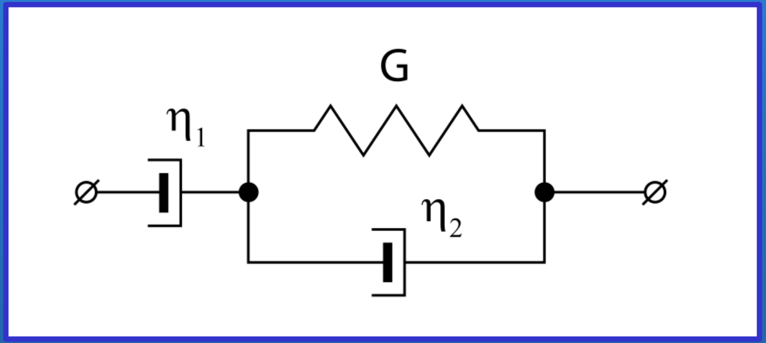


Fig.8. a) Liquid I b) Liquid II

Love wave phase velocity dispersion curves

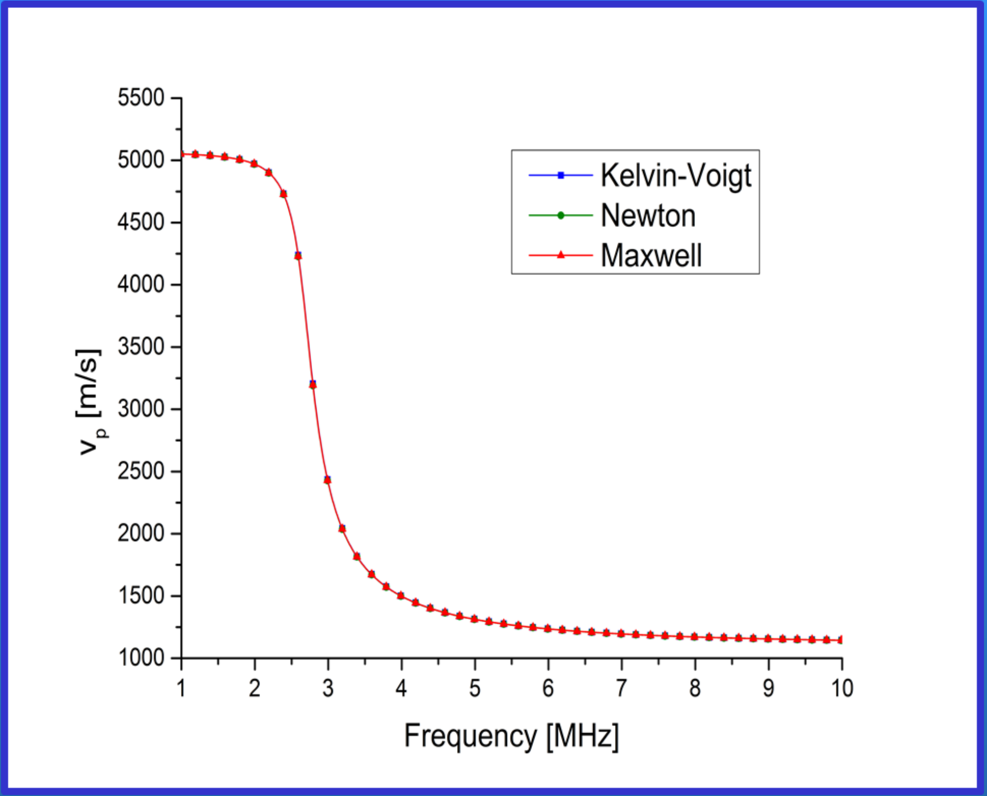


Fig.9. Phase velocity of the Love surface wave, propagating in a lossless elastic waveguide loaded with three different types of lossy viscoelastic materials, i.e., Kelvin - Voigt, Newton and Maxwell, in low frequency limit: $\tan\delta \in [0.125 - 1.25]$, $G = 5 \times 10^4\ Pa$, $\eta = 1\ mPa \cdot s$.

Love wave phase attenuation dispersion curves

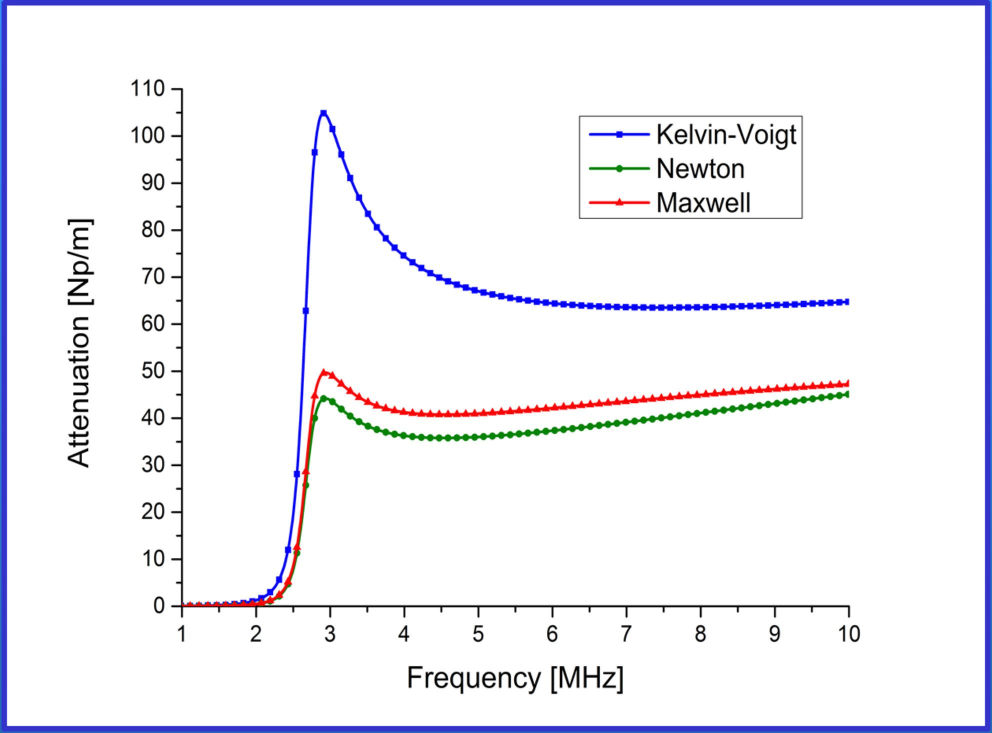


Fig.10. Attenuation of the Love surface wave, propagating in a lossless elastic waveguide loaded with three different types of lossy viscoelastic materials, i.e., Kelvin - Voigt, Newton and Maxwell, in the low frequency limit: $\tan\delta \in [0.125 – 1.25]$, $G = 5 \times 10^4\ Pa$, $\eta = 1\ mPa \cdot s$.

Love wave phase attenuation dispersion curves

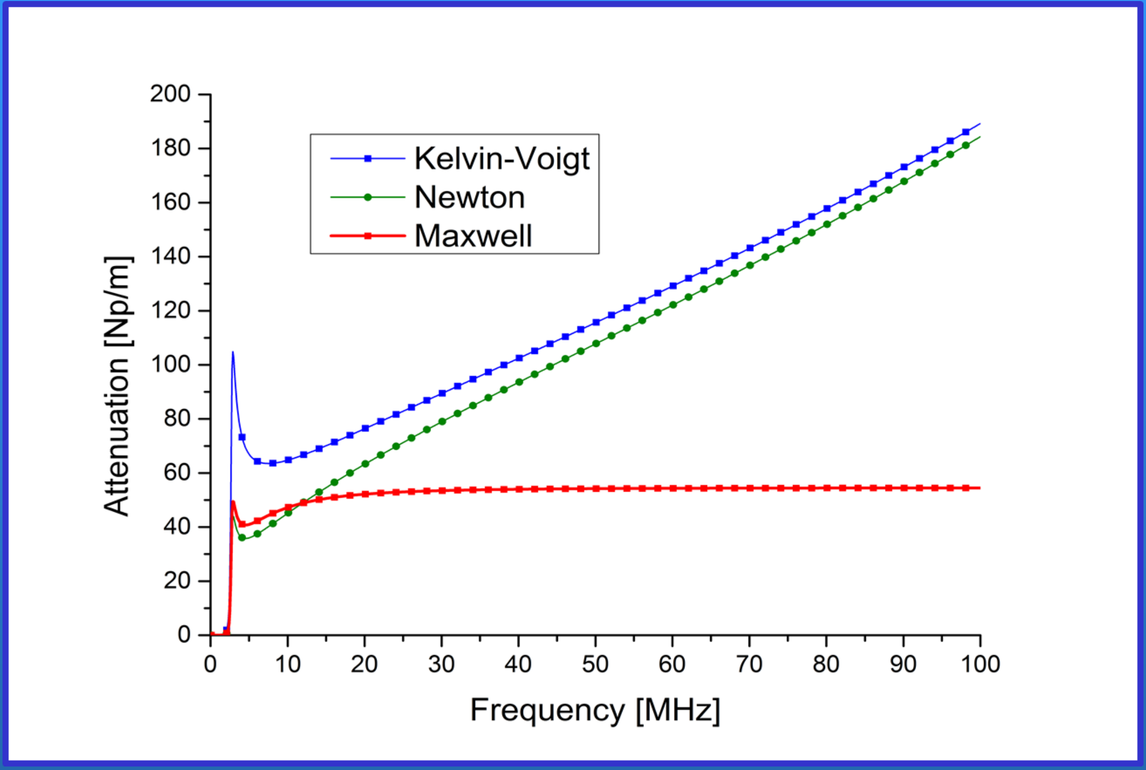


Fig.11. Attenuation of the Love surface wave, propagating in a lossless elastic waveguide, loaded with 3 different types of lossy viscoelastic materials, i.e., Kelvin - Voigt, Newton and Maxwell. Low and medium frequency limits: $\tan\delta \in [0.125 - 12.5]$, $G = 5 \times 10^4\, Pa, \eta = 1\, mPa \cdot s$.

Love wave phase attenuation dispersion curves

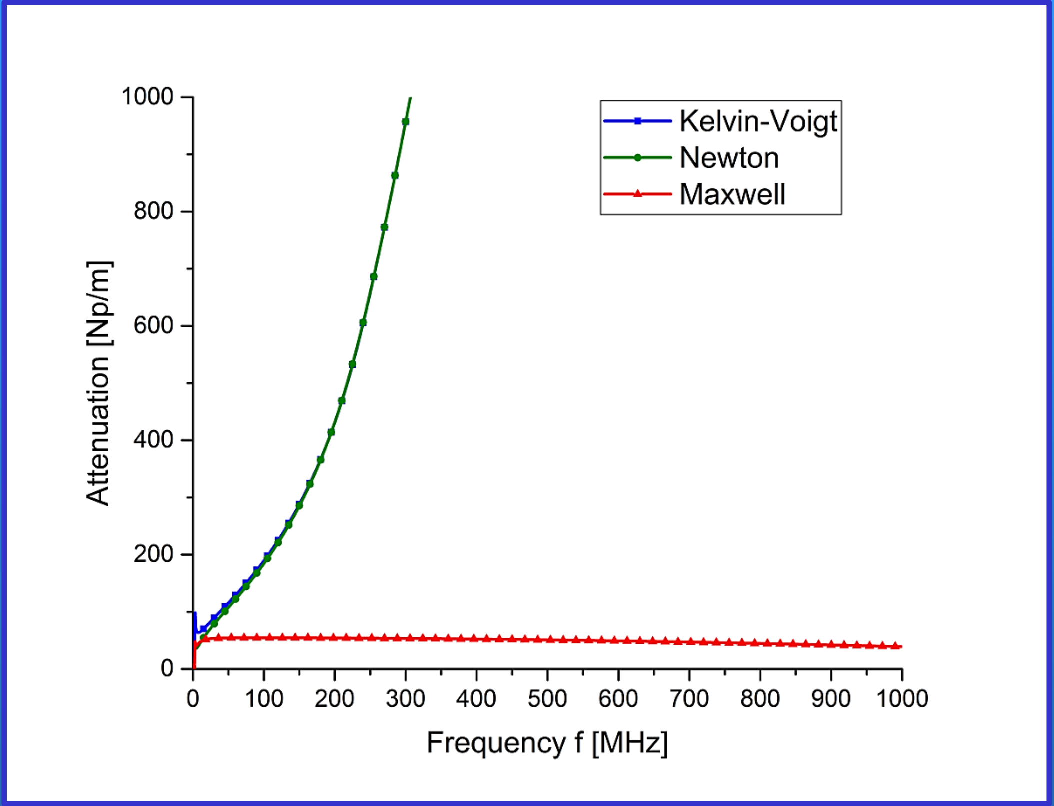


Fig.12. Attenuation of the Love surface wave, propagating in a lossless elastic waveguide, loaded with 3 different types of lossy viscoelastic materials, i.e., Kelvin - Voigt, Newton and Maxwell. Low, medium and high frequency limits: $\tan\delta \in [0.125 - 125.0]$, $G = 5 \times 10^4\ Pa$, $\eta = 1\ mPa \cdot s$.

Conclusions

1. The results show that the Love waves can propagate in the invesigated layered viscoelastic media

2. The impact of the rheological parameters on dispersion curves of the phase velocity and attenuation of Love wave was evaluated.
   Love wave phase velocity differs slightly for the Newtonian, Maxwelian and Kelvin-Voigt materials.

3. In the low frequency limit $\tan\delta \ll 1$ the attenuation of the Love wave due to the Maxwellian liquid and that due to the Newtonian liquid are almost the same.

4. In the high frequency limit $\tan\delta \gg 1$ the attenuation of the Love wave due to the Kelvin -Voigt material and that due to the Newtonian liquid are almost identical.

Future works:

Determination of the rheological parameters (elasticity, viscosity, density) of viscoelastic media $\mu = G' + jG''$.

Inverse Sturm-Liouville Problem:

Dispersion curves $\Rightarrow$ $\mu_B^0, \ \eta, \ \rho$

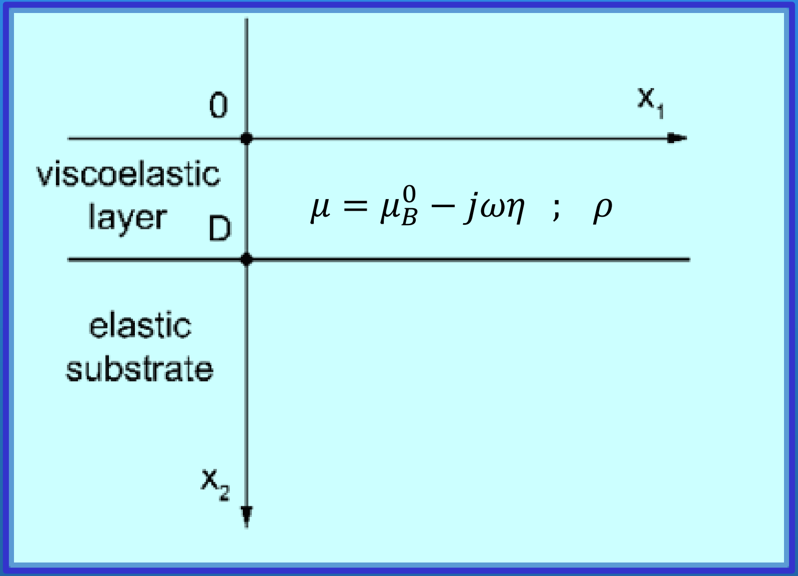


Fig.13. a) Viscoelestic layer over an elastic substrate

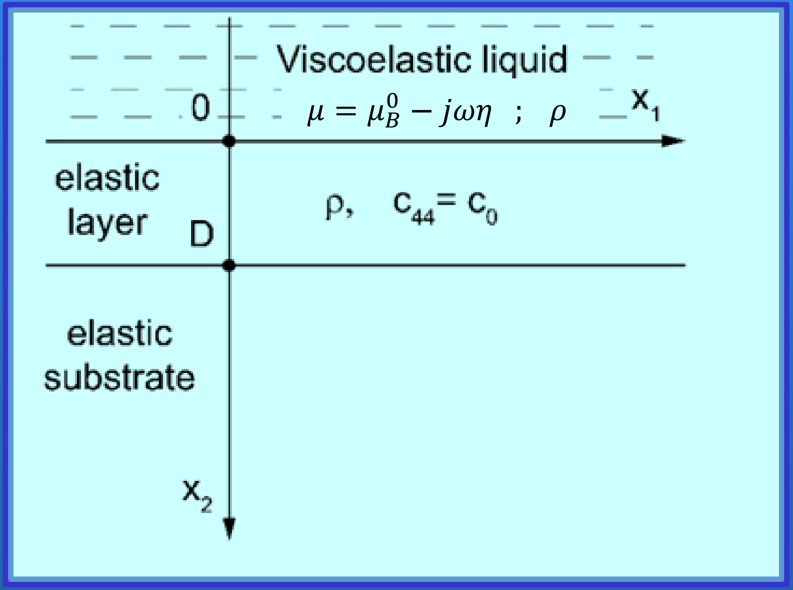


Fig.13. b) Viscoelastic liquid loading the waveguide surface

Potential applications of the Inverse Method

The results of the study can constitute the theoretical basis for application works in various branches of industries, namely:

1) in on-line investigation of liquid polymers during the course of technological processes (e.g., during processing of liquid polymers, during the pressurized encapsulation)

2) in on-line controlling of the viscoelastic properties of drilling fluids in petroleum and mining industries, during the oil and natural resources exploration

3) in the investigation of the viscoelastic properties of liquid food products (e.g., oils, fats, juices etc.).

4) in theory, design, and optimization of the ultrasonic sensors of the physical properties, chemo and biosensors, based on the use of surface Love waves

5) in geophysics and seismology