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New Fascinating Properties and Potential Applications of Love Surface Waves

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***Abstract*—In this work we present a general analysis of the extraordinary properties of surface Love waves and the unexpected wave phenomena that can occur in the Love wave waveguides. A brief history of the Love waves and their applications to Love wave sensors is given. The results of the author's recent research on Love wave sensors are presented. The analytical formula for the mass sensitivity of the Love wave sensor is shown. Extraordinary properties that reveal Love waves propagating in lossy media are introduced. Counterintuitive phenomena in Love wave waveguides such as: a) minimum of phase velocity as a function of liquid viscosity and b) maximum of attenuation as a function of liquid viscosity are reported. Moreover, the application of new mathematical tools in the analysis of Love wave sensors such as: Inverse Methods is discussed. New possible directions for research on Love wave sensors have been indicated.**

Keywords—Love waves, Love wave sensors, mass sensitivity, dispersion equation, Newtonian liquid, Inverse methods

I. Introduction

Love surface waves propagating in elastic layered waveguides have many unique features that differentiate them from other types of surface waves, such as Rayleigh, Lamb or Stoneley waves. In fact, Love surface waves:

1. have only one shear horizontal (SH) component of vibration (mechanical displacement)
2. have relatively simple mathematical description [1-4]
3. have some similarities to electromagnetism (planar dielectric waveguides)
4. have some similarities with quantum mechanics (movement of quantum particles in potential wells)

Love surface waves were predicted theoretically in 1911 by A. E. H. Love, who analyzed seismic data registered in wake of Earthquakes. Love surface waves revealed their benign face by the end of the twentieth century with the advent of Love wave sensors, biosensors and chemosensors with parameters superior to those achievable with other types of acoustic wave sensors.

Despite their centennial history Love surface waves do not stop to surprise us by unveiling new unexpected properties and possibilities for novel applications. Indeed, in recent two years the author discovered a number of new original phenomena that occur in lossy Love wave layered waveguides loaded with a Newtonian liquid that were entirely unexpected and are completely counterintuitive, e.g.,

1. abrupt changes in phase velocity v_p, as a function of viscosity η of the loading Newtonian liquid
2. maximum in attenuation α as a function of viscosity η of the loading Newtonian liquid
3. minimum in phase velocity v_p as a function of viscosity η of the loading Newtonian liquid [5].

II. How Love waves look like?

Love surface waves have only one SH (shear-horizontal) component of mechanical displacement polarized perpendicularly to the direction of propagation x_1 and paralell to the surface (along the x_3 axis), see Fig.1. The mechanical displacement of Love surface waves decays rapidly in function of the distance from the free surface of the waveguide (in function of depth x_2). Love wave waveguides must have at least one surface layer with the velocity of bulk SH waves lower than that in the substrate. The frequency of seismic Love waves spans the frequency range from ~0.001 Hz to ~100 Hz and in sensor technology from ~1 MHz to ~10 GHz.

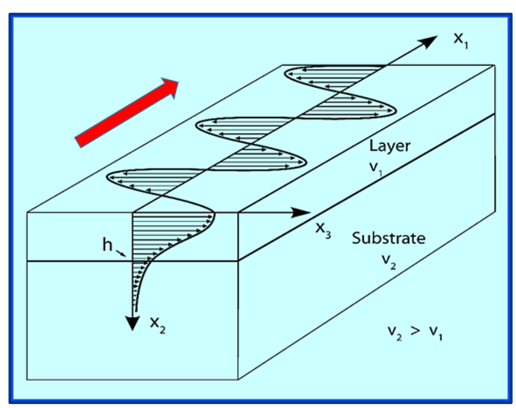

Fig.1. Mechanical displacement of the surface Love wave propagating along the x_1 axis.

III. HISTORICAL PERSPECTIVE FOR LOVE SURFACE WAVES

Elastic surface waves of the Love type were proposed theoretically in 1911 by British scientist and mathematician A.E.H. Love. Interestingly, another type of elastic surface waves, i.e., Rayleigh surface waves was also predicted theoretically some 25 years earlier in 1985. First electromagnetic surface waves were proposed in 1907 by Zenneck and Sommerfeld.

After Love waves, the following acoustic waves were discovered: 1) Lamb waves (plate waves - 1917), 2) Stoneley waves (at solid-solid interface - 1924), 3) Scholte waves (at solid-liquid interface - 1947) and Bleustein-Gulyaev waves (SH surface waves in piezoelectrics - 1968), [6].

IV. SIMILARITIES OF LOVE WAVES TO ELECTROMAGNETIC WAVES AND QUANTUM PHENOMENA

Love waves exhibit similarities to some electromagnetic waves. As an example of the electromagnetic Love wave counterparts, we can specify planar microwave waveguides and planar optical waveguides.

In the domain of quantum mechanics, we can find also some physical phenomena which can display similarities to the properties of Love waves. As an example, we can point out the movement of a quantum particle in the rectangular potential well.

These similarities that characterize Love waves, can be generally explained by the similar mathematical description of these three different physical phenomena.

V. CHRONOLOGY OF IMPLEMENTATION OF LOVE WAVES INTO THE LOVE WAVE SENSORS, BIOSENSORS AND CHEMOSENSORS

Love waves have the highest mass sensitivity among all other acoustic waves. Therefore, they an attractive candidate to be employed in Love wave sensors.

First attemps to employ Love waves into sensors, biosensors and chemosensors were carried out at the Polish Academy of Sciences in 1981, exactly 70 years after the discovery of A.E.H. Love (1911), namely:

1) P. Kiełczyński and R. Płowiec, Polish Patent (1981)
2) P. Kiełczyński, W. Pajewski, European Mechanics Colloquium (1987), (Nottingham, Great Britain)
3) P. Kiełczyński, W. Pajewski, IEEE Ultrasonic Symposium (1988), (Chicago, USA)
4) P. Kiełczyński, R. Płowiec, “Determination of the shear impedance of viscoelastic liquids using Love and Bleustein-Gulyaev surface waves”, Journal of the Acoustical Society of America”, 86 (2), August 1989, [7].

In these papers we have developed a theoretical (perturbation) model of the Love wave sensors along with its experimental verification. This model is the basis for the operation of a) biosensors, b) chemosensors and c) sensors of physical quantities (e.g., viscosity).

The first similar papers on Love wave sensors, biosensors and chemosensors appeared in the USA 3 years later:

1. G. Kovacs et al., IEEE Ultrasonic Symposium (1992) [8]
2. A. Venema et al., Applied Physics Letters, (1992) [8]
3. M.J. Vellekoop et al., IEEE Ultrasonic Symp. (1994) [8]
4. E. Gizeli et al., IEEE Trans on UFFC, (1992) [9]

VI. MASS SENSITIVITY $S_\sigma^{v_p}$ OF LOVE WAVE SENSORS

We consider the following structure of the Love wave sensor presented in Fig.2.

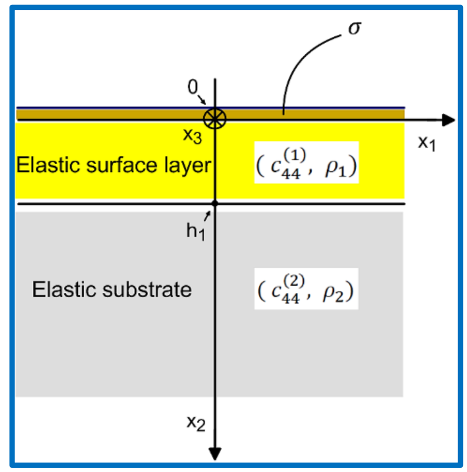

Fig.2. Cross-section of the waveguide of the Love wave sensor. The PMMA surface layer is covered by an infinitesimally thin layer of the mass density σ. The elastic substrate constitutes the ST-cut Quartz semi-space.

In the first step, using a full-wave theory, the author developed the dispersion equation for Love waves propagating the waveguide from Fig.2.

$$tan(q_1 \cdot h_1) \cdot \left\{\left(c_{44}^{(1)} \cdot q_1\right)^2 + (\sigma \cdot \omega^2) \cdot \left(c_{44}^{(2)} \cdot b\right)\right\} + \left(c_{44}^{(1)} \cdot q_1\right) \cdot \left\{(\sigma \cdot \omega^2) - \left(c_{44}^{(2)} \cdot b\right)\right\} = F\left(v_p, \sigma, h_1, f\right) = 0 \quad (1)$$

where: $k_1 = \frac{\omega}{v_1}$; $k_2 = \frac{\omega}{v_2}$; $q_1 = \sqrt{k_1^2 - k^2}$; $b = \sqrt{k^2 - k_2^2}$; σ is the surface mass density loading the surface of the waveguide and k is the complex wavenumber of the Love wave.

The dispersion equation (Eq.1) is (among others) an implicit function $F\left(v_p, \sigma, h_1, f\right)$ of the phase velocity, surface mass density, surface layer thicknees and frequency.

The formal definition of mass sensitivity is the following:

$$S_\sigma^{v_p} = \frac{1}{v_p} \cdot \frac{dv_p}{d\sigma} \quad (2)$$

To calculate this derivative in Eq.2 we used “the implicit function theorem”, namely:

$$\frac{dv_p}{d\sigma} = -\frac{\partial F/\partial \sigma}{\partial F/\partial v_p} \quad (3)$$

Using the rules of differentiation of implicit functions (Eq.3) and the dispersion equation (Eq.1), the author arrived at the following analytical formula for the mass sensitivity:

$$S_{\sigma}^{v_p} = \frac{\omega^2 \frac{1}{k}\left\{\left(c_{44}^{(1)} q_1\right) + \left(c_{44}^{(2)} b\right) \cdot tan(q_1 h_1)\right\}}{\frac{h_1}{cos^2(q_1 h_1)} \frac{\partial q_1}{\partial k}\left\{\left(c_{44}^{(1)} q_1\right)^2 + \left(c_{44}^{(2)} b\right)(\sigma\omega^2)\right\} + tan(q_1 h_1)\left\{2 q_1 \left(c_{44}^{(1)}\right)^2 \frac{\partial q_1}{\partial k} + c_{44}^{(2)} \frac{\partial b}{\partial k}(\sigma\omega^2)\right\} + c_{44}^{(1)} \frac{\partial q_1}{\partial k} \cdot \left\{(\sigma\omega^2) - \left(c_{44}^{(2)} b\right)\right\} - c_{44}^{(2)} \frac{\partial b}{\partial k}\left(c_{44}^{(1)} q_1\right)} \tag{4}$$

This formula (Eq.4) enables the optimal selection of the thickness of the surface layer and material parameters of the waveguide in order to obtain the highest sensitivity. Using the developed formula 4, the author plotted the dependence of the mass sensitivity versus surface layer thickness, see Fig.3.

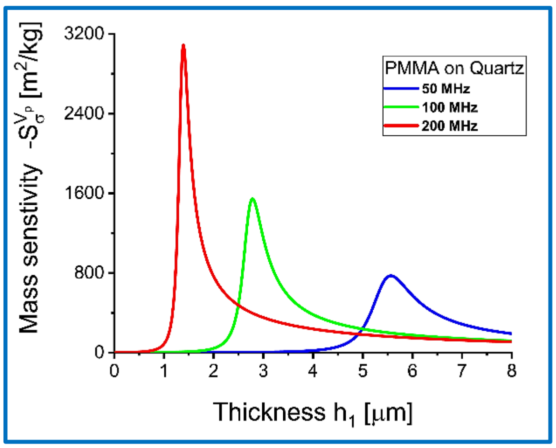

Fig.3. Mass sensitivity $S_{\sigma}^{v_p}$ of Love waves propagating in PMMA-Quartz waveguides versus surface layer thicknees h_1.

Figure 3 shows that the mass sensitivity attains maxima for selected values of surface layer thickneeses h_1.

VII. NEW UNEXPECTED COUNTER INTUITIVE PHENOMENA DISPLAYED BY LOVE WAVES IN WAVEGUIDES LOADED WITH A LOSSY LIQUID

In Love wave waveguides, with a single surface layer, loaded with a lossy liquid the author discovered unexpectedly the following counterintuitive phenomena:

1) phase velocity of the Love wave displays a global minimum as a function of the viscosity of the loading lossy liquid [5]
2) attenuation of the Love wave displays a global maximum as a function of viscosity of the loading lossy liquid.

Geometry of the analyzed Love wave waveguide is shown in Fig.4.

Complex dispersion equation for Love waves propagating in waveguide shown in Fig.4 is given by Eq.5, [5]:

$$\sin(qD) \cdot \{(\mu_1)^2 \cdot q^2 + \mu_2 \cdot b \cdot \lambda_1 \cdot j\omega\eta\} - \cos(qD) \cdot \{\mu_1 \cdot \mu_2 \cdot b \cdot q - \mu_1 \cdot q \cdot \lambda_1 \cdot j\omega\eta\} = 0 \tag{5}$$

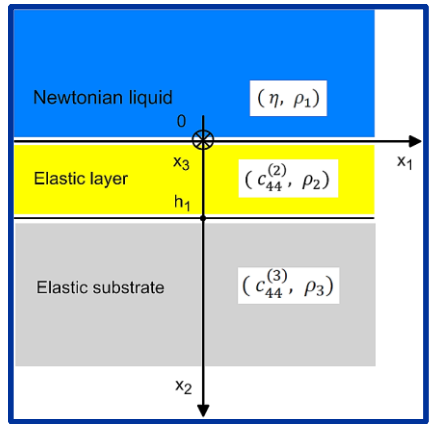

Fig.4. Cross-section of the Love wave waveguide. The PMMA surface layer is covered by a Newtonian semi-space. The elastic substrate is the ST-cut Quartz half-space, $f = 3\ MHz$.

Having used this dispersion equation (Eq.5) we plotted the following graphs (Figs.5 and 6).

These graphs present the relations between the phase velocity and attenuation versus liquid viscosity for the Love wave propagating in the waveguide structure from Fig. 4.

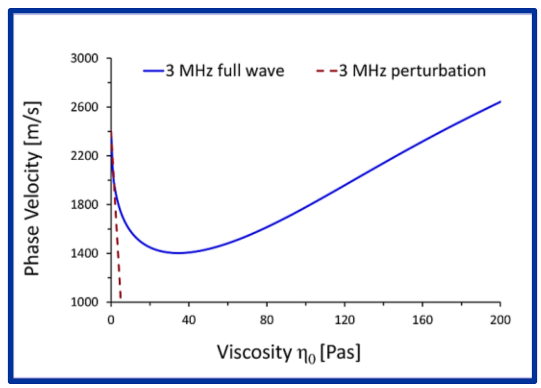

Fig.5. Plot of the Love wave phase velocity as a function of liquid viscosity.

As it is seen in Fig.5, initially the phase velocity decreases, but later on it saturates and starts to diminish.

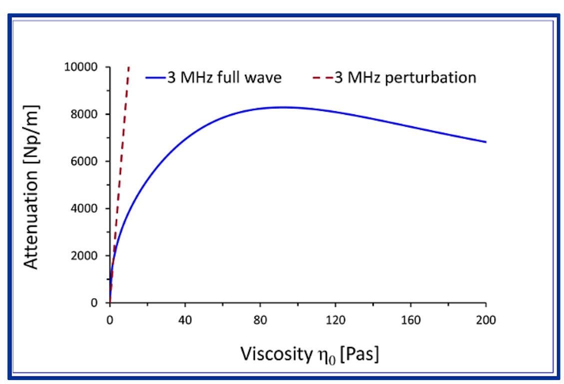

Fig.6. Plot of the Love wave attenuation versus liquid viscosity.

Figure 6 shows that, attenuation of the Love wave initially grows, but later on it starts to saturate and finally for larger viscosities decreases.

Solid curves from Figs. 5 and 6 were obtained from a full wave theory. The results obtained from the perturbation theory are traced with a red dashed line. Both phenomena shown in Figs.5 and 6 by solid curves are completely counter-intuitive and against common sense.

VIII. New Mathematical Tools Applied by the Author in Analysis of Love Wave Sensors

To analyze the operation of Love wave sensors, the author has applied formalism of the Inverse Problems. Inverse Methods are a powerful mathematical tool used to determine internal parameters of the system from external measurements. The inverse problem is often formulated as a global optimization problem, whose solutions can be obtained numerically using the appropriate numerical procedures.

The author employed the Inverse Problems Procedures to solve a very important and difficult task, i.e., the simultaneous determination of the density and viscosity (ρ_l, η) of a liquid, from the Love wave dispersion curves measurement data.

The sensor proposed by the author is very simple and consists of only one Love wave waveguide (just a piece of metal), see Fig.7. By contrast, the existing so far sensors for the simultaneous measurement of viscosity and density of liquids are extremely complex and complicated (Jakoby et al., [10]).

Fig.7. Love wave waveguide (on the right) consisting of an elastic surface layer (Cu) deposited on an elastic substrate (steel).

I have achieved excellent results [11], using only a piece of metal along with the Inverse Methods Procedures. The accuracy of the liquid viscosity and density determination was high (in the range from 1 to 2%).

IX. Future Direction of Research and Perspectives for Love Wave Sensors

We can indicate two directions of future research:

1) Application of new analytical methods:

a) Inverse Problems (higher accuracy)
b) Optimization Methods in Banach space

2) Application of new materials and waveguide structures:

a) multilayer (N>10) LSW waveguides (wideband characteristics)
b) higher operating frequencies 2-5 GHz (higher sensitivity)
c) new fast materials for the substrate: Diamond, (BN) boron nitride, (AlN) aluminum nitride.

X. Conclusions

In this study, we have shown that Love waves are really special and unique waves. From the mathematical point of view, Love waves can be regarded as electromagnetic waves, but from the mechanical point of view, Loves waves are mechanical waves. Among all existing acoustic waves, only Love waves have similarities in Electromagnetism and Quantum Mechanics.

Acknowledgment

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