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Properties and Applications of Love Surface Waves in Seismology and Biosensors

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Abstract

Shear horizontal (SH) surface waves of the Love type are elastic surface waves propagating in layered waveguides, in which surface layer is "slower" than the substrate. Love surface waves are of primary importance in geophysics and seismology, since most structural damages in the wake of earthquakes are attributed to the devastating SH motion inherent to the Love surface waves. On the other hand, Love surface waves found benign applications in biosensors used in biology, medicine, and chemistry. In this chapter, we briefly sketch a mathematical model for Love surface waves and present examples of the resulting dispersion curves for phase and group velocities, attenuation as well as the amplitude distribution as a function of the depth. We illustrate damages due to Love surface waves generated by earthquakes on real-life examples. In the following of this chapter, we present a number of representative examples for Love wave biosensors, which have been already used to DNA characterization, bacteria and virus detection, measurements of toxic substances, etc. We hope that the reader, after studying this chapter, will have a clear idea that deadly earthquakes and a beneficiary biosensor technology share the same physical phenomenon, which is the basis of a fascinating interdisciplinary research.

Keywords: Love waves, biosensors, earthquakes, surface acoustic waves, wireless sensors, dispersion curves

1. Introduction

It is interesting to note that many outstanding physicists (Kelvin, Michelson, and Jolly) expressed in the second half of the nineteenth century an opinion that classical physics (how we name it nowadays) is in principle completed and nothing interesting or significant rests to be discovered. Needless to say, forecasting development of future events was always and

still is a very risky business, especially in physical sciences and engineering. Indeed, in these disciplines of human endeavors, one must take into account not only an inherently volatile human factor but also the impact of potential discoveries of unknown yet laws of nature, which often open new unanticipated possibilities and horizons. We may try to justify such an obvious complacency, attributed to the abovementioned scientists, by the historical spirit of the Belle Époque (1870–1914), that believed in harmony, good taste, optimism, unlimited progress and generally in positivistic philosophical ideas.

Anyway, not waiting for the revolution heralded by quantum mechanics (1900) or general theory of relativity (1917), classical physics was already shaken by the emergence of the theory of chaos (Poincaré 1882 and Hadamard 1898), which later on in the twentieth century will effectively eliminate deterministic description from many physical problems, such as weather forecasting, etc. Another new significant achievement of the classical physics (although not revolutionary) was the discovery of surface waves. At first, elastic surface waves were discovered in solids (Rayleigh 1885 and Love 1911) and then in electromagnetism (Zenneck 1907 and Sommerfeld 1909).

In fact, the existence of surface waves in solids was predicted mathematically by the celebrated British scientist Lord Rayleigh in 1885, who showed that elastic surface waves can propagate along a free surface of a semi-infinite body. By contrast to bulk waves, the amplitude of surface waves is confined to a narrow area adjacent to the guiding surface. Since surface waves are a type of guided waves, they can propagate often longer distances than their bulk counterparts and in addition, they are inherently sensitive to material properties in the vicinity of the guiding surface. It will be shown in the following of this chapter that these two properties of surface waves are of crucial importance in geophysics and sensor technology.

First, seismographs were constructed by British engineers in 1880, working in Japan for Meiji government. Consequently, the first long distance seismogram was registered in 1889 by German astronomer Ernst von Rebeur-Paschwitz in Potsdam (Germany), who was able to detect seismic signals generated by an earthquake occurred in Japan, some 9000 km away from Potsdam (Berlin). It was obvious soon that long distance seismograms display two different phases. First (preliminary tremor), a relatively weak signal arriving with the velocity of bulk waves (P and S) and second (main shock) with a much higher amplitude arriving with the velocity close to that of Rayleigh surface waves. However, this Rayleigh wave hypothesis was not satisfactory, since large part of the main shock energy was associated with the shear horizontal (SH) component of vibrations, absent by definition in Rayleigh surface waves composed of shear vertical (SV) and longitudinal (L) displacements. This dilemma was resolved in 1911 by the British physicist and mathematician Augustus Edward Hough Love by a brilliant stroke of thought [1]. Firstly, Love postulated that the SH component in the main shock is due to the arrival of a new type of surface waves (named later after his name) with only one SH component of vibrations. Secondly, Love assumed that SH surface waves are guided by an extra surface layer existing on the Earth's surface, with properties different than those in the Earth's interior. Using contemporary language, we can say that he made a direct hit.

It is noteworthy that the existence of Rayleigh and Love surface waves was first predicted mathematically prior to their experimental confirmation. This shows how beneficial can be the mutual interaction between the theory and experiment. Indeed, the theory indicates directions of future experimental research and the experiment confirms or renders the theory obsolete. It is worth noticing that the existence of a new type of electromagnetic surface waves was predicted mathematically quite recently, i.e., in 1988, and soon confirmed experimentally.

It is interesting to note that Love surface waves have direct counterparts in electromagnetism (optical planar waveguides) and quantum mechanics (particle motion in a quantum well). By contrast, a similar statement is not true for Rayleigh surface waves, which therefore remain a unique phenomenon within the frame of the classical theory of elasticity.

Surface waves of the Love type have a number of unique features. Firstly, they have only one SH component of vibrations. As a result, Love surface waves are insensitive to the loading with liquids of zero or negligible viscosities. Thus, Love surface waves can propagate long distances without a significant attenuation. Indeed, Love waves propagating many times around the Earth's circumference have been observed experimentally. On the other hand, it was discovered much later (1981) that Love waves are very well suited for measurements of viscoelastic properties of liquids. Secondly, the mathematical description of Love surface waves is much simpler than that for Rayleigh surface waves. A relative simplicity of the mathematical model enables for direct physical insight in the process of Love wave propagation, attenuation, etc.

The idea to employ Love surface waves for measurements of viscoelastic properties of liquids was presented for the first time in 1981 by Kiełczyński and Płowiec in their Polish patent [2]. In 1987, the theory of the new method was presented by Kiełczyński and Pajewski on the international arena at the European Mechanics Colloquium 226 in Nottingham, UK [3]. In 1988, they presented this new method with equations and experimental results at the IEEE 1988 Ultrasonic Symposium in Chicago [4]. In 1989, Kiełczyński and Płowiec published a detailed theory and experimental results in the prestigious Journal of the Acoustical Society of America [5]. It is noteworthy that subsequent publications on Love wave sensors for liquid characterization appeared in USA not earlier than in 1992 [6], but nowadays, we witness about 100 publications per year on that subject [7].

We hope that the reader, after studying this chapter, will agree that the nature has many different faces and that the same physical phenomenon can be sometimes deadly (earthquakes) and in different circumstances, can be beneficiary (biosensor technology). As a consequence, SH surface waves of the Love type are an interesting example of an interdisciplinary research.

This chapter is organized as follows. Section 2 presents main characteristics and properties of Love surface waves, including basic mathematical model and examples of dispersion curves and amplitude distributions. More advanced mathematical treatment of the Love surface waves can be found, for example, in [8]. Section 3 shows the importance of Love surface waves in geophysics and seismology. Section 4 describes applications of Love surface waves in biosensors used in biology, medicine, chemistry, etc. Section 5 contains discussion of the chronological development of SH ultrasonic sensors starting from bulk wave sensors and then first surface

wave sensors. We show also that the results of research conducted in Seismology and geophysics can be transferred to biosensor technology and vice versa. Conclusions and propositions for future research in biosensor technology employing Love surface waves are given in Section 6.

In addition to biosensors, Love surface waves are used in chemosensors, in non-destructive testing (NDT) of materials, and in sensors of various physical quantities such as:

1. humidity of air [9];

2. spatial distribution of elastic parameters in solid functionally graded materials (FGM) [10];

3. elastic parameters of nanolayers [11];

4. porosity of the medium [12]; and

5. dielectric constant of liquids [13].

Recently, Love surface waves were also employed in the construction of the magnetic field sensor system with outstanding characteristics (sensitivity, dynamic range, etc.) [14].

2. Properties of Love surface waves

Shear horizontal (SH) surface waves of the Love type are elastic waves propagating in a surface waveguide, which is composed of a surface layer rigidly bonded to an elastic substrate, see **Figure 1**. The existence of an elastic surface layer is a necessary condition for propagation of Love surface waves, since it can be easily shown that on an elastic half-space alone, SH
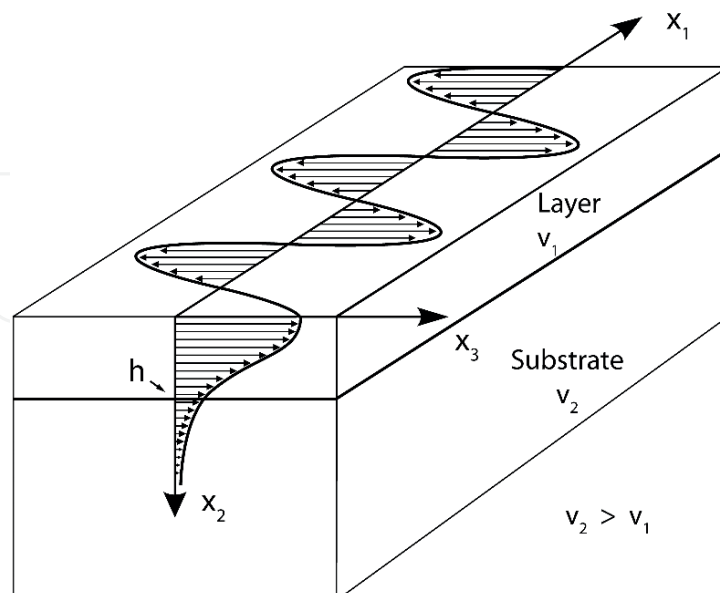

Figure 1. Basic structure of a free Love wave waveguide, not loaded with a viscoelastic liquid. An elastic surface layer of thickness "h" and a shear velocity v_1 is rigidly bonded to the underlying semi-infinitive substrate with a shear velocity v_2.

surface waves cannot exist. The extra surface layer must also be "slower" than the substrate, i.e., the following condition must hold [15]:

$$v_1 < v_2 \tag{1}$$

where v_1 and v_2 are phase velocities of bulk shear waves in the surface layer and substrate, respectively. In fact, the condition expressed by Eq. (1) allows for entrapment of partial waves in the surface layer due to the total reflection phenomenon occurring at the layer-substrate interface ($x_2 = h$). By contrast, if the condition given by Eq. (1) is not satisfied ($v_1 > v_2$), then Love waves are evanescent in the direction of propagation x_1 and, on average, no net power is transmitted along the surface waveguide.

2.1. Dispersion equation of the Love surface wave

Mechanical displacement u_3 of a time-harmonic Love surface wave propagating in the direction x_1 has the following form:

$$u_3(x_1, x_2, t) = f(x_2) \, exp \left[j(k\,x_1 - \omega t) \right] \tag{2}$$

where the function $f(x_2)$ describes the amplitude of the Love wave as a function of the depth (x_2 axis), $k = \omega/v_p$ is the wavenumber of the Love wave, $\omega = 2\pi f$ is its angular frequency, v_p is the phase velocity of the Love wave and $j = \sqrt{-1}$. Since the surface waveguide is assumed to be lossless, the wavenumber k in Eq. (2) is a real quantity.

Substitution of Eq. (2) into Newton's equation of motion leads to the Helmholtz differential equation for the transverse amplitude $f(x_2)$. Solutions of the resulting Helmholtz differential equation have the following form [16]:

$$f(x_2) = \begin{cases} A \dfrac{cos(q_1 x_2)}{cos(q_1 h)}, & for \ 0 \leq x_2 < h \ (surface \ layer) \\ A\,e^{-q_2(x_2-h)}, & for \ h \leq x_2 \ (substrate) \end{cases} \tag{3}$$

where

$$\begin{aligned} q_1^2 &= k_1^2 - k^2 \\ -q_2^2 &= k_2^2 - k^2 \end{aligned} \tag{4}$$

$$\begin{aligned} k_1^2 &= \frac{\omega^2}{v_1^2} \\ k_2^2 &= \frac{\omega^2}{v_2^2} \end{aligned} \tag{5}$$

and A is an arbitrary constant. In isotropic solids, Love surface waves have two stress components, τ_{23} and τ_{13}, associated with the SH displacement u_3. From Eq. (3), it follows that stress τ_{23} can be expressed by the following formula:

$$\tau_{23}(x_2) \ = \ \mu_{1,2} \frac{\partial f(x_2)}{\partial x_2} \ = \ \begin{cases} -\mu_1\, q_1\, A\, \dfrac{sin\,(q_1\, x_2)}{cos\,(q_1\, h)}, & \text{for } 0 \le x_2 < h \text{ (surface layer)} \\[2mm] -\mu_2\, q_2\, A\, e^{-q_2(x_2-h)}, & \text{for } h \le x_2 \text{ (substrate)} \end{cases} \tag{6}$$

where μ_1 and μ_2 are shear moduli of elasticity in the surface layer and substrate, respectively.

The mechanical displacement u_3 and the associated stress τ_{23} must satisfy the appropriate boundary conditions, i.e., the continuity of u_3 and τ_{23} at interfaces $x_2 = 0$ (free guiding surface) and $x_2 = h$ (the interface between the surface layer and the substrate). Substituting Eqs. (3) and (6) into the boundary conditions at $x_2 = 0$ and $x_2 = h$, one obtains the following dispersion relation [16], for Love surface waves propagating in a planar waveguide shown in **Figure 1**:

$$F[\omega, k(\omega)] \ = \ \mu_1\, q_1\, tan\,(q_1\, h) - \mu_2\, q_2 \ = \ 0 \tag{7}$$

Using Eq. (4), one can rewrite Eq. (7) in a more explicit form as:

$$F[\omega, k(\omega)] \ = \ \mu_1 \left(\sqrt{\frac{1}{v_1^2} - \frac{1}{v_p^2}} \right) tan \left[2\pi \left(\sqrt{\frac{1}{v_1^2} - \frac{1}{v_p^2}} \right) (fh) \right] - \mu_2 \left(\sqrt{\frac{1}{v_p^2} - \frac{1}{v_2^2}} \right) \ = \ 0 \tag{8}$$

Eq. (8) shows that the unknown phase velocity v_p of the Love surface wave is de facto an explicit function of the normalized product frequency-thickness (fh), with v_1 and v_2, being parameters. This property does not, however, hold for lossy Love wave waveguides where the elastic moduli μ_1, μ_2 as well as the velocities v_1 and v_2 are implicit functions of the frequency f and are obviously independent of the surface layer thickness h.

The dispersion relation Eq. (8) is a transcendental algebraic equation for the unknown phase velocity v_p and therefore can be solved only numerically using, for example, the Newton-Raphson iterative method [17].

2.2. Modal structure of the Love surface wave

The dispersion relation [Eq. (8)] reveals that phase velocity v_p of the Love surface wave is a function of frequency. Hence, Love surface waves are dispersive. Moreover, since the function tangent in Eq. (8) is periodic, i.e., $tan(q_1 h) = tan(q_1 h + n\pi)$, where $n = 0, 1, 2, …,$etc., Love surface waves display a multimode structure.

The amplitude $f(x_2)$ of the fundamental ($n = 0$) mode of the Love surface wave, as a function of the distance x_2 from the guiding surface $x_2 = 0$, is shown in **Figure 2**. It is clear that for sufficiently high frequencies, the energy of the Love wave is concentrated mostly in the surface layer in the vicinity of the guiding surface $x_2 = 0$. By differentiation of Eq. (3), it is easy to show that the maximum of the amplitude $f(x_2)$ occurs exactly at the free surface $x_2 = 0$. By contrast, the associated stress τ_{23} vanishes at $x_2 = 0$, i.e., at the free surface of the waveguide.
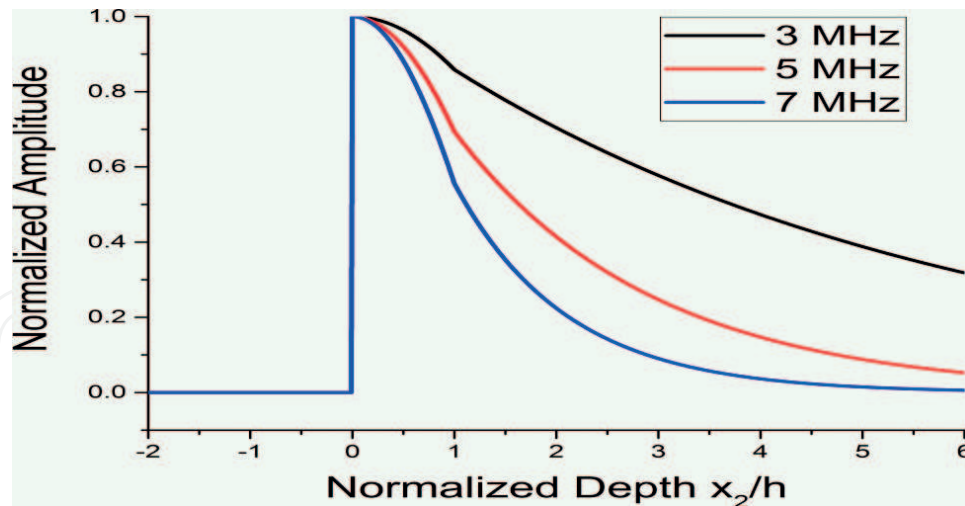
Figure 2. Amplitude of the fundamental (n = 0) Love wave mode, as a function of the normalized depth x_2/h, in a copper-steel waveguide, for different wave frequencies f = 3, 5, and 7 MHz, and surface layer thickness h = 100 μm.

2.3. Phase and group velocity of the Love surface wave

The total derivative of the implicit function $F[\omega, k(\omega)]$ in the dispersion relation [Eq. (7)] with respect to the angular frequency ω equals:

$$\frac{\partial}{\partial\omega} F[\omega, k(\omega)] + \frac{\partial}{\partial k} F[\omega, k(\omega)] \frac{dk(\omega)}{d\omega} = 0 \tag{9}$$

Since group velocity v_g of the Love surface wave, which describes the speed at which pulse envelope of the Love surface wave propagates, is defined as $\frac{d\omega}{dk}$ from Eq. 9, it is clear that:

$$v_g = \frac{d\omega}{dk} = -\frac{\frac{\partial}{\partial k} F[\omega, k(\omega)]}{\frac{\partial}{\partial\omega} F[\omega, k(\omega)]} \tag{10}$$

As a consequence, using Eqs. (7) and (10), one can show [8, 15–19] that group v_g and phase v_p velocities of the Love surface wave are connected via the following algebraic equation:

$$\frac{v_g v_p}{v_2^2} = \frac{\mu_1 q_2 h \left[\frac{sin(2 q_1 h)}{2 q_1 h} + 1\right] + \mu_2 \cos^2(q_1 h)}{\mu_1 q_2 h \left(\frac{v_2}{v_1}\right)^2 \left[\frac{sin(2 q_1 h)}{2 q_1 h} + 1\right] + \mu_2 \cos^2(q_1 h)} \tag{11}$$

Eqs. (7) and (11) show that phase v_p and group v_g velocities of the Love surface wave in the low (f → 0) and high (f → ∞) frequency limits are the same and equal, respectively, v_2 and v_1.

The phase velocity resulting from the solution of Eq. (8) and the group velocity determined by Eq. (11) of the fundamental mode of Love surface waves, as a function of the normalized frequency *fh*, are given in **Figure 3**. From **Figure 3**, it is evident that for low frequencies, the
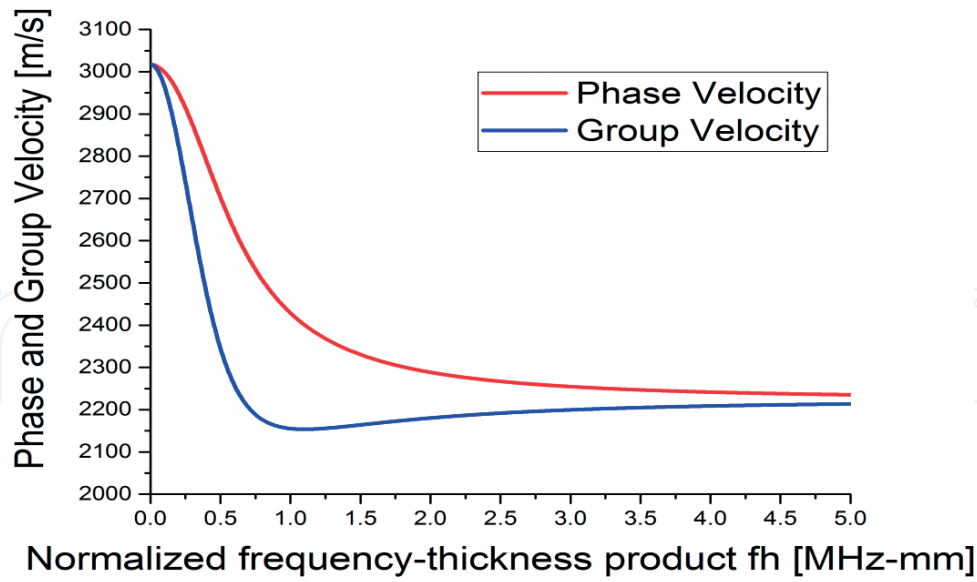
Figure 3. Phase v_p and group v_g velocities of the fundamental mode of the Love surface wave propagating in a copper-stainless steel waveguide, as a function of the normalized frequency-thickness product *fh* [MHz-mm], v_1 = 2223.5 *m/s*, and v_2 = 3017 *m/s*.

phase and group velocities of Love surface waves approach asymptotically that of bulk shear waves v_2 in the substrate. On the other hand, at high frequency limit, the phase and group velocities of the Love wave tend to the velocity v_1, namely to the velocity of bulk shear waves in the surface layer.

2.4. Influence of a viscoelastic liquid loading Love wave waveguides

It is noteworthy that in waveguides loaded with a lossy, viscoelastic liquid, the wavenumber k of the Love surface wave is a complex quantity, i.e., $k = \omega/v_p + j\alpha$, where α is the coefficient of attenuation of the Love wave. Three most popular viscoelastic liquids are described by Kelvin-Voigt, Newton and Maxwell models, respectively [20]. The dispersion relation of Love surface waves propagating in waveguides loaded with a viscous liquid can be found in [21]. In lossy waveguides, the group velocity of Love waves cannot be rigorously defined [22]. As a result, the formula 11 is valid only approximately in lossy Love wave waveguides. As a matter of fact, in a waveguide loaded with a viscoelastic liquid, the amplitude of the Love wave is non-zero in a thin layer of the liquid adjacent to the surface layer of the waveguide. The penetration of the Love wave energy into the adjacent liquid is of crucial importance in understanding the operation of Love wave biosensors. Indeed, if Love wave energy was not penetrating in the measured liquid, the parameters of the Love wave might not be affected by the liquid and the operation of the whole sensor would be essentially impossible.

3. Love surface waves in seismology

Since Love surface waves were originally discovered in seismology, we give here a brief description of their applications in seismic and geophysical research.

Propagation of Love surface waves on the Earth's surface is made possible by layered structure of the Earth. The outermost layer of the Earth, the crust, is made of solid rocks composed of lighter elements. Thickness of the crust varies from 5 to 10 km under oceans (oceanic crust) to 30–70 km under continents (continental crust). The crust sits on mantle, which in turn covers the outer and inner core. The destructive power of earthquakes is mainly due to waves traveling in this thin crustal layer [23].

As predicted by Love, the velocity of SH bulk waves increases with depth [24], i.e., as a function of distance from the free surface of the Earth.

The frequency of Love waves generated by earthquakes is rather low comparing to that used in sensor technology and ranges typically from 10 mHz to 10 Hz.

3.1. Investigation of the Earth's interior with Love surface waves

Love and Rayleigh surface waves travel along great circle paths around the globe. Surface waves from strong earthquakes may travel several times around the Earth without a significant attenuation. They are termed global Rayleigh wave impulses [25]. An example of surface waves traveling multiply around the Earth [26] is given in **Figure 4**.

Seismic waves, generated both by natural earthquakes and by man-made sources, have delivered an enormous amount of information about the Earth's interior (subsurface properties of Earth's crust). In classical seismology, Earth is modeled as a sequence of uniform horizontal layers (or spherical shells) having different elastic properties and one determines these properties from travel times and dispersion of seismic waves [27].

Love surface waves have been successfully employed in a tomographic reconstruction of the physical properties of Earth's upper mantle [28] as well as in diamond, gold, and copper exploration in Australia, South America, and South Africa [29].
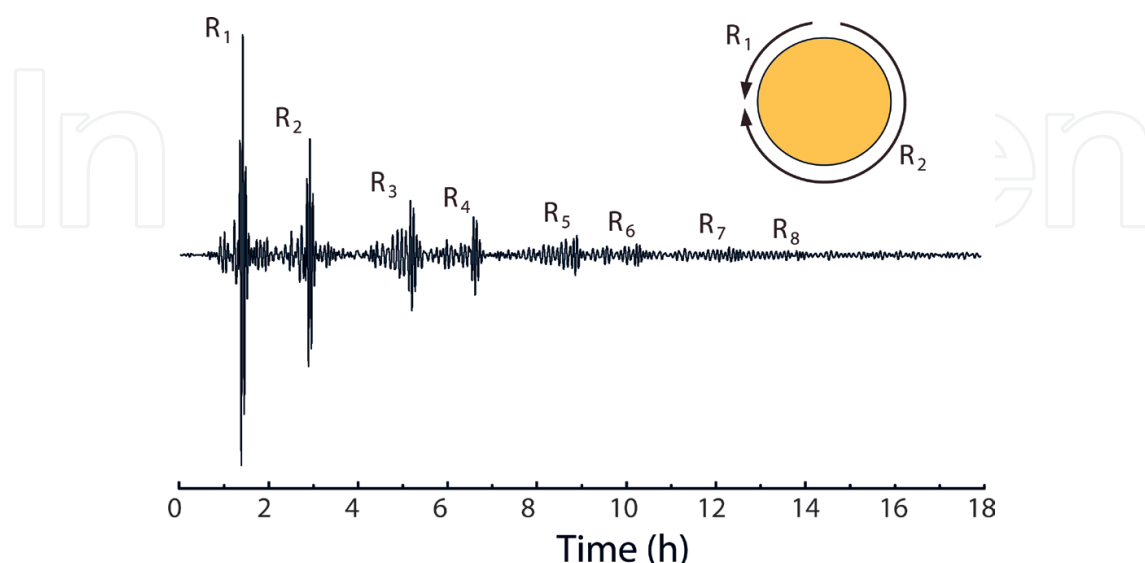

Figure 4. Illustration of a seismogram of Rayleigh surface waves triggered by an earthquake. Note that, Rayleigh wave packet traveled 8 times around the Earth's circumference.

Surface waves generated by earthquakes or man-made explosions were used in quantitative recovery of Earth's parameters as a function of depth. These seismic inverse problems helped to discover many fine details of the Earth's interior [30–32].

It is noteworthy that many theoretical methods were initially originated in seismology and geophysics before their transfer to the surface wave sensor technology (see **Table 1** in Section 5.5).

3.2. Structural damages due to Love surface waves generated by earthquakes

An example of structural damages made by surface waves of the Love type is shown in **Figure 5**. It is apparent that railway tracks were deformed by strong shear horizontal SH forces parallel to the Earth's surface. Love surface waves together with Rayleigh surface waves are the most devastating waves occurring during earthquakes.

3.3. Application of metamaterials to minimize devastating effects of Love surface waves in the aftermath of earthquakes

It is interesting to note that recently developed earthquake engineered metamaterials open a new way to counterattack seismic waves [33, 34]. The metamaterials actively control the seismic waves by providing an additional shield around the protected building rather than reconstructing the building structure. Compared with common engineering solutions, the advantage of the metamaterial method is that it can not only attenuate seismic waves before they reach critical targets, but also protect a distributed area rather than an individual building. The

Developments	Seismology	Biosensors
Basic theory	Love [1]	Kiełczyński [3]
Multilayered waveguides (transfer matrix method)	Haskell [72]	Kiełczyński [8]
Viscoelastic waveguides (theoretical analysis)	Sezawa [73]	Kiełczyński [74]
Inverse problems	Dorman [76]	Kiełczyński [77]
Nonlinear waves	Kalyanasundarm [78]	—
Phased arrays	Frosch [79]	—
Tomography	Nakanishi [80]	—
Higher-order modes	Haskell [81]	—
Solitary waves	Bataille [82]	—
Energy harvesting	Qu [83]	—
Waveguides with nanomaterials	—	Penza [84]
Piezoelectric waveguides	—	Kovacs [6]
Resonators	—	Kovacs [67]
Delay lines	—	Tournois [19]

Table 1. Chronology of developments in Love wave biosensors and Love wave seismology.
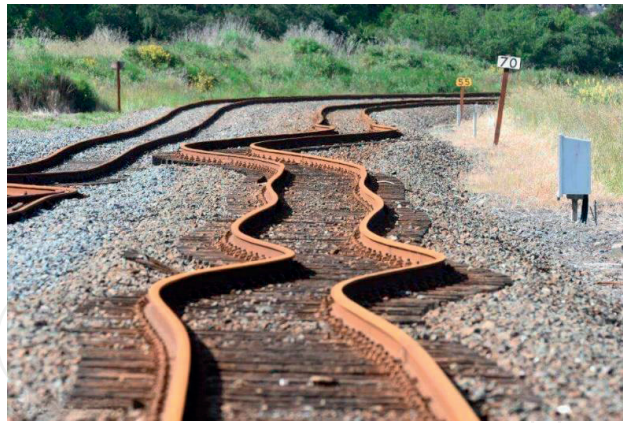
Figure 5. Twisted railroad tracks, an example of structural damages due to SH displacement of Love surface waves in the aftermath of an earthquake.

periodic arrangement of metamaterial structure creates frequency band gaps, which effectively prevent surface waves propagation on the Earth's surface via a Bragg scattering mechanism.

4. Biosensors employing Love surface waves

A biosensor can be described as a device which can generate a signal (usually electrical) that is proportional to the concentration of a particular biomaterial or chemicals in the presence of a number of interfering species [35]. This can be accomplished using biological recognition elements such as enzymes, antibodies, receptors, tissues, and microorganisms as sensitive materials because of their selective functionality for target analytes along with an appropriate transducer.

4.1. Confinement of the energy of Love surface waves near the free surface of the waveguide

High sensitivity of Love surface wave sensors can be explained by spatial concentration of the energy of Love waves. Indeed, it was shown in Section 2 that the energy of Love surface waves is localized mostly in the vicinity of the free guiding surface (**Figure 1**), looking in both sides from it. Moreover, the amplitude of Love surface waves reaches maximum at the free guiding surface $x_2 = 0$ (**Figure 2**). Therefore, we can expect that propagation of Love surface waves will be to a lesser or higher extent perturbed by a material (such as liquid) being in contact with the guiding surface. This feature of Love waves was exploited in the construction of various biosensors used for detection and quantification of many important parameters of biological and chemical substances [21, 36–40].

4.2. Correlation between concentration of the measured analyte and parameters of the Love surface wave

Surface waves of the Love type are especially suited to measure parameters of viscoelastic liquids, polymers, gels, etc., providing that they can form a good mechanical contact

(absorption and adhesion) with free surface of the waveguide. Since Love surface waves are, in principle, mechanical waves, they can measure the following mechanical parameters of an adjacent medium: density, modulus of elasticity, and viscosity. In waveguides composed of piezoelectric elements (substrate and/or surface layer), dielectric constant of the adjacent medium will also affect the propagation of Love surface waves. In practice, we are interested in detection and quantification other more specific properties of biological and chemical materials, such as concentration and presence of proteins, antibodies, toxins, bacteria, viruses, size and shape of DNA, etc. Therefore, the next step in the development of Love wave sensors is to correlate (experimentally or analytically) the abovementioned specific properties of the measured analytes with changes in density, viscosity, and elastic moduli of the surface (sensing) layer. Finally, we have to measure changes in phase velocity and attenuation of Love surface waves, which are due to changes in density, viscosity, and elastic moduli of this surface layer. It should be noticed that part of Love wave energy enters into the measured liquid to some distance (penetration depth) from the guiding surface. Such an energy redistribution changes certainly the phase velocity and attenuation of the Love surface wave. In practice, we often adopt a more empirical approach, i.e., we measure directly changes in phase velocity and attenuation of Love waves, as a function of the aforementioned specific properties of the measured material, such as the concentration of proteins and so on, without referring to changes in density, viscosity or elastic modulus of the measured material. However, the former step is indispensable during modeling, design, and optimization of Love surface wave sensors.

4.3. Parameters of the Love surface wave measured

As with other types of wave motion, we can measure in principle two parameters of Love surface waves, i.e., their phase and amplitude. Polarization of SH surface waves of the Love type is constant and therefore does not provide any additional information about the medium of propagation. Phase $\Phi(x_1, t)$ measurements in radians are directly related to the phase velocity v_p of Love surface waves via the following equation:

$$\Phi(x_1, t) = k x_1 - \omega t = \omega\left(\frac{x_1}{v_p} - t\right) \qquad (12)$$

Similarly, amplitude A measurements are correlated with the coefficient of attenuation α (in Np/m) of Love surface waves as follows:

$$\alpha = \frac{1}{(x_2 - x_1)} ln\left(\frac{A_1}{A_2}\right) [Np/m] \qquad (13)$$

where A_1 and A_2 are two amplitudes of the wave measured at points x_1 and x_2, respectively ($x_2 > x_1$). In order to obtain the coefficient of attenuation in dB/m, the coefficient α given by Eq. (13) must be multiplied by $20 \, log(e) \approx 8.686$.

4.4. Sensors working in a resonator and delay line configurations

Phase and amplitude characteristics of Love surface waves can be measured in a closed loop configuration by placing Love wave delay line in a feedback circuit of an electrical oscillator (resonator). Another possibility is to use network analyzer, which provides phase shift and insertion loss of the Love wave sensor working in an open loop configuration, due to the load of the sensor with a measured material. The typical frequency range used by Love wave sensors is from 50 MHz to 500 MHz [7].

The structure and cross section of a typical Love wave biosensor is shown in **Figure 6a** and **b**. A relatively thick (0.5–1.0 mm) substrate provides mechanical support for the whole sensor. Often the substrate material is piezoelectric (AT-cut quartz material [41]). In this case, a pair of interdigital transducers (IDTs) can be deposited on the substrate to form a delay line of the sensor. The guiding layer (SiO$_2$, ZnO, PMMA, etc.), deposited directly on the substrate, provides entrapment for surface wave energy. The sensing layer, made of gold (Au) or a polymer, usually very thin (~50-100 nm), serves as an immobilization area for the measured biological material. This thin-sensing layer interacts directly with the measured material (liquid) and serves often as a selector of the specific target substance, such as antigen, to be measured.

4.5. Sensors controlled remotely by wireless devices

An interesting solution for Love wave sensors was proposed in [42], where the Love wave sensor works in a wireless configuration without an external power supply. This design has many unique advantages, i.e., the sensor can be permanently implanted in a patient body to monitor continuously the selected property of a biological liquid. Readings of the sensor can be made on demand, totally noninvasively by a reading device connected to a broader computer system of patient monitoring. Another implementation of a remotely controlled wireless Love wave sensor was presented in [43]. The proposed sensor can measure simultaneously two different analytes using Love surface waves with a frequency of 440 MHz.

Wireless bioelectronics sensors may be used in a variety of fields including: healthcare, environmental monitoring, food quality control, and defense.
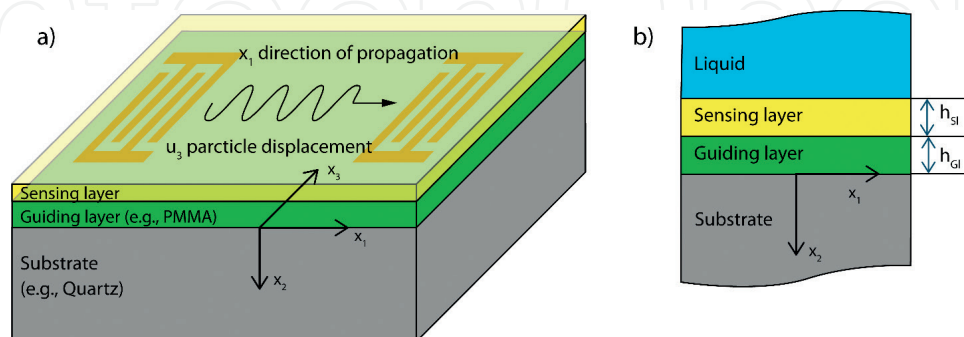

Figure 6. a) Layered structure of a typical Love wave sensor not yet connected to the external driving circuit and b) cross-section of this sensor structure + loading liquid.

4.6. Examples of laboratory and industrial grade Love wave sensors

To apply the measured analyte to the Love wave sensor, the sensor is often equipped with a flow cell, which separates interdigital transducers from sensing area of the waveguide [44]. A laboratory grade Love wave sensor equipped with a flow cell is shown in **Figure 7**.

A prototype of an commercial ready Love wave sensor was presented in 2015 in Ref. [45]. A 250 MHz delay line Love wave immunosensor was designed on the ST quartz substrate with a thin gold layer of thickness ~90 nm used as a guiding and sensing area, for antibodies or antigens can be easily immobilized on a gold surface. The changes of Love wave velocity and attenuation were due to antibodies-antigens interactions. A disposable test cassette with embedded Love wave immunosensor is connected to a handheld electronic reader, which in turn is connected wirelessly via bluetooth to a smartphone or a computer. This device is a strong candidate for clinical and personnel healthcare applications.

4.7. Examples of analytes measured by Love wave biosensors

Love wave biosensors have been used in measurement and detection of a large number of substances (analytes) [44]. As representative examples, we can mention the following:

- concentration of bovine serum albumin [46];

- real-time detection of antigen-antibody interactions in liquids (immunosensor) [47];

- simultaneous detection of Legionella and *E. coli* bacteria [48];

- virus and bacteria detection in liquids [49];

- detection of pathogenic spores *Bacillus anthracis* below inhalation infectious levels [50];

- investigation of lipid specificity of human antimicrobial peptides [51];

- Sin Nombre Virus detection at levels lower than those typical for human patients suffering from hantavirus cardiopulmonary syndrome [52];
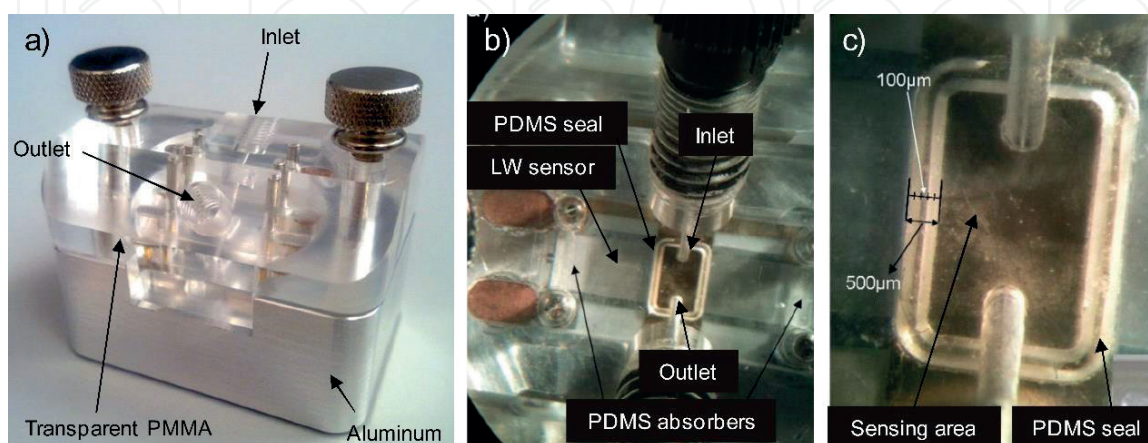

Figure 7. An example of a laboratory grade Love wave sensor with a flow cell [42].

- detection of nanoparticles in liquid media [53];

- okadaic acid detection [54];

- study of protein layers [55];

- antibody binding detection [56];

- toxicity of heavy metals [57];

- size and shape of DNA [58];

- real-time detection of hepatitis B [59];

- liquid chromatography [60];

- immunosensors for detection of pesticide residues and metabolites in fruit juices [61];

- detection of cocaine [62]; and

- detection of carbaryl pesticide [63].

4.8. Desired characteristics (features) of industrial grade Love wave sensors

This rather impressive list of achievements in R&D activities on biosensor technology suggests that biosensors employing Love surface waves have a huge potential. However, in order to compete with other types of biosensors, such as optical sensors based on the surface plasmon resonance [64], the biosensors employing Love surface waves should possess the following characteristics:

- high sensitivity to the measured property (measurand);

- high selectivity to the measured property (measurand);

- low limit of detection;

- zero temperature coefficient (high-thermal stability);

- high repeatability and stability;

- possibility of multiple reuse; and

- cost-effectiveness.

At present, none of the above targets have been fully achieved. Love wave biosensors are, in general, still in the laboratory research phase, where most developments are focused on the proof of concept and construction of a working prototype. Only one European company offers today commercially available Love wave sensors [7]. Nevertheless, as it was shown in this section, Love wave biosensors can be used to measurements of a surprisingly large number of biological substances (analytes) with a quite remarkable accuracy and sensitivity. Therefore, in our opinion, Love wave biosensors will reach soon an industrial grade level with numerous real-life applications in biology, medicine (clinical practice), and chemistry.

5. Discussion

5.1. Older sensors using bulk SH waves

It is interesting to note that first acoustic sensors for measurements of viscoelastic properties of liquids used to this end bulk (not surface) SH waves propagating in a solid buffer, loaded on one side with a measured viscoelastic liquid. This idea appeared in 1950 in works of such prominent ultrasonic scientists Mason and McSkimmin [65]. However, the main drawback of the bulk wave sensors was their inherent low sensitivity. For example, to perform measurements with a water-loaded sensor, one had to observe about 50 consecutive reflections in the solid buffer.

5.2. Emergence of new sensors using SH surface waves of the Love type

The breakthrough came with a proposition to employ to this end SH surface waves of the Love and Bleustein-Gulyaev types. This idea was first articulated by Kiełczyński and Płowiec in 1981 in their Polish patent no 130040 [2]. In 1987, the theory of the new method was presented by Kiełczyński and Pajewski on the international arena at the European Mechanics Colloquium 226 in Nottingham, UK [3]. In 1988, this new method, with equations and experimental results, was presented by Kiełczyński and Pajewski at IEEE 1988 Ultrasonic Symposium in Chicago [4]. In 1989, Kiełczyński and Płowiec published detailed theory and experimental results in the prestigious Journal of the Acoustical Society of America [5]. Their theory [3–5] was based on the Auld's perturbative technique [66] and gave satisfactory results for liquids of viscosities up to ~10 Pas. The main advantage of the Love surface wave sensors is their very high sensitivity, namely the sensitivity of a few orders of magnitude (10^2 to 10^4) higher than that of their bulk SH waves counterparts [3–5]. As a result, measurements of the viscosity of water (~1 mPas) and other biological substances (based largely on water) was no longer a challenge, what was the case with bulk SH wave sensors. In other words, due to the employment of SH surface waves, the way for development of the corresponding biosensors was widely open.

It should be noticed that next publications on the Love wave sensors for liquid characterization appeared in the open literature not earlier than in 1992 [6]. In fact, in papers published in 1992, Kovacs and Venema [67], and, in 1993, Gizeli et al. [68] confirmed our earlier discovery [3–5] that Love surface waves are much more sensitive to viscous loading than other types of SH waves. In another paper published in 1992, Gizeli et al. [69] developed theoretical analysis for Love wave sensors, using the same Auld's perturbative technique [66] as that employed by us in papers [3–5].

It is interesting to note that two other types of SH waves, i.e., leaky SH SAW waves and plate SH waves, were also tried to measure viscosity of liquids. Leaky SH SAW waves were proposed in 1987 [70] by Moriizumi et al. and SH plate waves in 1988 by Martin et al. [71]. However, these two types of SH waves were quickly abandoned, since the corresponding

viscosity sensors were of inherently low sensitivity, difficult in practical realization and difficult in theoretical analysis (leaky SH SAW waves). In fact, the energy of SH plate waves is uniformly distributed across the whole thickness of the plate. Therefore, SH plate waves are not so sensitive to viscous loading as Love surface waves, whose energy is highly concentrated in the surface layer of the waveguide. On the other hand, leaky SH SAW waves are not pure SH waves and contains in principle all three components of vibrations, not only the SH one. In particular, the component perpendicular to free surface of the waveguide will continuously radiate energy into the adjacent liquid. This will cause an additional attenuation for leaky SH SAW waves, which will be indistinguishable from that due to the viscous loading measured.

5.3. Mathematical apparatus and numerical methods used in analysis of Love surface waves

R&D activities in seismology and biosensor technology using Love surface waves focus inevitably on different problems and challenges. The main reason for these differences is the nature and scale of Love surface waves used in seismology and biosensor technology, i.e., in seismology, they are a natural phenomenon and in biosensors, they are controlled within man-made devices. It is instructive to compare the chronology of developments made in seismology and in biosensor technology (see **Table 1**). In fact, the theory of Love waves published in 1911 [1] was developed for the simplest surface wave waveguide, namely for that composed of linear, isotropic, and lossless materials (surface layer on a substrate). Since loading viscoelastic liquids are always lossy, the corresponding theory of Love wave sensors had to use perturbative [3] or numerical methods [37]. The theory of Love waves in multilayered waveguides, developed in Seismology [72], uses a conventional transfer-matrix method based on the elementary matrix algebra. By contrast, the theory developed for biosensors extends the transfer-matrix method to a more advanced formalism of matrix differential equations with eigenvectors and eigenvalues and operator functions [8]. First theories of Love waves propagating in viscoelastic waveguides, were developed in Seismology [73], long before the advent of modern fast digital computers. By contrast, the corresponding theory developed for biosensors [74] in 2016 heavily relates on numerical methods.

5.4. Milestones in developments of Love wave seismology and Love wave biosensors

Examination of **Table 1** reveals that a number of R&D activities already well established in Seismology were not yet initiated in biosensor technology. As examples, one can mention the applications of nonlinear Love waves, higher-order Love wave modes or solitary waves. This suggests that in future research, it may be advantageous to employ higher-order modes, nonlinear Love waves, metamaterials, etc., to increase biosensors sensitivity [75] or lower their limit of detection. Other technologies not yet used in biosensor technology are phased array

and tomography. Indeed, applied to biosensors they may allow for a 2D characterization of the analyte distribution, electronic beam steering, focusing, etc. These indications for future research in biosensor technology show clearly advantages of multidisciplinary R&D activities, in this case seismology and biosensor technology. Indeed, it is much easier to adapt an existing technology already developed in other fields to a new domain than to invent a new technology from scratch without any prior feedback.

5.5. Novelty of the present chapter

Despite the fact that the first theory of Love surface waves was published as early as in 1911 [1], surprisingly, a large number of problems concerning the theory of Love surface waves have not yet been solved.

This chapter contains theoretical foundations and calculation results regarding the propagation of the Love wave in various media. A new interpretation of the Love wave dispersion equation was given. This equation is presented in the form of an implicit function of two variables, i.e., (ω, k). This allowed to evaluate the analytical dependencies on group velocity of Love wave propagating in a wide class of layered waveguides, e.g., in graded waveguides. This problem will be the subject of future author's works.

The obtained results can be employed in the design and optimization of not only biosensors but also chemosensors and sensors of physical quantities that use Love waves. In addition, the obtained results can be used in seismology and geophysics for the interpretation of seismograms and determining the distribution of elastic parameters of the Earth's crust.

This chapter contains also a novel comparison of milestones in developments made in Love wave seismology and Love wave biosensors (see Section 5.4). Since Love wave biosensors appeared exactly 70 years [2] after emergence of Love surface waves in seismology [1], it is not surprising that many discoveries and developments were made first in seismology and then transferred to biosensors (see **Table 1**). This cross-pollination between the two seemingly distant branches of science is very beneficial and can significantly accelerate developments made in either of them.

6. Conclusions

In this limited space chapter, it was impossible to address or even mention all interesting problems relevant to the properties and applications of Love surface waves in seismology and biosensor technology. Instead, we tried to present only main properties of the Love surface waves, such as their dispersive nature, phase and group velocities, amplitude distribution, etc., as well as their most iconic applications in seismology and biosensor technology. We think that presentation of the Love surface waves R&D activities in a broader historical

perspective gives an invaluable insight in the process of developments made in this fascinating interdisciplinary domain of research.

In this chapter, we attempted to present a variety of aspects that can be attributed to SH surface waves of the Love type. As a matter of fact, Dr. Jekyll and Mr. Hyde Love surface waves possess simultaneously two diametrically different faces, i.e., first benign (biosensors) and second deadly (earthquakes). The good news is that developments made in one of these domains can be easily transferred to the second one and vice versa. In fact, Love surface waves were first discovered in seismology (1911). They finally enabled for precise interpretation of seismograms registered in the aftermath of earthquakes. Beneficiary applications (biosensors) of Love surface waves were announced exactly 70 years later (1981) in a Polish patent.

Since earthquake is a natural phenomenon, we have little or no influence on its occurrence and dynamics. By contrast, the construction and the operation of biosensors can be optimized by mathematical modeling and experimental studies. At present, the mathematical modeling of Love wave biosensors is an active domain of research. On the other hand, progress in electronics and computer technology will lead to development of new compact and reliable instrumentation working in conjunction with Love wave biosensors.

Despite their centennial heritage, Love surface waves are subject of an intensive research activity. For example, one can mention the application of inverse problem techniques to recover material parameters of surface layers from measurements of velocity and attenuation of Love surface waves. Inverse problem techniques have been successfully employed in seismology and geophysics [25] and recently also pioneered by the authors [74, 77, 85] and others [86, 87] in the biosensor technology.

Other open problems in the theory and technique of Love surface waves are non-linear Love waves, extremely slow Love waves [88], Love waves in layered nanostructures [89], energy harvesting with Love waves, and metamaterial-based seismic shielding, [33, 34], etc.

Finally, coming back to the idea expressed at the beginning of the introduction in this chapter, we want to assure the reader that there exist still many significant unresolved problems in the theory and technique of the Love surface waves, which deserve to be addressed in future R&D activities. We hope that this chapter may be helpful in this endeavor.

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