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Research Article

Ultrasonic helical sensor for monitoring fuel adulteration and concentration

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ABSTRACT

This paper presents a novel approach for monitoring fuel adulteration using ultrasonic helical waveguide sensor. The longitudinal L(0,1), torsional T(0,1), and flexural F(1,1) modes were transmitted and received simultaneously through stainless steel helical waveguide. Here, we used shear transducer with 45° orientation of the waveguide axis, following the pulse-echo (PE) concept. We conducted experiments by preparing various fluid samples and altering the blend percentage mixture from 5% to 50%. The combinations included (a) a blend of kerosene and diesel, (b) a blend of kerosene and petrol, (c) a blend of ethanol and diesel, and (d) a blend of ethanol and petrol. Finding fuel quality at distribution point is critical to prevent fuel adulterations effectively. Monitoring fuel adulteration involves measuring attenuations in the helical waveguide sensor's reflected signal and velocity of waves. This sensor technique can also detect the ≤ 4% adulterations of fuel by re-configuring the helical sensor. Also, the measurement error from the different test samples was discussed based on experimental results. The implementation of this simple technique has potential to detect fuel adulterations at fuel stations and manufacturing plants. That helps to reduce air pollution levels effectively, significantly enhance the performance of automobile engines or fuel-based vehicles.

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INTRODUCTION

Automobile emissions are a primary environmental concern as the automobile users grow. The fractional distillation of crude oil produces fossil fuels (gasoline and diesel). They separated it into fuel fractions based on the boiling points of hydrocarbons with varying chain lengths. We derived the diesel fuel from crude petroleum oil through distillation at temperatures ranging from 230° to 380° C. Each barrel of crude oil yields approximately 25% gasoline via the fractional distillation process. The utility of diesel and gasoline-powered machines is more extensive, such as automobiles, ships, tractors, and diesel water pumps used in power generation. In the automobile industry, petrol and diesel are commonly used as the main fuels. Automobile emissions are among the leading causes of air pollution and global warming. This issue is exacerbated by the intentional adulteration of gasoline and diesel fuel at retail distribution points. Also, it enhances air pollution [1-4] and subsequently affects public health in the form of

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numerous ailments. For example, it produced tremendous amounts of smoke [5-8] when blending kerosene with diesel and gasoline fuel, which pollutes the environment. This is due to poor fuel combustion in the IC engine as a result of contaminated fuel. Due to the imposition of different tax structures on different hydrocarbon fuels by South Asian countries, retailers are engaging in illegal activities, such as adulterating gasoline and diesel fuel, to increase their profit margins. These governments heavily subsidize the cost of kerosene to make it accessible to the general public. In these regions [9], diesel fuel is commonly adulterated by adding kerosene, and gasoline is often contaminated by blending it with diesel or kerosene. It limited this sort of adulteration to small volumes of fractions, making it difficult for the user to identify. In both instances, fuel adulteration is often between 10 to 30 percent by volume. Typically, fuel adulteration < 10% may be unprofitable [10], and >20% may increase air pollution, which can reduce the performance of the internal combustion (IC) engine. Despite the fact that petrol and ethanol blends are widely accessible in several countries (including Brazil), the government agency must monitor their mass composition closely. The maximum permitted mix (blend) is 25% ethanol (E25) into the gasoline and 20% of biodiesel in diesel with a ±1% variance [11,12]. However, appropriate authorities must investigate and prosecute fuel adulteration. The mixing of ethyl alcohol, aromatics, and paraffinic hydrocarbons adulterates gasoline, despite laws and frequent monitoring. Several methods have been developed [13,14] for detecting the fuel adulterations. The most common tests are: Distillation test, evaporation test (ASTM D3810), and gas chromatography. The density test (ASTM D3810) and the detection of ash content (ASTM D482). Most available tests are laboratory based, while the density test is simple and portable for field assessment. We need to identify the adulteration of fuels in situ; it is essential to develop techniques that are robust, accurate, and non-destructive. Industries generally use invasive and non-invasive methods[15] for the measurement of fluid properties. In the invasive type, the sensors are directly in contact with the fluid or immersed into the liquids, for example, dip probes and ultrasonic waveguide methods. However, a non-invasive technique (acoustic and ultrasonic transducer) does not come in contact with the fluid medium. Hence, ultrasonic waveguides (as an invasive technique) can be easily accessed in the hazardous region and simultaneously used for monitoring the fluid properties.

Typically, researchers reported two types of ultrasonic methods for fluid properties measurement, the pulse-echo method (PE) [15-17] and through transmission (TT) [18,19] technique. Both ultrasonic approaches[20] have been utilized extensively in several stages of chemical processes, including acceleration of chemical reactions and the identification and analysis of chemicals.

Many researchers reported ultrasonic waveguide techniques for fluid level sensing, determining viscosity, density, and mass concentration of solid particles in the fluid, temperature measurement, and glass slurry [15,17-23]. A single shear transducer has the capability to produce various ultrasonic wave modes [15,21] when oriented at different angles (0°, 45°, and 90°) with respect to the axis of a thin circular waveguide. These modes include L(0,1), T(0,1), and F(1,1) modes. The propagation of these modes through the waveguides allows for monitoring of different properties of the surrounding fluid medium [15,21,23], including temperature, level, and density, as previously described in the literature. In addition, a range of sensor configurations for waveguides [15,18,21,23-25], including straight, bent, and helical designs, have been investigated for their suitability in high-temperature applications and fluid property measurements. In ultrasonic waveguide techniques, the measuring parameters are wave velocity, attenuation, frequency shift, and shift in flight time; all can measure by utilising TT and PE methods. These parameters can detect fuel adulteration, such as adding water or other substances based on changes in density, viscosity, and acoustic properties.

Sampa et al. [26] proposed an ultrasonic method to detect oil and grease in water. Mishra and Roy et al. [27,28] used fibre optic sensor to monitor gasoline and diesel fuel adulteration using kerosene. Based on the speed of ultrasound, B. Liu et al. [29] reported an ultrasonic technique for measuring the adulteration of ethanol fuel with the blending of known water concentrations. Yusuf C. et al. [30] introduced an ultrasonic method to quantify the alcohol concentration in a water-ethanol mixture based on acoustic velocity. Monique et al. [11,12] reported an ultrasonic method for monitoring the adulteration of biofuel (ethanol) with water based on ultrasonic attenuation and wave velocity. Anil Kumar et al. [31] demonstrated an ultrasonic technique to monitor adulteration of a fuel sample. Also monitor blend of water and ethanol were reported using an ultrasonic technique. It has been described as fuel adulteration or the change in viscosity and density of fuel significantly affecting the ultrasonic velocity. The petrochemical and pharmaceutical industries are looking for measuring instruments to identify liquid characterization and discrimination with better precision and sensitivity.

This study, we conducted experiments using an ultrasonic helical waveguide sensor to detect adulteration of petrol and diesel by the controlled addition of ethanol and kerosene. Prepared the test samples by blending various concentrations of kerosene and ethanol into the petrol and diesel. We utilised the PE technique to transmit and receive L (0, 1), T (0, 1), and F(1, 1) modes concurrently in the helical waveguide.

ULTRASONIC WAVEGUIDE SENSOR DESIGN

The propagation of guided waves through a waveguide is influenced by several factors, including material characteristics, operating frequency, group velocity, and dimensions of the waveguide. In order to minimize dispersion

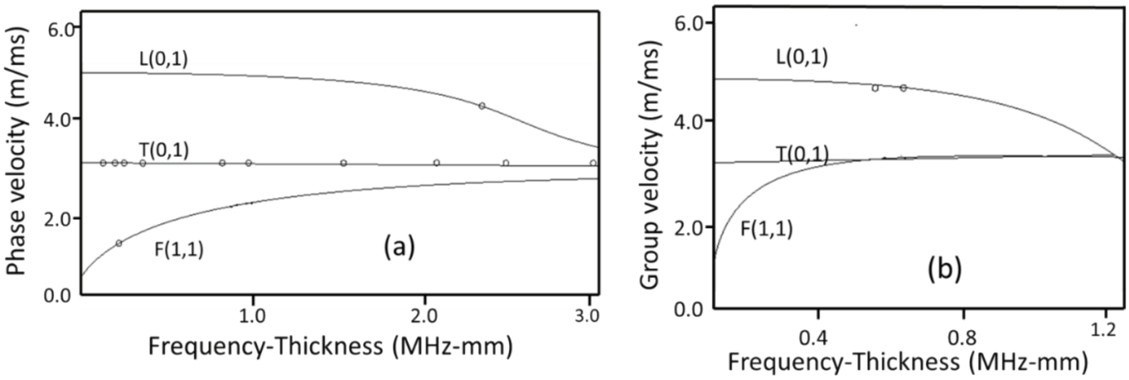

Figure 1. (**a**) Phase velocity, (**b**) Group velocity for all three modes for stainless steel wire with diameter 1.2 mm.

effects in the signal, it is crucial for the mean diameter of the helical waveguide sensor to be larger than 2λ. The straight section of the sensor, connected to the shear wave transducer operating at a frequency of 0.5 MHz and oriented at 45 degrees, is utilised in this research to transmit and receive all three modes: L(0,1), T(0,1), and F(1,1). The JSR (DPR 300) ultrasonic pulse-receiver is used in a pulse-echo configuration to achieve this. These modes exhibits non-dispersive nature within a low-frequency range (300 to 500 KHz), presented in Fig.1. The dispersion curve is important for comprehending and choosing proper guided wave modes with non-dispersive characteristics. It assists in identifying the suitable operating frequency range for the system. The phase and group velocity dispersion curves for a helical waveguide with a wire diameter of 1.2 mm were derived using a specially developed dispersion software [32] are shown in Figure 1(a, b).

MATERIALS AND METHODS

The test sample was a mixture of (a) gasoline and ethanol, (b) gasoline and kerosene, (c) diesel and ethanol, and (d) diesel and kerosene. The blend fuel concentrations range from 5% to 50% in pure gasoline and diesel. We used the samples, gasoline, diesel, ethanol, and kerosene, in the experiments, which procured from the local fuel sale depot of the IOCL. Ethanol was purchased from the local supplier with 99.9% purity. The density of the test sample was measured using gravimetric methods [9]. The obtained density results well matched the report provided by the local depot. We used the glass test tube (dimensions; height =80 mm and dia =70 mm) to fill the less quantity of samples, and a helical waveguide sensor was kept inside the test tube, as shown in Figure 2. The straight portion of the waveguide's end was associated with the shear wave transducer (0.5 MHz) at 45^{o} orientations to transmit and receive L(0.1), T(0.1), and F(1.1) modes simultaneously using the

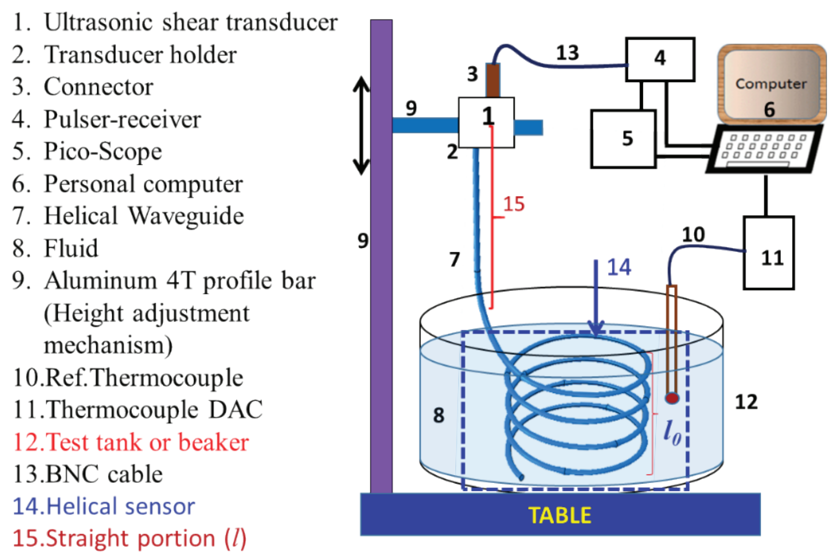

Figure 2. Shows a schematic diagram of the experimental setup.

Table 1. Fuel properties of the test sample. [From Kumar et al. [24, 25], our early reported works].

Fluid medium	Density (kg/m³)	Bulk modulus (GPa)
Petrol	737	1.07
Ethanol	789	1.10
Kerosene	797	1.25
Diesel	820	1.3

Table 2. Waveguide material properties and experimental parameters

Waveguide Material Stainless steel	
Young's modulus (GPa)	202
Density of waveguide (ρ) kg/m³	8002
Poission's ratio (μ)	0.3
Waveguide wire diameter (mm)	1.2
Total length of wire (L) in m	1.08
Pitch of helix (P) in mm	6.6
Mean diameter of helix (D) in mm (>2λ from ref. 21)	32
Sampling rate (Ms/s)	125
Input voltage (V)	450

JSR (DPR 300) ultrasonic pulse-receiver in a pulse-echo manner. The received ultrasonic signals from the pulse receiver were interfaced with a personal computer utilising Picoscope (3000 series). Here, we used a single shear wave transducer to perform the experimental investigations.

Ultrasonic Parameters

Ultrasonic attenuations, shift in flight time, and change in wave velocity are the ultrasonic parameters that can be used experimentally to monitor petrol and diesel adulteration. In this study, L(0,1), T(0,1), and F(1,1) modes were concurrently transmitted/received in a helical waveguide when immersed in a fluid mixture. We used the ultrasonic parameters (ultrasonic attenuations and change in wave velocity) to detect adulteration. Numerous factors contribute to ultrasonic attenuation or amplitude loss, including absorption, diffraction loss, scattering, and impedance mismatch. In ultrasonic wave propagation, the surrounding medium plays an important role. An impedance mismatch occurs when ultrasonic waves travel from one medium to another with a different acoustic impedance, which alters the wave propagation behavior. The ultrasonic parameters measured "ultrasonic attenuation" based on each test sample's ultrasonic guided wave signal behavior. Initially, wave propagation through the waveguide was conducted in an air (reference sample) medium, and the obtained signal is considered as reference signal.

The experimental attenuation can be calculated using Eq. (1),

$$Att\ (\propto) = \frac{10\ log\left(\frac{V_{ref}}{V_A}\right)}{L_e} \quad [dB/cm] \tag{1}$$

Where, V_{ref} is the reference signal from air, V_A is the effective amplitude corresponding to various concentrations of test sample, and L_e is waveguide length/region immersed in the sample.

RESULTS AND DISCUSSION

The adulterations of fuel were estimated based on measuring the ultrasonic wave propagation behavior in the helical waveguide. The fluid sample was varying concentrations of (a) gasoline and ethanol, (b) gasoline and kerosene, (c) diesel and ethanol, and (d) diesel and kerosene. The concentration of gasoline in the prepared sample ranges from 50% to 100%, whereas the ethanol content is 0% to 50% by mass. Similarly, different concentrations of diesel were mixed with various concentrations of ethanol and kerosene. The experimental study was conducted with 20 ml of the prepared sample and a 2 mm immersion level of the waveguide. The designed helical waveguide sensor's mean coil diameter was >2λ, as reported by an earlier researcher, to avoid the dispersion effects. The waveguide sensor was immersed into the sample using a glass test tube. This study used a single shear transducer to transmit and received all three modes altogether through the helical waveguide as depicted in Fig. 3, when there is a 45° orientation between the waveguide axis and transducer. Based on earlier reported work, we found that F(1,1) mode have more sensitivity than other modes. Therefore, selected the F(1,1) mode for fuel adulteration detections. The adulterations of fuel were detected based on measuring the ultrasonic wave velocity and attenuations of the received signal

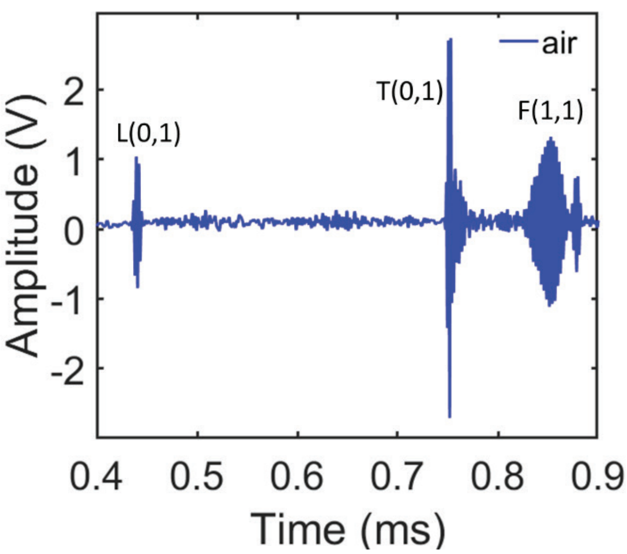

Figure 3. Received a-scan signals from air medium.

from the fuel test sample. Also, the received signals from one test sample were compared with different concentrations of the same test sample based on the amplitude (attenuation) of the signal.

In this study, the fuel concentration detection is considered into four cases: Case1:- Kerosene blend with diesel with different percentages (0, 5, 10, 15, 20, 25, 30, 40, 50). Case 2:- Kerosene blend with petrol with the same percentage. Similarly, in case 3 and case 4:- Ethanol blended with gasoline and diesel with similar percentage variation. Firstly, the sensor was placed in an air medium and the signal acquired from it was regarded as the reference signal, as depicted in Figure 3; later, poured samples into the test tube. Corresponding to each sample with the same quantity received A-scan signals, as displayed in Fig. 4. The A-scan signals were analyzed by noticing the decrease in amplitude with varying concentrations of ethanol and kerosene. However, difficult to track the peak amplitude and change in time of flight for each case (test sample) using obtained A-scan signal. Therefore, the Hilbert transform used an alternative tool to track the peak amplitude from the time domain (A-scan) signal and the received A-scan signals, as illustrated in Fig. 5.

Using Hilbert transform tool, we measure amplitude drop for each test sample. Here, we observed that when we blended kerosene or ethanol with diesel, the mixture fuel density decreased gradually as the blend percentage increased. This causes an estimated drop in the reflected signal amplitude, increasing the blend percentage. However, when we blended kerosene and ethanol with petrol, the mixture fuel density increased as increasing the blend percentage. Due to the increase in thickness (density) of adultered fuel, the amplitude of the signal increased as the blend percentage in petrol increased. After that, we evaluated the ultrasonic attenuation for every sample using Equation 1. We determined the error value for all the cases (1-4) based

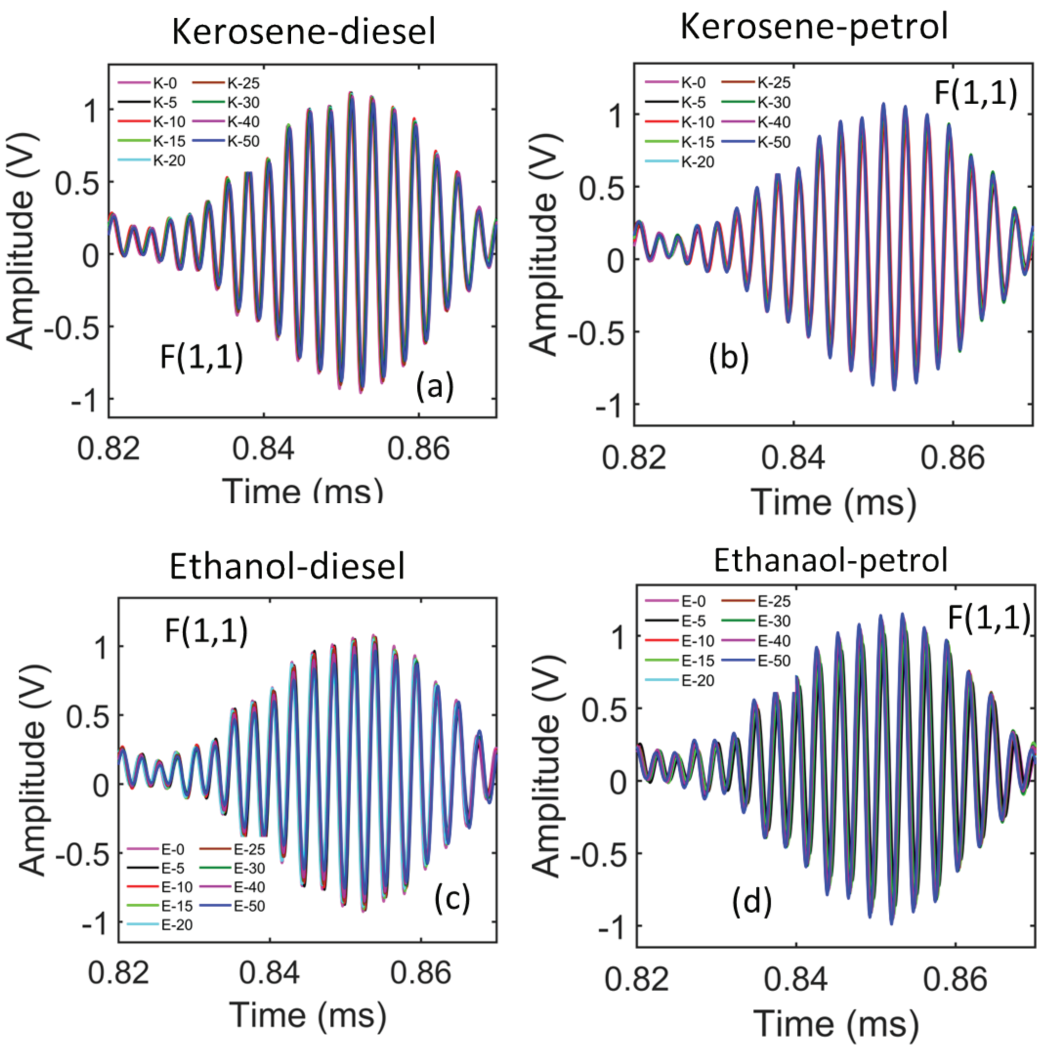

Figure 4. Obtained A-scan for different cases, (a) kerosene bend with diesel, (b) kerosene blend with petrol, (c) ethanol blend with diesel, and ethanol blend with petrol.

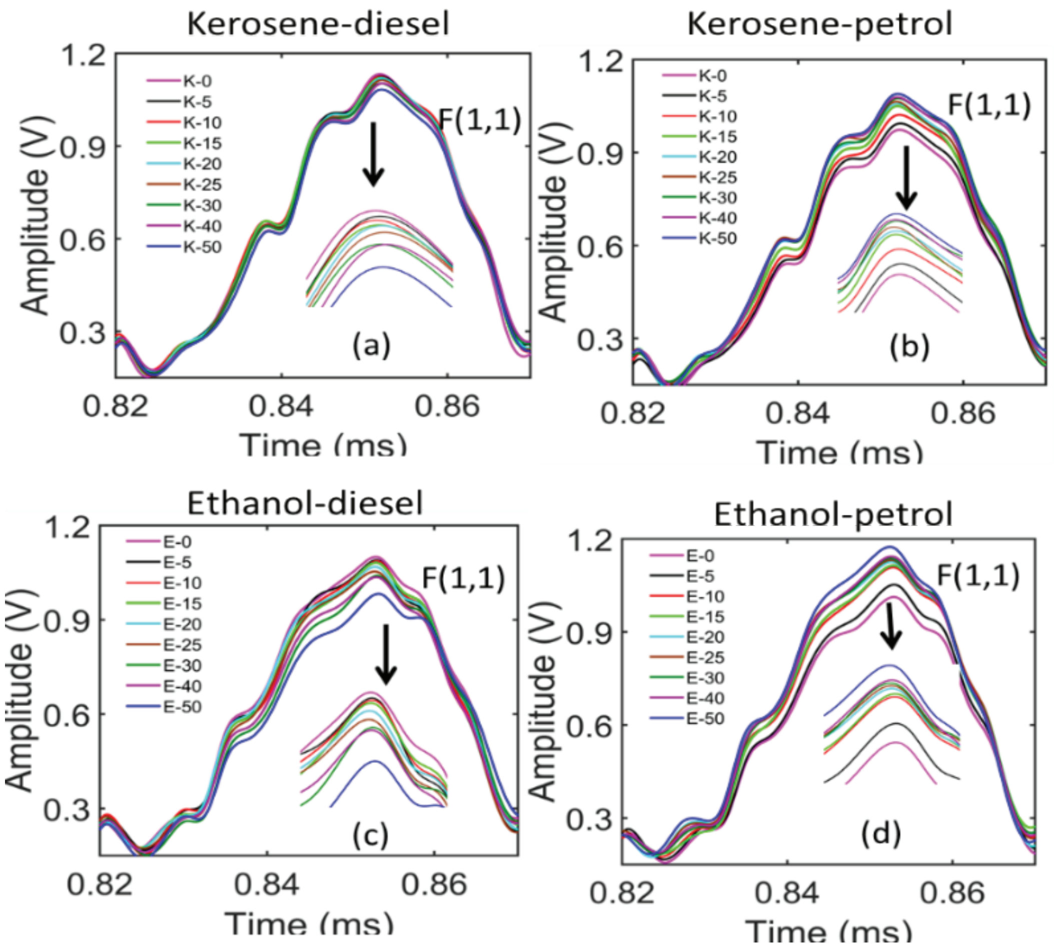

Figure 5. Hilbert transform of the obtained A-scan signal for (a) kerosene-diesel, (b) kerosene-petrol, (c) ethanol-diesel, and (d) ethanol-petrol.

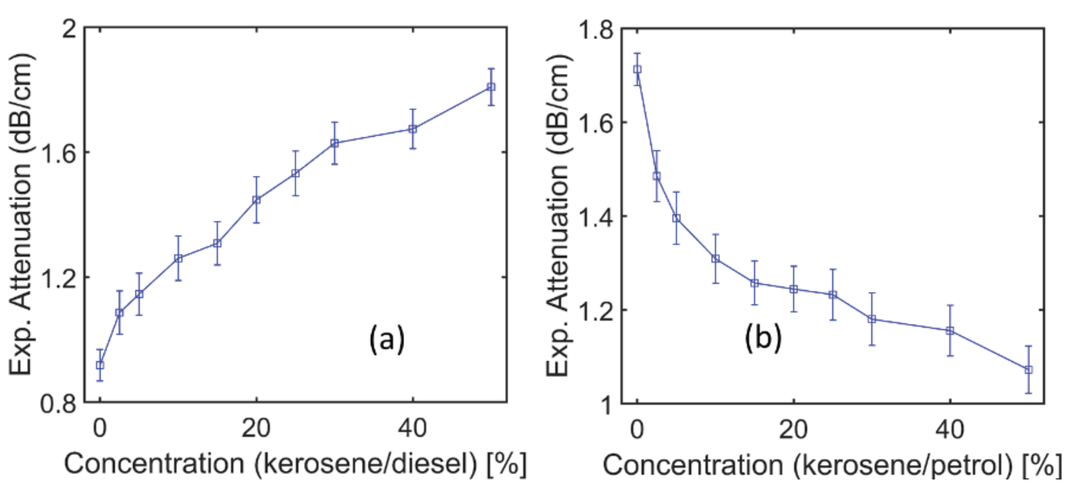

Figure 6. Shows the error bar plot of attenuation with different concentration in (a) kerosene with diesel, (b) kerosene with petrol.

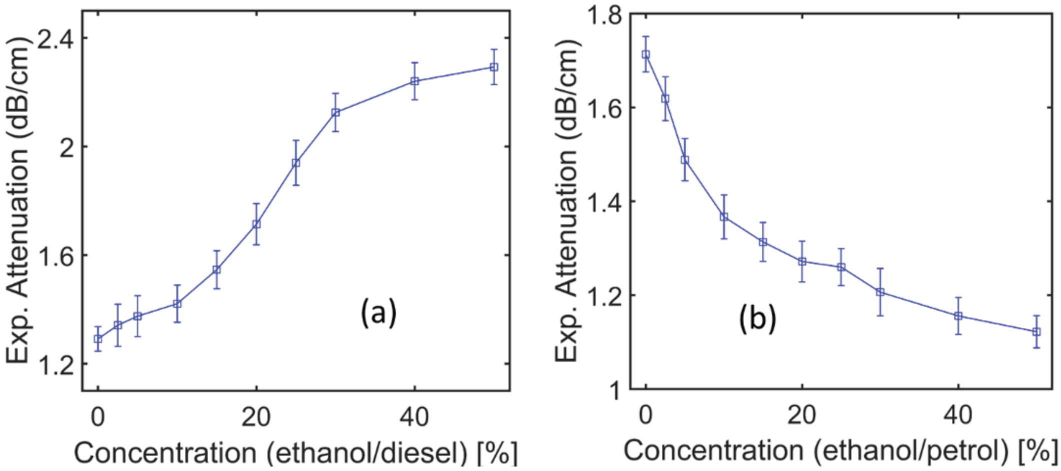

Figure 7. Shows the error bar plot of attenuation with different concentration in (a) ethanol with diesel, and (b) ethanol with petrol.

on the experimental study results. The error bars were plotted between attenuation and different blended fuel mixture concentrations of kerosene-diesel, kerosene-petrol, ethanol-diesel, and ethanol-petrol.as shown in Figs. 6(a–b) and Figs. 7(a-b). Based on the obtained error value at different blend percentages, we determine the average error between 4 and 6 percent.

CONCLUSION

The ultrasonic guided wave methods is proven as an important tool to analyse the fuel adulterations. Here, we developed an ultrasonic helical waveguide sensor using flexural F(1,1) modes based on pulse-echo methods to monitor the adulterations of petrol and diesel by the addition of ethanol and kerosene.This methods mainly based on different physical properties of the fuel sample, such as density, viscosity and acoustic impedance. Fuel adulterations were detected based on ultrasonic attenuations (amplitude variations) and ultrasonic wave velocity of the F(1,1) wave mode signal. Here, we found that ultrasonic attenuations provided more reliable result to estimate the fuel adulterations with kerosene and ethanol. Ultrasonic waveguide method, wave velocity variations are not appropriate for fuel adulterations detections.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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