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# Ultrasonic Modelling of Open Trenches Used as Seismic Barriers Against Traffic-induced Ground Vibrations

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**Abstract**

Various types of seismic barriers are used in practice to protect buildings from traffic-induced ground vibrations, mainly from propagating Rayleigh surface waves. One of the widely used types of seismic barriers are open trenches. Experimental investigations of real size trenches at frequencies typical for traffic-induced ground vibrations, i.e. at 10-100 Hz, are costly and time consuming. In the present work, an alternative and much less expensive approach is proposed - a reduced-scale experimental modelling using ultrasonic Rayleigh wave propagation over very small-scale replicas of real trenches. Experimental investigations of propagation of Rayleigh wave pulses with the central frequency of 1 MHz, which corresponds to the value of scaling factor of about 1:1000, have been carried out for a single trench and for periodic combinations of trenches. The results of the measurements of transmission and reflection coefficients of Rayleigh waves for different incident angles show that, for typical values of the parameters used in the experiments, periodic combinations of trenches represent efficient seismic barriers against traffic-induced ground vibrations.

**Keywords**: Ground vibrations; Open trenches, Rayleigh waves, Ultrasonic modelling.

## *Ультразвуковое моделирование открытых траншей, используемых в качестве сейсмических барьеров для защиты от грунтовых вибраций, вызванных дорожным движением*

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***Аннотация***

*Различные типы сейсмических барьеров используются на практике для защиты зданий от грунтовых вибраций, вызванных дорожным движением, главным образом от распространяющихся поверхностных волн Рэлея. Одним из широко используемых типов сейсмических барьеров являются открытые траншеи. Экспериментальные исследования траншей реальных размеров на частотах, типичных для вибраций, вызванных дорожным движением, т. е. при 10-100 Гц, являются дорогостоящими и требуют много времени. В настоящей работе предлагается альтернативный и гораздо менее дорогостоящий подход - экспериментальное моделирование с уменьшенным масштабом и с использованием распространения ультразвуковых волн Рэлея по очень мелким репликам реальных траншей. Экспериментальные исследования распространения импульсов рэлеевских волн с центральной частотой 1 МГц, что соответствует значению масштабного коэффициента около 1: 1000, были проведены для единичной траншеи и для периодических комбинаций траншей. Результаты измерений коэффициентов прохождения и отражения волн Рэлея при различных углах падения показывают, что при типичных значениях параметров, используемых в экспериментах, периодические комбинации траншей представляют собой эффективные сейсмические барьеры для защиты от грунтовых вибраций, вызванных дорожным движением.*

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***Ключевые слова***: *грунтовые вибрации; открытые траншеи, волны Рэлея, ультразвуковое моделирование.*

## Introduction

One of the ways to reduce ground vibrations from railways or road traffic is to influence the propagation path from source to receiver by introducing seismic barriers. The advantage of interventions on the propagation path is that no modifications of the track or road are required. Several types of seismic barriers have been proposed in the past to protect buildings from traffic-induced ground vibrations, mainly from propagating Rayleigh surface waves. Among such barriers are trenches (both open and in-filled) [1-6]. large concrete blocks embedded in the ground [7-9], rows of vertical piles [10-13], periodic arrays of vertical holes [14], heavy masses placed on the ground surface [15, 16], etc. Open trenches represent one of the types of seismic barriers that are used most frequently, partly because of the relative simplicity of their construction.

Theoretical predictions of Rayleigh wave propagation through trenches, as well as through other types of seismic barriers, are very difficult. Analytical solutions are possible only for a limited number of cases, for example in the case of very shallow trenches, where perturbation theory can be used [17]. In the majority of situations though the only methods of theoretical prediction are numerical approaches, which require much of computation time. For that reason, in order to obtain a reliable prediction of the behaviour of seismic barriers in specific locations, a typical practical solution is to use direct experimental measurements on real size seismic barriers at frequencies typical for traffic-induced ground vibrations, i.e. at 10-100 Hz [18, 19]. Such direct measurements are costly and time consuming.

In the present paper, an alternative and much less expensive approach to a full-scale experimental testing of trenches is proposed. This is their reduced-scale experimental modelling using ultrasonic Rayleigh wave propagation over very small-scale replicas of real trenches. Note that very similar problems are considered also in the field of ultrasonic non-destructive testing used for detection and identification of cracks and other defects in solids and structures (see e.g. [20-23]). In the present work, we describe the methodology of the approach and the results of the experimental investigations of propagation of Rayleigh wave pulses with the central frequency of 1 MHz, which corresponds to the scaling factor of about 1:1000, through a single trench and through combinations of periodically positioned trenches. The results of the measurements of transmission and reflection coefficients of ultrasonic Rayleigh waves over the above-mentioned reduced-scale replicas of open trenches demonstrate that the proposed experimental approach is simple and efficient, and it helps to quickly evaluate the ability of single trenches and of their periodic combinations to suppress the transmitted Rayleigh waves. Part of the material described in this paper has been presented at the recent conference on noise and vibration engineering [24].

## 1. Manufacturing of Experimental Samples

The experimental samples have been made of 20 mm-thick Aluminium plates having horizontal dimensions of 350 x 250 mm (each of these samples can be considered as an elastic half space for Rayleigh waves at frequencies around 1 MHz). In order to investigate ultrasonic Rayleigh wave propagation over model trenches, very small-scale replicas of combinations of periodically positioned trenches, including a single trench, have been made. A CNC (Computer Numerically Controlled) milling machine was used to produce model trenches. The central frequency of Rayleigh wave pulses used in the experiments was 1 MHz, which corresponds to the Rayleigh wavelength in Aluminium $\lambda_R$ = 2.9 mm.

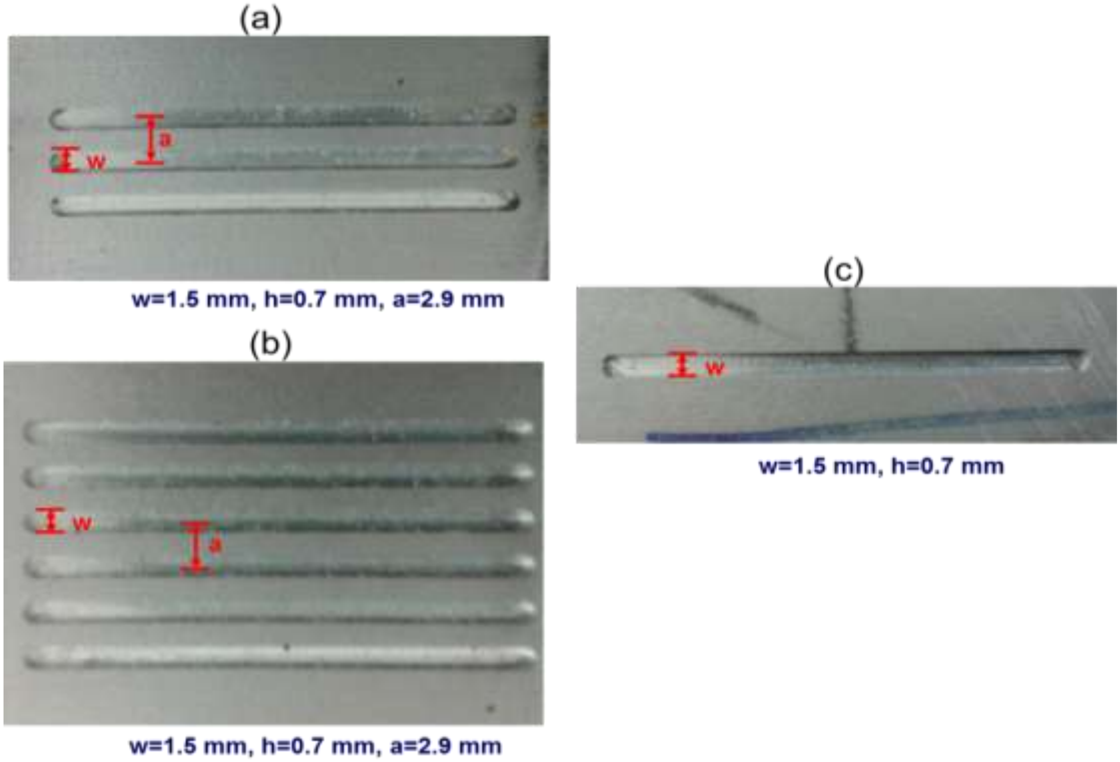


*Fig. 1.* Close up photographs of the combinations of periodically positioned trenches, and of a single trench, made on the surfaces of Aluminium rectangular blocks: (a) three trenches, 3Th07a29w15, (b) six trenches, 6Th07a29w15, and (c) a single trench, 1Th07w15.

A single trench (1Th07w15) and three (3Th07a29w15) and six (6Th07a29w15) periodically positioned trenches with the same length (29.4 mm) were produced on the surfaces of Aluminium rectangular plates with a constant depth, $h$ = 0.75 mm, and width, $w$ = 1.5 mm. The distance, centre-to-centre, between two trenches $a$ was selected to be equal to the Rayleigh wavelength in Aluminium at frequency of 1 MHz, i.e. $a = \lambda_R$ = 2.9 mm. Figure 1 shows photographs of a single model trench (c), and of periodic combinations of three (a) and six (b) trenches.

## 2. Experimental Setup

The laboratory arrangement used for measurements of transmission and reflection coefficients of propagating Rayleigh wave pulses with the central frequency of 1 MHz, which corresponds to the value of scaling factor of about 1:1000, over model trenches is shown in Fig. 2.

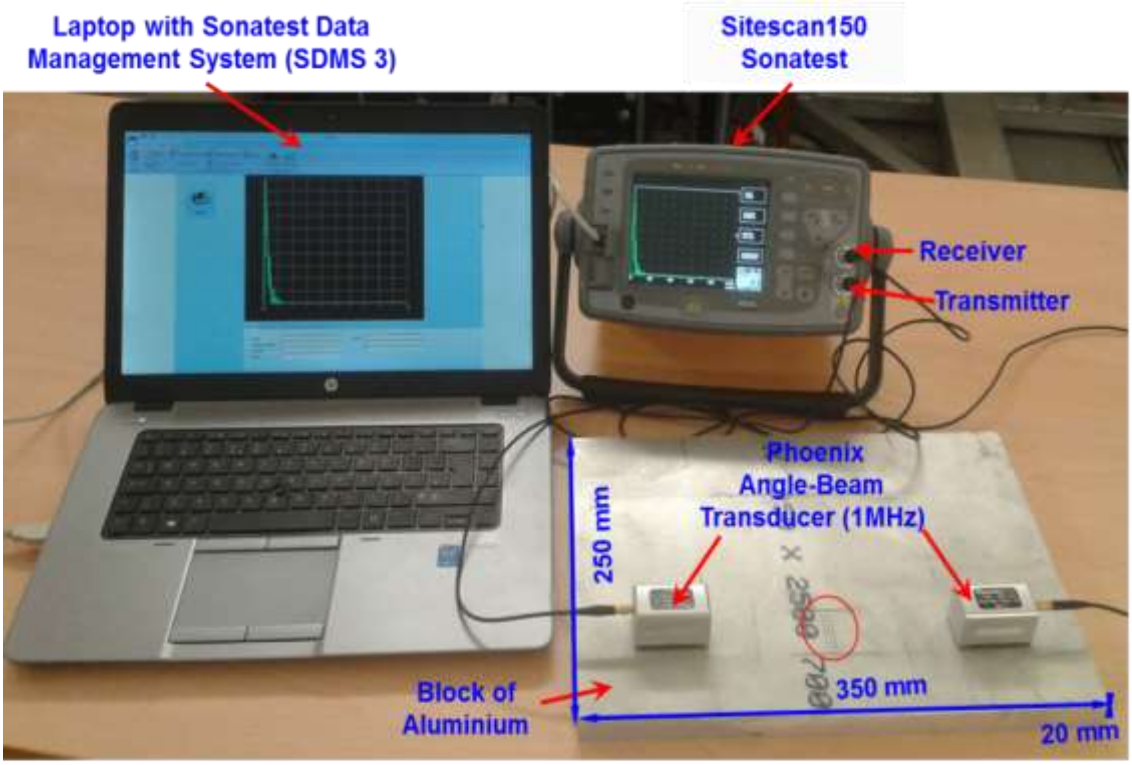


*Fig. 2.* Photograph of the experimental setup showing the Perspex angle-beam transducers with the central frequency of 1 MHz, an Aluminium rectangular sample, a Sitescan150, and a Laptop with SDMS 3

Two Phoenix angle-beam piezoelectric ultrasonic transducers with the central frequency of 1 MHz, 20 mm diameter crystal and linear dimensions L51xW27xH31 mm were used to generate and receive ultrasonic Rayleigh waves on the surfaces of Aluminium rectangular blocks. A Sitescan150 ultrasonic testing system from Sonatest Ltd was used both to drive the transducer and to receive/display the ultrasonic signals. A Sonatest Data Management System version 3 (SDMS 3) was installed in the Laptop to interface and record the acquired data from Sitescan150 for further post processing.

The separation between the transmitter and the receiver was $d$ = 5 cm. The reduced-scale models of open trenches were produced in the middle of one half of the Aluminium rectangular plates. Another half was used for the measurements of the propagation of ultrasonic Rayleigh waves over smooth surface (in the absence of trenches) for reference purposes. Measurements were performed in transmission mode. The transducer connected to the Transmitter of Sitescan150 generated an ultrasonic Rayleigh wave pulse on the surface of an Aluminium plate. Another transducer was connected to the Receiver of Sitescan150 and placed behind the seismic barriers, separated by distance $d$, and received the ultrasonic Rayleigh waves generated by the transducer (transmitter).

## 3. Experimental Results and Discussion

Single open trenches and periodic combinations of open trenches as seismic barriers were investigated in order to study their effects on Rayleigh wave propagation. Single trenches, both open and in-filled, are used widely as seismic barriers against train- and traffic-induced ground vibrations [1-6].

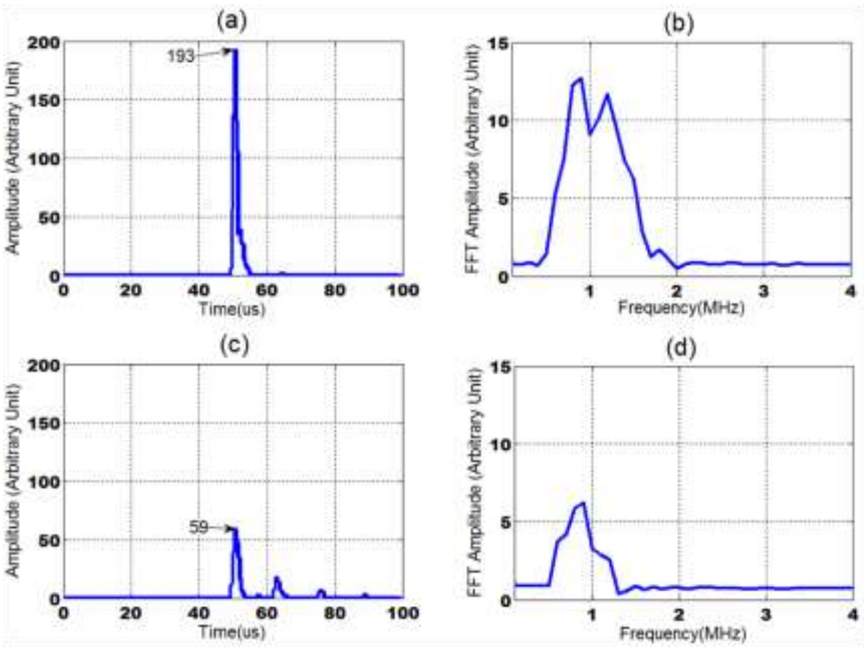


*Fig. 3.* Signals of ultrasonic Rayleigh waves, $\theta_i$ and $\theta_r = 0^o$: (a) Full wave rectifier signal transmitted over a smooth surface, and (b) the corresponding frequency spectrum; (c) Full wave rectifier signal transmitted over a single trench, and (d) the corresponding frequency spectrum

Periodic combinations of trenches are not known to be used as seismic barriers, but they are used widely as reflective gratings (with periods $a = \lambda_R/2$) in electronic signal processing devices using different types of surface acoustic waves, including Rayleigh waves (see e.g. [17]). In what follows we describe the results of reduced-scale ultrasonic investigations of the behaviour of single trenches and of their periodic combinations as seismic barriers.

A single trench has been produced on the surface of an Aluminium plate with the dimensions mentioned above. The transducers (transmitter and receiver) were initially located in the normal position and separated by the distance $d$ = 5 cm. The measurements results for ultrasonic Rayleigh wave propagation over a smooth surface and over a single trench are shown in Fig. 3. It can be seen that the amplitude reduction factor for a single trench, calculated from the data displayed in Fig. 3 as 59/193, is about 0.30, which is in line with the earlier published measurements (see e.g. [22]).

For oblique incidence and for the receiver being in the normal position, the measured transmission pulses are shown in Fig. 4. The amplitude reduction factors in these cases are 0.16 and 0.02 for the angles of incidence $\theta_i = 30^o$ and $60^o$ respectively.

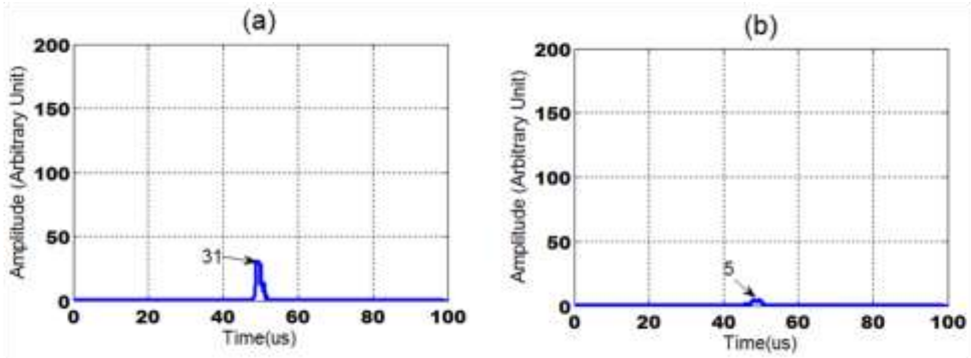


*Fig. 4.* Full-wave rectifier signal of ultrasonic Rayleigh wave transmitted over a single trench at oblique incidence, the receiver is at the normal position, $\theta_r = 0^o$: (a) Transmitter at $\theta_i = 30^o$, (b) Transmitter at $\theta_i = 60^o$

In the case of Rayleigh wave reflection from a single trench at oblique incidence, the obtained results are shown in Fig. 5. The reflection coefficients calculated from the observed amplitudes are 0.19 and 0.29 for the angles of 30° and 60° degrees respectively.

Measurements of Rayleigh wave transmission were repeated for the cases of three and six periodically positioned trenches when both transducers (transmitter and receiver) were located in the normal position. The results for Rayleigh wave transmission over a smooth surface and over three trenches, as well as over a smooth surface and over six trenches are shown in Figs. 6 and 7 respectively.

The corresponding amplitude reductions factors are 0.1 and 0.04 - for three trenches and for six trenches respectively. A strong attenuation of the signals for these cases is apparent. These results demonstrate that, for the values of the parameters used in the experiments, the attenuation of Rayleigh waves propagating over periodic systems of trenches, if the period is equal to the Rayleigh wavelength, is strong enough, and their practical use can be recommended when generated ground vibrations are severe.

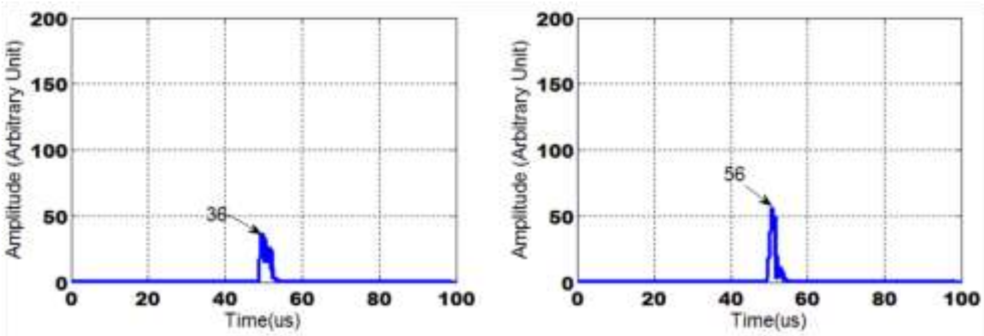


*Fig. 5.* Full-wave rectifier signal of ultrasonic Rayleigh wave reflection from a single trench: (a) $\theta_i$ = 30°, $\theta_r$ = 30°, (b) $\theta_i$ = 60°, $\theta_r$ = 60°

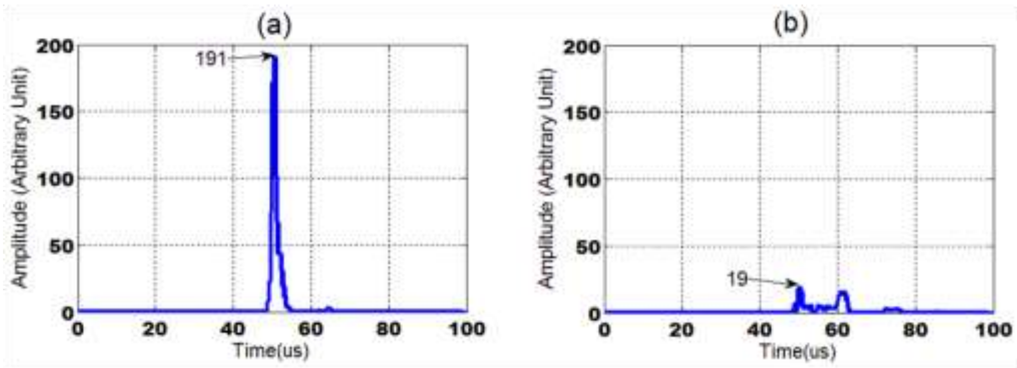


*Fig. 6.* Full wave rectifier signals of ultrasonic Rayleigh waves, $\theta_i$ and $\theta_r$ = 0°: (a) signal transmitted over a smooth surface, and (b) signal transmitted over three trenches

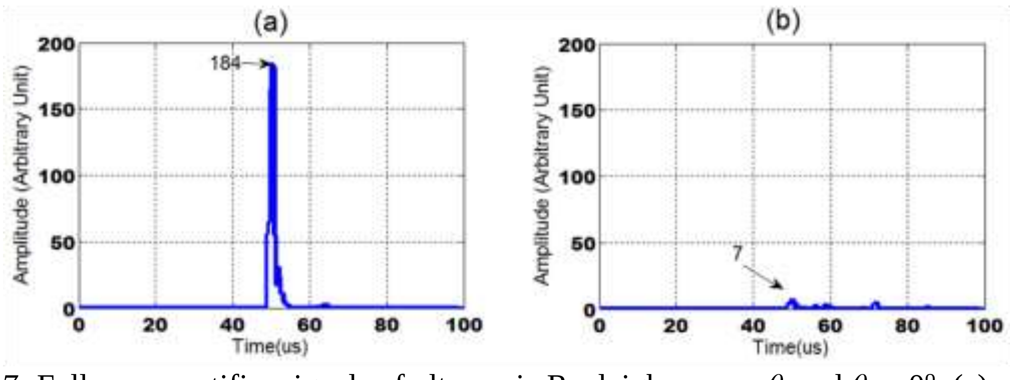


*Fig. 7.* Full wave rectifier signals of ultrasonic Rayleigh waves, $\theta_i$ and $\theta_r$ = 0°: (a) signal transmitted over a smooth surface, and (b) signal transmitted over six trenches

For oblique incidence of Rayleigh waves and for the receiver being in normal position, the transmission measurement results for the case of three trenches are shown in Fig. 8. The amplitude reduction factors are 0.07 and 0.02 for $\theta_i = 30^o$ and $60^o$ respectively.

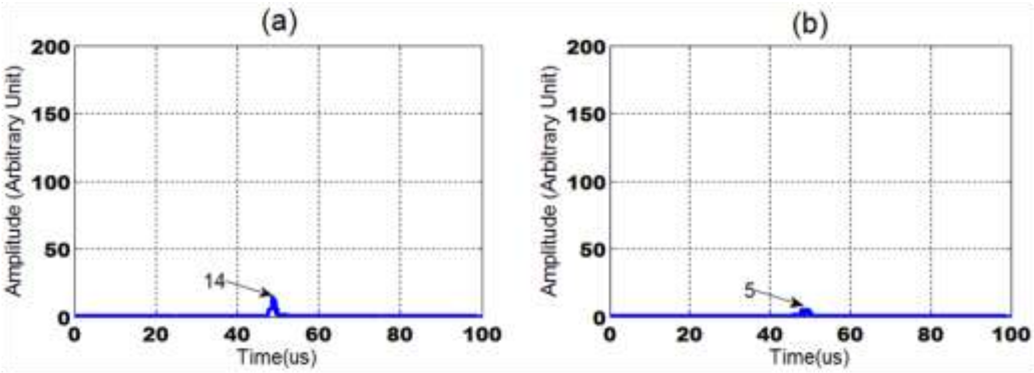


*Fig. 8.* Full-wave rectifier signals of ultrasonic Rayleigh waves propagating over three trenches, receiver at normal position, $\theta_r = 0^o$: (a) Transmitter at $\theta_i = 30^o$, (b) Transmitter at $\theta_i = 60^o$

Measurements of Rayleigh wave reflection from periodic combinations of three trenches and six trenches have been carried out using two combinations of incidence and reflection angles: ($\theta_i = 30^o$, $\theta_r = 30^o$) and ($\theta_i = 60^o$, $\theta_r = 60^o$). The results of the measurements are shown in Figs. 9 and 10.

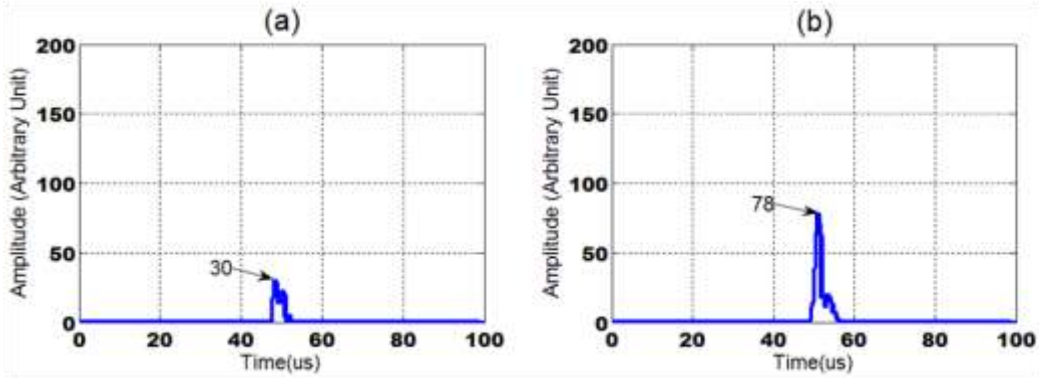


Fig. 9. Full-wave rectifier signals of ultrasonic Rayleigh wave reflection from three trenches: (a) $\theta_i = 30^o$, $\theta_r = 30^o$, (b) $\theta_i = 60^o$, $\theta_r = 60^o$

The observed reflection coefficients for the case of three trenches are 0.16 and 0.40 for $30^o$ and $60^o$ respectively, and for the case of six trenches they are 0.12 and 0.15 for $30^o$ and $60^o$ respectively.

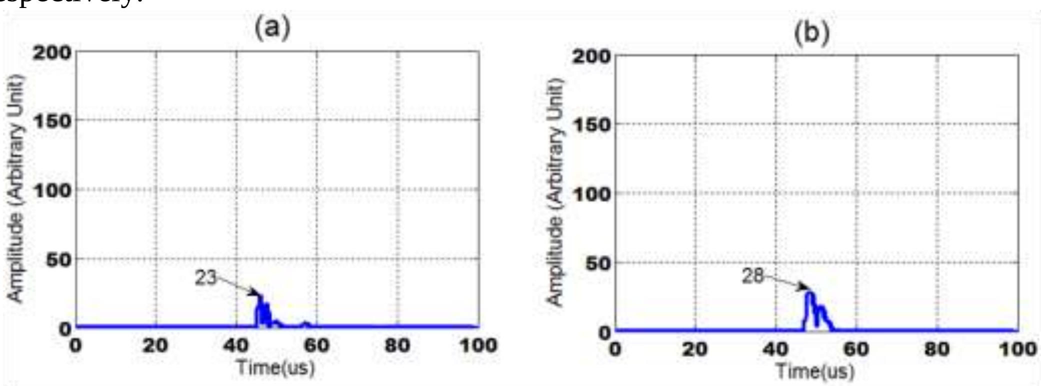


*Fig. 10.* Full-wave rectifier signals of ultrasonic Rayleigh wave reflection from six trenches: (a) $\theta_i = 30^o$, $\theta_r = 30^o$, (b) $\theta_i = 60^o$, $\theta_r = 60^o$.

## 4. Conclusions

It has been demonstrated in this paper that reduced-scale ultrasonic modelling of Rayleigh wave interaction with open trenches used as seismic barriers against railway- and traffic-induced ground vibrations can be a useful tool for experimental investigations of the reflection and transmission properties of different types of trenches and their periodic combinations.

The advantage of reduced-scale ultrasonic modelling over full-scale experimental measurements is that it is compact (all experiments can be conducted on a laboratory table) and much less expensive (it is easy to manufacture numerous experimental samples modelling different configurations and combinations of trenches).

The main disadvantage of reduced-scale ultrasonic modelling is that standard ultrasonic transducers used for generation and reception of Rayleigh waves are relatively narrow band devices designed for specific central frequencies, in contrast to real sources of railway- and traffic-induced ground vibrations that are broadband, typically between 10 and 100 Hz. Broadband sources of ground vibrations can be modelled using measurements with several pairs of ultrasonic transducers having different central frequencies. Another possible solution is using a single pair of ultrasonic transducers working in a non-resonant regime, i.e. when the frequencies of interest are much less than the resonant frequencies of piezoelectric plates in the transducers. In the latter case though the efficiency of generation and reception of Rayleigh waves is significantly reduced.

Considering the specific measurements of transmission and reflection of Rayleigh waves on a number of Aluminium samples modelling open trenches as seismic barriers, it can be concluded that, for the parameters used in the experiments, periodic combinations of three and six open trenches provide the most efficient suppression of transmitted Rayleigh waves. Such periodic combinations of trenches can be recommended for protection against severe ground vibrations, e.g. associated with ground vibration boom from high-speed trains [25].

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