Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Optimum signals for acoustic cargo security screening

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PACS: 43.28.WE

ABSTRACT

This paper demonstrates that it is possible to transmit acoustic signals in the frequency range 100 Hz - 100 kHz through objects in air. This approach can be used potentially to perform cargo screening at border crossings and transport hubs, to find illicit cargo. A feasibility study has been performed, which has shown that acoustic signals can be transmitted through a simulated container, with the curtain side-walls as usually seen on European road transportation vehicles. It has been found that careful selection of acoustic waveforms and processing is necessary to perform a measurement. Research has shown that novel forms of signal, involving discrete frequencies, can help in obtaining more information. Time reversal techniques also help in the identification of resonances within the cargo container. These resonances will form the basis of future research into acoustic tomographic imaging of such containers for security screening applications.

INTRODUCTION

Cargo containers and the trailers of freight vehicles have become a means for the smuggling of people across borders, and their detection is of interest to many different countries and jurisdictions. Cargo screening is dominated at present by through-transmission X-ray, γ-ray and neutron methods. This has received much impetus recently with a future requirement for scanning of all shipping containers in the USA. X-ray Compton back-scatter has been proposed as a single-sided technique for imaging metallic cargo containers, as certain explosives and drugs give good signals because of their scattering characteristics [1]. γ-ray and neutron techniques are usually used in through-transmission, and can be used singly [2] or in combination [3]. For the canvas-sided lorries that are common on EU roads, THz imaging has been applied [4], and indeed has been trialled at ferry terminals using background radiation. However, it is not yet widely adopted.

The aim of this study was to show the feasibility of a cargo screening method based on acoustic transmission. Various types of acoustic signal and processing were to be utlised, to try and maximise data collection from signals passing through a typical road trailer. If such data could be collected, then it could be used as the basis for a longer, more detailed study. Before this could happen, however, the basic hypothesis had to be proven, i.e. that such measurements were possible. Acoustic data could be used to identify resonances within received signals caused by intra-compartmental reverberation; alternatively, the total wave-propagation time through the cargo-container of the solid and void elements comprising the cargo within the trailer-container could be measured. Both types of data could form the basis for acoustic tomography of the cargo-container (e.g. the frequency of resonance could be the variable in an image reconstruction). This would be achieved using a scanning system to collect data from acoustic transmission paths through the object, as shown in Figure 1.

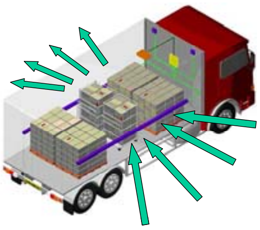

Figure 1. Schematic diagram of tomographic imaging applied to a road cargo container

One major advantage that these methods offer over existing technology is that they would be cheap to manufacture and present little hazard to human health, being non-radiological and non-ionising.

In this study, we have used both Constant Frequency (CF) and Frequency Modulated (FM) signals to investigate the complex propagation medium presented by lorry transported, trailer-container and its cargo. Many practical systems for layered media do not use the classic impulse signal, but use signals with a limited frequency band, and then employ techniques to reduce the reflected or transmitted time series to the impulse response of the medium in which the waves have propagated. Generally, this technique is called ‘pulse compression’ and often employs processes such as the deconvolution or cross-correlation of the signal that was originally transmitted from the recorded time series.

Various types of acoustic signals can be used, and have been tried experimentally. These include: FM chirps (where the instantaneous frequency is linearly changing over the time); stepped chirps (where each frequency or step is coded in an integer number of cycle ensuring a smooth phase continuity between steps), this allows us to apply a classical tools such as Discrete Fourier Transform (DFT) to analyse the signal and estimate the phase, amplitude, and frequency variation with high accuracy; ladder chirps (constructed via a temporal superposition of all the frequencies within the required bandwidth and all frequencies are transmitted or localised over the same time period) [5]; and finally a form of pseudo-random sequence known as a Golay code enables very large S/N ratio improvement when complementary coded signal pairs are used to overcome the self-noise generated by the correlation process.

MODELLING OF RESPONSE

An acoustic transmission line model can be used to model reverberation within bounded, layered media, and thus is useful in the current study to determine the likely response of transport containers. This modelling approach describes a given medium via its characteristic acoustic impedance *Z*, equal to the product of the material bulk density and longitudinal acoustic velocity. Multiple layers are then developed as a transmission line concept. The transmission of acoustic signals through a trailer containing cargo can be treated in this way. Thus, for instance, an empty cargo container could be considered as a reverberant cavity bounded by air, where maximum transmission would occur at specific frequencies. In this work we have used an approach for multiple layers based on transfer matrices. The multi-layered model is shown in Figure 2.

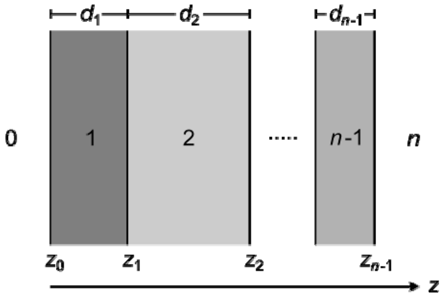

Figure 2. The multi-layer transmission-line model

Predictions of such a model using a linear FM chirp can be illustrated using air-filled cargo (e.g. an empty crate), and an example is shown in Fig. 3. Here, resonances associated with both the crates and the air gaps between the vinyl sides and the crate walls are created. For example, air cavities of 1.45 m width result in a resonance of 136 Hz and cavities of 1.25 m in a resonance of 226 Hz.

In the case of the air-filled crate, where the crate width is 0.50 m, resonances associated with vibrations of the object are also present, e.g. 340 Hz. Reducing the cargo internal cavity dimension from 0.5 m to 0.1 m results in the appearance of significantly greater acoustic energy at frequencies between 20 Hz to 50 Hz. Inspection of these results, and of further analyses of this type of transmission line model, indicates that diagnostic information to determine cavity widths and infill appears to be contained within the signal transmitted through the container to the other side. In Fig.3, the reflected signals are similar in form (but of different amplitude). However, if the crates were positioned asymmetrically, the signals reflected back towards the source would contain more information relating to cavity position (which is not present in through-transmitted signals). Thus, a suitable acoustic cargo screening system would ideally be equipped to record and analyse both transmitted and reflected signals.

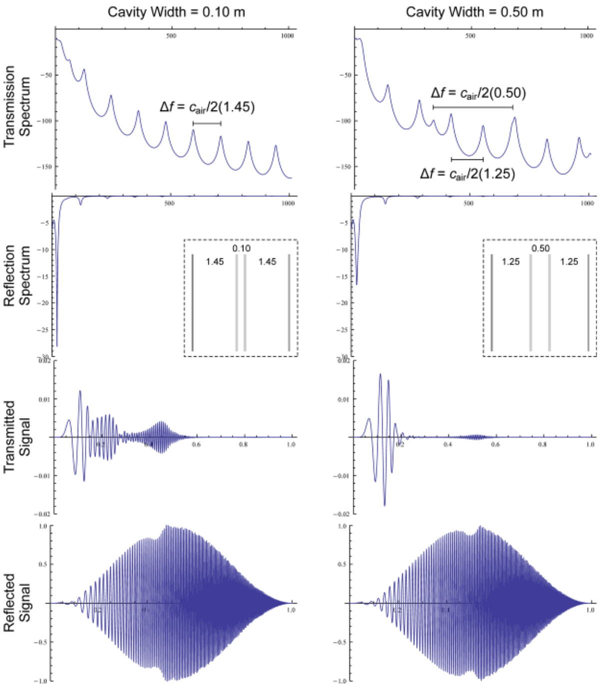

Figure 3. Transmission and reflection spectra and signals for 0.1 m (left) and 0.5 m (right) wide air-filled crates in the centre of the 2m wide cargo space. Insets show model configurations.

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EXPERIMENTAL ARRANGEMENT

A number of small scale experiments were carried out to demonstrate the underlying principals and examine the feasibility of implementing some form of acoustic screening on curtain-sided cargo lorries. The general setup for all these experiments, shown schematically in Figure 4 consisted of a National Instruments PXI system with a NI-PXI-5412 100MS/s arbitrary waveform generator and NI-PXI-5105 60MS/s digitiser controlled with LabView. The Labview program developed for these experiments was capable of generating several standard types of drive signal programmatically, or reading in signals from a file, to drive the arbitrary waveform generator. The output of the arbitrary waveform generator provided the input to an audio power amplifier driving the speaker. On the receiver side, a Brüel &Kjær type 4939 ¼" microphone connected to a Brüel &Kjær Nexus conditioning amplifier was used, the output of which was recorded by the digitiser. The received waveform, FFT and cross-correlation with the drive signal could all be saved for offline processing.

Various different acoustic sources were used. For the higher frequency ranges, a Fountek NeoCD 2.0 ribbon tweeter was used, with a nominal frequency range of 1.2 KHz – 40 KHz, powered by a Yamaha XP1000 power amplifier and protected with a 2 KHz high pass filter. For lower frequencies a conventional 20cm speaker cone was used with the same power amplifier. In addition, for larger scale testing which would simulate a real test, a pair of Quad ESL2905 reference loudspeakers was combined with a Quad 909 power amplifier and Quad 99 preamplifier.

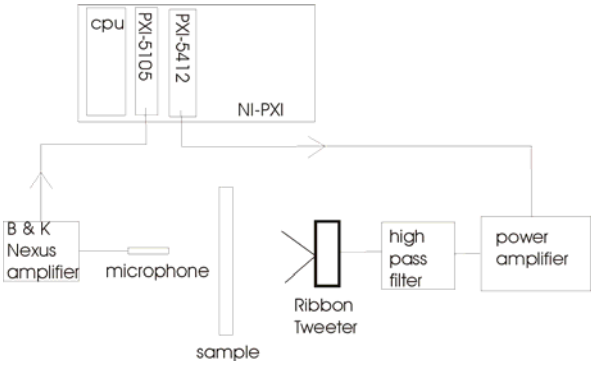
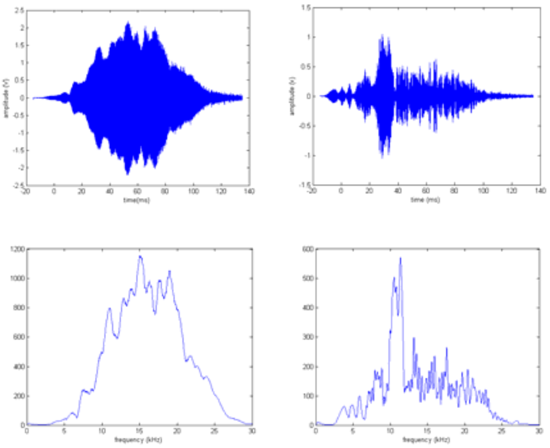


Figure 4. Schematic diagram of experimental arrangement

EXPERIMENTAL RESULTS

Lab-based experiments at higher frequencies

Initial experiments were carried out on the bench in a normal laboratory using the ribbon tweeter, driven with a 2 kHz-30 kHz linear swept frequency chirp with a Hanning window applied, recording the response through a number of samples. Figure 5(a) shows the received experimental signal and spectrum through air with no sample present. Placing a sample between the speaker and microphone produces a significant reduction in signal amplitude - a large proportion of the signal is reflected due to the acoustic impedance mismatch. However, signals can still be recovered. Figure 5(b) shows the result of placing a 16 mm thick box between source and receiver – the expected resonance is observed at approximately 11 kHz.

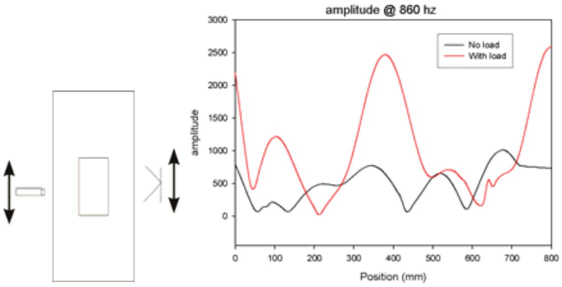


(a) (b)

Figure 5. Acoustic signals (top) and frequency spectra (bottom) of (a) the received signal with no sample present, and (c) in the presence of the 16 mm thick box. The expected resonance is arrowed**.**

In order to simulate something closer to the conditions that would be experienced in trying to image through a curtain sided lorry a wooden box with open sides was constructed to act as a scale model of a curtain sided cargo lorry trailer. The dimension were 600 mm wide x 400 mm high and 800 mm long was constructed, the width being chosen to be ¼ that of a standard lorry, whilst the other dimensions were down to the limitations of being able to get the box into the acoustic chamber rather than trying to keep everything to scale. The open sides were covered with 910 gsm (~0.75 mm thick) PVC sheeting as used on curtain sided lorries.

Primary resonances due to the trailer walls and cavities within a real load would be of the order of a few hundred Hz, or even lower, namely below the frequency range so far investigated. Further tests were thus carried out at lower frequencies with the conventional 20cm cone speaker driven with a 20 Hz-2 kHz linear chirp. To illustrate the type of results that could be obtained, an experiment was performed moving both speaker and microphone together across the container and past the box within it, as shown in Figure 6(a), while transmitting a signal at 860 Hz. It is clear from Figure 6(b) that there is a significant correspondence of received power level with the position of the load within the model, demonstrating that a through-transmission experiment has detected the presence of a crate between the side walls of the simulated trailer.

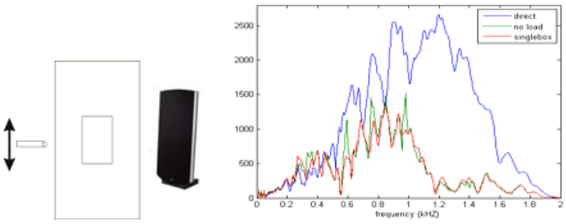


(a) (b)

Figure 6. A microphone and speaker were moved in unison (a) across a single box load at 860 Hz, to give the plot in (b).

Experiments with large sources and different waveforms

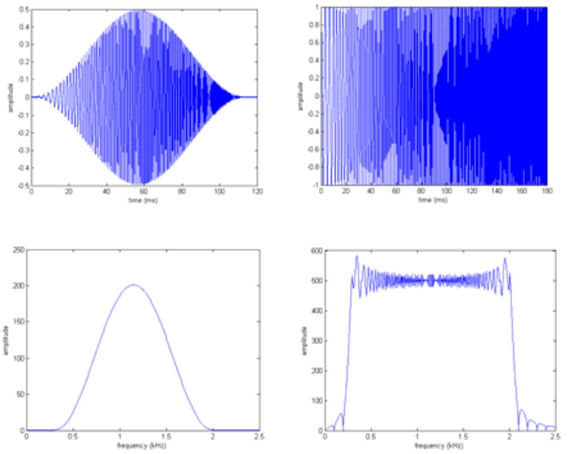
In the experiments detailed so far, the acoustic source has been relatively small compared both to the target and also the wavelength for the lower frequency tests. In any proposed practical system it is envisaged that a much larger loudspeaker, or array of speakers be used. For this purpose we have performed a number of experiments using a Quad electrostatic speaker which is a large (680 mm wide 1400 mm high) reference quality flat panel speaker. This required finding an alternative larger acoustic chamber. Initial experiments repeated some of the previous tests with the model container and loads as before. Figure 7 compares the spectra for no load, a single box and a four box load, demonstrating that it is still possible to see differences between the varying conditions. Note in particular the sharp peak at 600 Hz.



(a) (b)

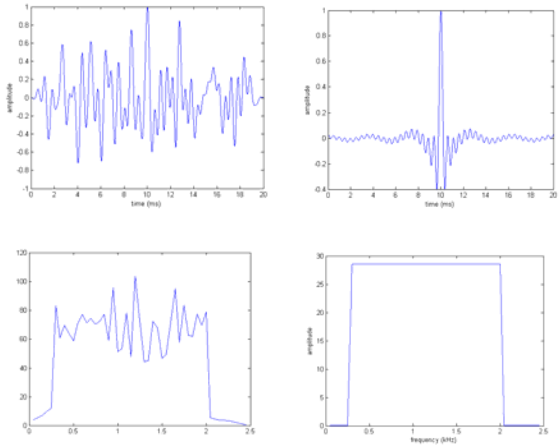
Figure 7. (a) Experiment using a Quad electrostatic loudspeaker. (b) Received spectra using a Quad source driven with a 20 Hz – 2kHz linear FM chirp, showing the direct signal (no container), with an empty container (no load) and with a single box load.

In order to have a larger scale test, two lengths of PVC curtain side material were suspended in the chamber to form parallel walls approximately 2.5m wide x 2 m high, separated by 1.7 m. This is closer to the scale of a lorry trailer. In addition to the linear chirp signals used throughout earlier tests, a stepped chirp, random phase ladder chirp and zero phase ladder chirp, with the same bandwidth were also tested. In addition a time reversal technique, where the received signal is time reversed and retransmitted, was also tried. With the time reversal it was found necessary to apply a high pass filter with a 200 Hz cut-off to avoid overdriving the speakers with very low frequencies at high power. The different drive signals, all with a bandwidth of 300 Hz - 2 kHz, together with their respective frequency spectra, are shown in Figures 8 and 9. These four signals were investigated, to see which would be best for testing containers. It was found that the signal shown in Figure 8(b), the zero phase ladder chirp, was very useful, in that it gave good delineation of extra resonances caused by the introduction of simulated cargo.



(a) (b)

Figure 8. Drive waveforms (top) and spectra (bottom) for (a) a linear chirp, (b) a stepped chirp, (c) a random phase ladder chirp and (d) a zero phase ladder chirp.



(a) (b)

Figure 9. Drive waveforms (top) and spectra (bottom) for (a) a random phase ladder chirp and (b) a zero phase ladder chirp.

Use of a zero phase ladder chirp and time reversal

It was found that the signals provided by modulated signal such as the zero phase ladder chirp gave a lot of information. This is illustrated in Figure 10, where the response of a simulated cargo is shown, both in the presence and absence of a simulated load in the form of a cardboard box. Differences in the spectra can be clearly seen, and there is evidence of additional resonances caused by the cargo. However, these are masked by the other reverberations within the walls of the container, the responses of the loudspeaker, other propagation effects and other outside influences.

While these masking effects could be removed systematically from the measurement, using forms of deconvolution, it was thought that a better approach was to use time reversal techniques. The result was a marked increase in clarity, with resonance detected with a much increased signal to noise ratio, and with a better discrimination from the background.

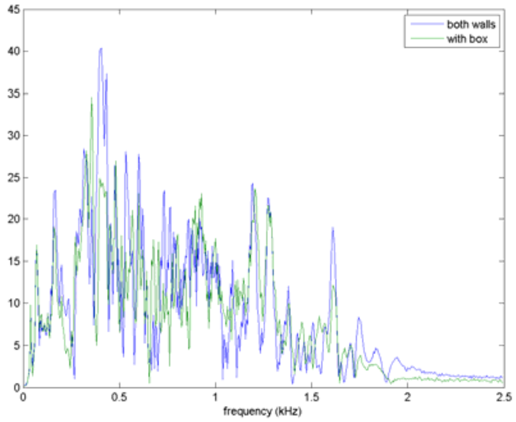


Figure 10. Spectra obtained using a zero phase ladder chirp as the transmitted acoustic waveform for the larger container, botht with the cargo absent (labelled “both walls”) and in the presence of a cardboard boc (“with box”).

This is illustrated in Figure 11, where the result of two time reversal operations is shown. The time reversal has highlighted the reverberations within the container, while suppressing those that were not associated with these resonances.

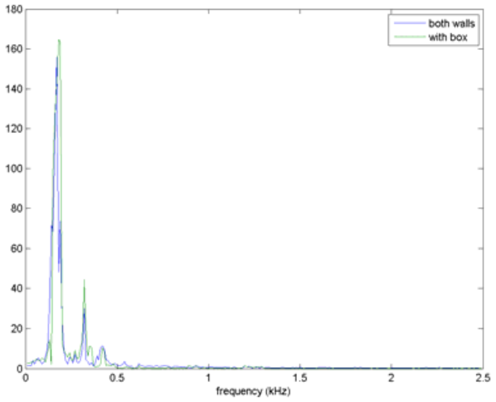


Figure 11. The result of processing the data of Figure 9 using time reversal techniques.

CONCLUSIONS AND FURTHER WORK

This feasibility study has shown that it is indeed possible to use acoustic signals to collect data from conventional cargo containers, as used on the roads of the EU. These tend to have flexible curtain side walls. A simulation using a transmission line model has shown that

through-transmitted acoustic signals would contain information concerning the size of crates within the container, whereas extra information would also be obtained from reflected acoustic signals (e.g. the relative position of cavities). The form of these signals was studied. It was shown that broad bandwidth signals would be required, to collect the reqired spectral information. While linear FM chirps are a good signal for many measurements, there may be real advantage to be gained by using a zero phase ladder chirp, especially when combined with time reversal techniques.
It is thus concluded that this feasibility study has been a success, in that it has demonstrated for the first time that acoustic signals can be used to characterise such containers. The type of information shown in Figures 9 and 10, which were collected using a realistic acoustic source and real trailer curtain walls, shows that data such as resonant frequencies can be measured.

Such data sets could be used along multiple paths to provide images using tomography. Hence, the concept of acoustic resonance tomography is a real practical possibility for acoustic cargo screening. The exact geometrical approach that could be considered would need to be determined. However, a linear array of acoustic sources on either side of the container, together with a similar array of microphones, could be used very effectively to capture acoustic signals along selected paths through the object. It is hoped that this work will commence in due course.

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