SWEPT FREQUENCY MULTIPLICATION (SFM) TECHNIQUES FOR IMPROVED AIR-COUPLED ULTRASONIC NDE

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ABSTRACT. A new technique has been investigated for improving the signals that can be obtained in air-coupled NDE. This relies on the broad bandwidth available from polymer-filmed capacitive transducers. The technique relies on a swept-frequency “chirp” signal, which is transmitted from a transducer in air, passes through the sample under test, and is then detected at the far side using a separate receiver in through-transmission. The new technique differs from existing time-domain correlation techniques, such as pulse compression, in that a single multiplication process is performed in the time domain to give a difference frequency signal. This can then be easily isolated in the frequency domain. It will be demonstrated that this new Swept Frequency Multiplication (SFM) approach gives excellent resolution between overlapping signals, and indeed has several potential advantages over pulse compression. Examples will be shown of air-coupled images, obtained using SFM processing, which demonstrate the wide application of the technique to air-coupled NDE.

INTRODUCTION

In many ultrasonic experiments, there is a need to improve the accuracy of an individual measurement, while also trying to improve the signal to noise ratio (SNR). There are many techniques available for signal enhancement, such as signal averaging and correlation techniques that could be used to recover a wanted signal from noise. This paper describes a new technique known as Swept Frequency Multiplication (SFM). This technique makes use of a swept frequency or “chirp” signal, and is a modification to a technique in optics known as Optical Frequency Domain Reflectometry (OFDR). The OFDR technique has been widely used to solve Fresnel reflections for optical fiber links and it has good time accuracy [1-3]. With this technique, useful information is obtained from the frequency domain so that time-domain signals can be extracted. The SFM technique is now applied to an ultrasonic system using two broadband capacitance transducers. This paper describes the basis of the technique, and the resulting characteristics and performance, when applied to the particular case of air-coupled testing.

THEORY OF THE SFM TECHNIQUE

Consider the case where the voltage drive waveform is a linear FM frequency sweep (or chirp). This is shown in Figure 1 as signal A, where the frequency is increasing...
FIGURE 1. Expected results of the SFM technique (a) when the transmitted and received signals are two broadband signals (b) when the transmitted signal is broadband while the received signal is narrow band.

as a linear function of time to give the inclined straight line shown. This is the reference signal that will be used for multiplication. The signal detected after transmission through air and/or a sample is assumed to be delayed version of the same waveform, and this is shown as line B.

The recovered signal (B) is now multiplied by the original reference signal (A). The result is sum and difference frequencies. The difference frequency, $f_d$ exists only in the time region where the two signals overlap, i.e. between the vertical dotted lines shown. As both signals have the same slope, in Figure 1(a), the difference frequencies $f_d$ will be a horizontal line on the same graph as shown. The selection of $f_d$ is a simple matter of applying a low pass filter. The result will be a single spectral peak, with a low noise level.

Note that the value of $f_d$ is a measure of the propagation time delay from source to receiver, and will be an accurate method for time of flight measurement. The sum frequency $f_s$ will have a more complicated form, shown as a linear increase in slope in the figure. However, if the received signal is a single frequency (arising from the resonant frequency of the test sample), the multiplication process will give the sum and difference of two broadband components at high and low frequencies, as shown in Figure 1(b).

Assuming that the generated chirp has constant amplitude, multiplication of two chirp signals is given by:

$$ M(t) = \sin(2\pi f_1 t + \frac{\pi B t^2}{T}).\sin(2\pi f_1(t + \tau) + \frac{\pi B (t + \tau)^2}{T}) \quad 0 \leq t \leq T $$

where
B – bandwidth of the chirp signal, $f_2$-$f_1$
$\tau$ – delayed time
T – duration of the chirp signal

This can be further simplified using the trigonometrical identities into,
Equation (2) shows that there are two frequencies resulted from sum and difference. If there is no delay, i.e. $\tau=0\ \mu s$, the above equation then becomes:

$$M(t) = \frac{1}{2} \left( \cos \left( 2\pi f_0 t + \frac{2\pi B t}{T} + \frac{\pi \tau^2 B}{T} \right) - \cos \left( 4\pi f_0 t + 2\pi f_0 \tau + \frac{2\pi B \tau^2}{T} + \frac{2\pi B \tau}{T} + \frac{\pi \tau^2 B}{T} \right) \right)$$ (2)

This shows that, under such conditions, the first frequency term in Eq. (2) is zero while the second frequency spectrum has been doubled.

SIMULATION OF THE SFM TECHNIQUE

In order to illustrate this technique, a reference signal is required. This is as shown in Figure 2(a). The chirp signal has a central frequency of approximately 1.15 MHz and a bandwidth of 2.1 MHz. The duration of the chirp is set to 50$\mu$s. Assuming that the chirp signal is transmitted across air and a test sample, the signal level is reduced and it is partially embedded in noise. This is as shown in Figure 2(b). The noisy signal is then filtered within the chirp bandwidth, i.e. from 100kHz to 2.2MHz.

In order to implement the technique, multiplication of the transmitted chirp must be within the duration of the reference chirp (i.e. there must be some overlap between A and B in Figure 1). In the situation where the delay time caused by ultrasonic propagation is greater than the duration of the initial reference chirp, the position of the reference chirp can be shifted in time so that it is close to the received chirp. The frequency spectrum of the multiplied signal is as shown in Figure 3(a). The FFT spectrum shows a narrow band

![Figure 2](image-url)

**FIGURE 2.** (a) A reference chirp signal at $t = 0\mu s$ and (b) Transmitted chirp signal embedded in noise, delayed by 12$\mu$s.
component as a sharp spectral peak at approximately 500kHz and a wideband frequency range above 1MHz. There are two methods to extract the information from the frequency spectrum of the multiplied signals. In order to extract the transmitted signal with the first technique, a band pass filter is applied at 500kHz. This is as shown in dashed line in Figure 3(a). The filtered signal is as shown in Figure 3(b). The arrival time of the signal is at about 12μs and it can be seen that the noise has been removed.

The second method is based on the chirp slope characteristic, as shown in Figure 4. In this case the slope of the chirp is given by 0.042MHz/μs. In Figure 3(a), the peak narrow frequency is found to be at ~500kHz. By dividing the slope and the peak value, the time of arrival of the signal was found to be ~12μs.

EXPERIMENTAL SETUP OF THE SFM TECHNIQUE

The SFM technique was applied to an ultrasonic air-coupled system. Two broadband capacitance transducers [4] were separated by 110mm. The source transducer was driven by a chirp signal together with a dc bias of +200V. The chirp signal had a central frequency and bandwidth of 300kHz. The duration of the chirp was set to 250μs.
FIGURE 5. Experimental setup for ultrasonic imaging.

As before the receiver was connected to a Cooknell charge amplifier. The output of the amplifier was then fed into a Tektronix oscilloscope and then stored in a PC. Further signal processing such as multiplication and filtering were performed offline using Matlab™ software.

To illustrate the use of the SFM signal processing technique for ultrasonic imaging, a through transmission imaging system was established, using the same pair of capacitive transducers scanned as a fixed pair across flat plates of material. This is illustrated in Figure 5. When the transducers had been carefully aligned, the chirp signal that had propagated across the air medium was recorded. This was taken as a reference signal. After recording the signal, a composite fibre plate of thickness 17.7mm was placed in the air path, and a through-transmitted signal again recorded. Imaging was also performed. Firstly, a piece of Perspex of thickness 12.7mm was tested. The plate contained a square, flat-bottomed hole with an area of 13mm x 13mm and a depth of 4mm machined in one surface. Secondly, a 16 ply uni-directional carbon-fibre reinforced composite plate of thickness 3.1mm was investigated. This sample had an internal defect, inserted into it during manufacture, which was made of pre-cured ply containing random chopped fibres. The area of the defect was approximately 25mm x 25mm. In order to perform a raster scan, the pair of transducers was moved using two linear stages (X and Y axis). An area of 50mm x 50mm was scanned.

RESULTS AND DISCUSSION

Figure 6(a) shows the transmitted chirp signal across the air gap of 110mm, and Figure 6(b) shows the waveform across the composite plate. It can be seen that the latter signal has a lower signal to noise ratio (SNR) and has a lower amplitude. As the velocity of the signal through the solid plate is higher than in air, the reference signal is shifted so
that the arrival time is reduced. The signal in Figure 6(b) was then multiplied with the shifted reference signal. The spectrum of the multiplied signal (SFM signal) is as shown in Figure 6(c). The lower frequency component is more prominent compared to the higher frequency. Hence, by applying a band pass filter centred at approximately 62kHz, the wanted component is obtained as shown in 6(d). It can be seen that the noise component has been clearly removed. By comparing Figures 6(b) and 6(d), it can be seen that the signal has been shifted by about 50μs. Hence by using the slope technique, the time of arrival was found to be shifted by ~52μs, with a slope of 1.2kHz/μs.

Finally a raster scan was conducted on the Perspex plate of thickness 12.7mm, to illustrate the SFM technique. The chirp signal was transmitted through the sample and detected by the receiver was subsequently multiplied with a reference chirp, and the resultant multiplied signal then filtered at the selected $f_d$ value. The image after the SFM technique was applied is as shown in Figure 7, for (a) peak amplitude and (b) time of arrival of the chirp. In these figures, the area of defect is represented by dark contours. The area of defect in Figure 7(a) is slightly larger than 13mm x 13mm, due to the resolution of the transducer aperture and the scanning resolution.
FIGURE 7. Images of the defect in the Perspex plate using SFM technique (a) Peak amplitude, and
(b) Time of arrival.

FIGURE 8. Images of the defect in the composite plate using SFM technique (a) Peak amplitude and
(b) Time of arrival.

The Perspex sample was then changed to a 16-ply UD composite plate of thickness 3.1mm. The resulting image of the 25mm x 25mm artificial defect is as shown in Figure 10. In Figure 8(a), the reduction in signal amplitude represents the presence of an anomaly within the scan area. This can also be shown using the time of arrival, which gives a better image, as in Figure 8(b). These figures clearly illustrate the position of the defect.

CONCLUSIONS

A new signal processing technique has been developed using a broadband chirp signal. The SFM technique is another new approach to recover signal from noise in air-coupled experiments. The advantages are:
• The captured noisy signals were transferred to a lower frequency band, \( f_d \). At \( f_d \), the signal can be easily filtered and amplified.
• Like the pulse compression technique, the long pulse and broad bandwidth of the chirp signal can be used to transmit high levels of ultrasonic energy and thus give a good SNR.

REFERENCES