FREQUENCY MODULATED (FM) TIME DELAY-DOMAIN THERMAL WAVE TECHNIQUES, INSTRUMENTATION AND DETECTION: A REVIEW OF THE EMERGING STATE OF THE ART IN QNDE APPLICATIONS

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INTRODUCTION

In this work, the concept of the frequency modulation (FM) technique is applied to thermal wave systems. Heyser [1] introduced this technique in the field of acoustical measurements of loudspeakers and named it time delay spectrometry (TDS). Through its implementation and long-term use in acoustic engineering, TDS has been shown to outperform any other time selective technique with respect to noise rejection and nonlinearity suppression from measurements of systems with linear behavior [2]. The time delay technique, based on a linear frequency sweep of the excitation function, has been specifically compared to the impulse response transformation method and the wide-band random noise method [3] and has been proven to have superior measurement dynamic range properties. The present first application of TDS to a thermal wave system and subsequent comparison with a pseudo-random noise method has shown that our FM technique is superior to the more conventional types of excitation and signal analysis, consistently with conclusions presented in Ref. [3].

THEORETICAL BACKGROUND

The excitation function in a TDS system is characterized by an excellent dynamic range. This is a direct consequence of its nature as a minimum phase system [4]. As such, the instantaneous value of the frequency-like quantity \( f_1(t) \) is given by [1]

\[
f_1(t) = \left( \frac{\Delta f}{f} \right) t + f_c
\]

where \( \Delta f = f_2 - f_1 \) is the carrier signal modulation bandwidth, \( f_c = \frac{1}{2}(f_2 + f_1) \) is the average carrier frequency, \( T \) is the total sweep period, and \( S = \Delta f / T \) is the (constant) sweep rate (in Hz/s). Assuming the excitation function to be a cosinusoidal carrier wave, an FM thermal wave system input will be given by

\[
X(t) = A(t) \cos[\phi_1(t)]
\]

where \( A(t) \) is the amplitude modulation (AM) function, usually chosen to be constant. \( \phi_1(t) \) can be shown to be [5]

\[
\phi_1(t) = (\pi S)^2 + \omega_c t + \phi_0
\]

where \( \phi_0 = \phi_1(0) \) is the input phase at \( t=0 \).
The experimental conditions chosen for thermal wave measurements are [6-8]: \( \phi_0=0, \phi_1=0, \) and \( \phi_1(T+\delta t)=\phi_1(\delta t) \) for \( \delta t>0 \); and \( A=\text{constant} \). These correspond to a linear sawtooth frequency sweep between DC and \( f_2=f_{\text{max}} \) with multiple fast repetitions of the sweep process every period \( T \) (chirp). The signal generated using the linearly swept wave \( X(t) \) of eq. (2) is a special case of the more general class of Phase-angle Modulated systems [9]. It is in this context that TDS thermal wave excitation can be regarded as similar to a Frequency Modulated (FM) wave, with the time integral of the applied swept wave

\[
m(t)=2\pi\int_0^t (\Delta f/T)q \, dq
\]

in eq. (3) acting as the FM wave modulating the baseband signal \( f_C \).
In either case the instantaneous frequency \( f_1(t) \) is the sum of the time-varying component and the unmodulated carrier wave, \( f_C \).

EXPERIMENTAL

The first reported photothermal wave system with FM Time Delay Domain optical excitation is a recent photothermal deflection spectroscopic (PDS) apparatus assembled in our laboratory [7] and shown in Fig. 1. We investigated the performance of the PDS apparatus using a blackbody reference sample (anodized aluminum) in water, as well as thin quartz films of variable thickness. A fast beam position detector was fabricated using a pinhole-photodiode arrangement with a 34 ns response time. The excitation beam from a 2 W Nd\(^{3+}\):YAG pump laser was expanded over the sample in order to facilitate the (one-dimensional) theoretical interpretation of the data. Frequency modulation of the pump beam intensity was effected using an HP 3325A Synthesizer/Function Generator. The system output was registered as a photo-voltage whose amplitude was proportional to the spatial deflection of the He-Ne probe beam due to the Mirage effect [10]. All the necessary Frequency and Time Domain functions were calculated via a Nicolet Scientific Corp. Model 660A dual channel FFT analyzer.

The magnitude and phase of the complex transfer function \( H(f) \) of the blackbody/water interface is shown in Fig. 2(i). These data were taken between DC (\( f_1=0 \)) and 1280 Hz (\( f_2 \) in eq. (1)) with \( T=0.41 \) sec and a sweep rate \( S=3.122 \) kHz/sec applied to the acousto-optic modulator. Correlation and spectral processing, averaged over 1000 frequency sweeps with 1024 data points per sweep, required approx. 6-7 min. This time can be reduced, however, to be as low as 1 min., corresponding to a minimum number of ca. 200 sweeps/average. This time is by far shorter than the time required to obtain the same information dispersively using lock-in detection as in Fig. 2 (ii). The reliability of the data shown in Fig. 2(ii) is, furthermore, inferior to that of Fig. 2(i), as the mean of only 20 samples per average was taken over 14 data points. From this comparison it was concluded that the superior speed and reliability of the FM Time Delay system make it a very attractive candidate for thermal mapping or depth-profiling applications in environments requiring fast turn-around, such as industrial quality control laboratories. Using a raised Hanning FIR filter (i.e. cosine to the fourth power window [2]), the input autocorrelation function \( R_{XX}(\tau) \) was found to be extremely narrow on the time scale of the PDS experiments and could be accurately approximated by the Dirac delta function. It thus follows [5] that the input-output cross-correlation function is equal to the unit impulse response of the system: this was also verified experimentally [7].
Fig. 1. FM time delay mirage effect spectrometer; 1: Nd\(^{3+}\):YAG pump laser; 2: cw 1.06-\,\mu m beam; 3: acousto-optic (A/O) modulator; 4: alignment lens; 5: water; 6: sample; 7: sample holder; 8: He-Ne probe laser; 9: 632.8-nm probe beam; 10: focusing lens; 11: optical lever reflector mirror; 12, 13: lenses; 14: 50-\,\mu m-diam pinhole; 15: He-Ne beam interference filter; 16: fast rise-time photodiode; 17: wide bandwidth preamplifier; 18: dual channel FFT analyzer; 19: synthesizer/function generator; 20: A/O modulator driver; 21: A/O driver power amplifier; 22: A/O modulator power supply; 23: computer memory storage. \(X(t)\) and \(Y(t)\) are identified with input and output system functions, respectively.

Fig. 2. i) Magnitude (a) and phase (b) of the complex transfer function \(H(f)\) of the blackbody/water interface at 10 \,\mu m probe beam offset, using the FM Time Delay Domain PDS apparatus. ii) Same data obtained using lock-in detection.
The spectrometer was further used to measure the response from thin microscope quartz slide layers in direct contact with the backing material (anodized aluminum support). A single slide cut in many pieces was used for these experiments, to assure material uniformity. Each piece was etched in 50% HF: 50% H₂O down to the desired thickness. Fig. 3 shows a superposition of the impulse responses for two different thicknesses, 30 µm (curve a) and 100 µm (curve b). The cross-correlation functions show similar features, i.e. an increased peak delay time, a broadened FWHM and an increased trough time delay τ_min with increasing thickness. In each case data were taken at beam offset positions which maximized the PDS output at the detector.

The secondary oscillations on both wings of the main pulse in Fig. 3 were found to be consistent with thermal energy arrivals at the sample surface after multiple reflectins at the sample-backing interface. The delay time Δτ between two successive peaks corresponded roughly to twice the thermal transit time τ_transit=1/2α₂ through the bulk of the sample. Similar effects have been predicted theoretically by Burt [11] in fluids excited by pulsed lasers, and have been observed experimentally in liquids and solids by Tam et al. [12,13].

A theoretical model for the impulse response of the PDS system was also presented by us in Ref. [7], where we calculated the peak delay time τ₀ from the heat conduction Green's Function of the composite system:

\[ \tau_0 (l) = \frac{l^2}{6\alpha_3} \left[ 1 + \frac{\alpha_3}{\alpha_2} \right] \left[ \frac{l}{L_0} \right] \]

where \( \alpha_1, \alpha_2, \alpha_3 \) are the thermal diffusivities of the backing material, quartz layer and water, respectively; and \( l, L_0 \) are the quartz layer thickness and probe beam offset at the beam-waist, respectively. A fit of (5) to the data gave a value for \( \alpha_2 \) in good agreement with the published value [14]. Further experimentation with silicon wafer samples, on which 1 µm thick field SiO₂ oxides were grown thermally, showed that the FM

Fig. 3. Impulse response functions from quartz layers of thickness 30 µm (a) and 100 µm (b). \( \tau_0^a = 4.69 \text{ ms}, \tau_0^b = 6.04 \text{ ms}, \tau_{\text{FWHM}}^a = 0.42 \text{ ms}, \tau_{\text{FWHM}}^b = 0.39 \text{ ms}, \tau_{\text{min}}^a = 32.81 \text{ ms}, \tau_{\text{min}}^b = 10.94 \text{ ms}, \tau_{\text{FWHM}}^b = 28.6 \text{ ms}, \tau_{\text{min}}^b = 42.97 \text{ ms}. \)
Time Delay Domain technique was quite sensitive to the presence of such oxides on the silicon surface [7]. These results were deemed promising for the future of the technique as a non-destructive semiconductor probe capable of replacing the pulsed laser excitation conventionally used [12], the two main advantages of the FM method being a) its much higher pulse tolerance threshold on sensitive materials such as those used in optoelectronic and microelectronic applications; and b) its higher dynamic range than that of the impulsive excitation.

We [8] further made a detailed comparison between the FM Time Delay and the Pseudo-Random Binary Sequence (PRBS) method [15] of optical excitation and Mirage effect response. Fig. 4 shows a comparison of the auto-correlation functions $R_{XX}(\tau)$ and $R_{YY}(\tau)$ of inputs and outputs, respectively, of the two techniques. In Fig. 4b the secondary peaks of the PRBS input autocorrelation function are clearly seen at the onset of the second multiple of the frequency band spanned by the PRBS pseudo-period. These spikes are also present in the PRBS output autocorrelation, albeit much more broadened and of much lower magnitude. A comparison of $R_{XX}(\tau)$ between Figs. 4a and 4b shows that the PRBS function is more broadened than the FM Time Delay function on the time scale of the experiment. Therefore, it is expected that the PRBS $R_{XX}(\tau)$ convolution with the impulse response (i.e. the input/output cross-correlation function) will be somewhat broader than the PRBS impulse response function $h(\tau)$, a fact borne out by the experiments. On the other hand, the narrow $R_{XX}(\tau)$ of the FM Time Delay spectrometer is a closer representation of a Dirac delta function than the PRBS counterpart and produces essentially identical lineshapes between $h(\tau)$ and $R_{XY}(\tau)$.

![Fig. 4. Autocorrelation functions of system input and output: (a) FT Time Delay spectrometer; (b) PRBS spectrometer.](image-url)
Fig. 5 is a comparison between the coherence functions obtained from the signal inputs and outputs for the two techniques. The coherence function is a most sensitive indicator of the quality of the relation between input and output. The superior performance of the FM Time Delay spectrometer is unequivocally exemplified in this figure. Essentially no correlation can be found above 600 Hz for the PRBS method, while a strong relation between input and output well beyond 1 kHz is observed for the FM Time Delay system. The dips in the coherence functions are due to non-system related signal sources, such as line ripple and multiples of 60 Hz. These sources are completely deterministic at well-defined frequencies and they do not appear in the statistics of the coherence function. The coherence of the PRBS system exhibited large discrete sawtoothed band components with peaks and valleys of rapidly varying functional quality of the relationship between input and output. This resulted in a poor signal-to-noise ratio of the transfer function $H(f)$, as seen in Fig. 6. This figure indicates the degree of dynamic range superiority of the FT Time Delay spectrometer to that of the device operating with a PRBS excitation. The exceptional quality of the FM Time Delay spectrometer transfer function is intimately related to the quality of the impulse response, whose Fourier transform the transfer function is.

![Fig. 5. Coherence functions: (a) FT Time Delay spectrometer; (b) PRBS spectrometer.](image-url)
CONCLUSIONS

1. FT Time Delay and Pseudo-Random thermal wave methods are both suitable for nondestructive depth profiling of materials thermally and spectroscopically.

2. Advantages over frequency-domain methods:
   a) Much faster data acquisition and frequency response processing than lock-in detection.
   b) Better layer separation in time delay than dispersive thermal wave phase lag measurements.

3. Advantages over pulsed laser methods:
   a) Much higher thermal destruction/degradation tolerance threshold due to sequential deposition of laser energy.
   b) Higher dynamic range of the FT Time Delay method.

4. FT Time Delay is superior to PRBS in spectral function processing and signal quality. It holds great promise in NDE of delicate and sensitive materials, such as microelectronic and optoelectronic structures, probing of poor thermal conductors, ceramic subsurface flaw imaging etc.
REFERENCES