Calibration of Air-Coupled Transducers for Absolute Nonlinear Ultrasonic Measurements

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Motivation

Absolute Nonlinear Ultrasounds (NLU)

• Absolute NLU has the potential to detect material degradation and provide quantitative information about substructural changes in a material
• Precipitates and dislocations form in material
• Generation of a second-harmonic component in a monochromatic signal

This leads to a change in the material nonlinearity

Air-Coupled Transduction

• Air-coupled transducers are preferable for their low cost and greater robustness over other receiver technologies due to lack of dependence on contact and surface conditions
• Air-coupled transducers must be calibrated in order to provide absolute measurement data
• Standard pulse-echo (self-reciprocity) calibration doesn’t work because of low power output from the transducer

Objectives

• Calibrate an air-coupled transducer by experimentally identifying its force/voltage transfer function with a model-based, pitch-catch experimental configuration
• Confirm calibration with laser interferometer measurements of excited material surface

Theoretical Background and Methods

Second Harmonic Generation

• Material nonlinearity is measured when material defects and microstructural effects cause a monochromatic wave to distort into a fundamental (ω) and second harmonic (2ω) component
• For longitudinal waves, material nonlinearity is denoted by β and adheres to the relationship:

\[
\beta = \frac{8 A_2}{A_1^2 \omega^2 x^2}
\]

where \( A_1 \) and \( A_2 \) denote absolute amplitudes of fundamental and first harmonic wave frequency components

Multiple Gaussian Beam Modelling

• Computationally efficient method to model longitudinal wave propagation
• Source velocity expressed as sum of Gaussians, which propagate as Gaussians:

\[
V_1(t) = \sum_m A_m \exp \left( -\frac{V_m^2}{2} \right)
\]

• Source velocity is translated to pressure via the following relationships:

\[
\beta(x) = \rho V_1 \omega^2 \exp (\omega x) \left[ N_2(\beta(x), x) - N_2(\beta(0), 0) \right] \left[ P_2(\beta(x), x) - P_2(\beta(0), 0) \right]
\]

\[
\frac{\partial P_{2m}(\beta, x)}{\partial x} = \int_0^\infty \int_0^\infty \frac{P_{2m}(\beta', x')}{2\pi} \exp \left(-\frac{(x-x')^2}{2\sigma^2} \right) \exp \left(-\frac{(\beta-\beta')^2}{2\sigma^2} \right) \, dx' \, d\beta'
\]

• Pressure is then integrated over transducer surface to calculate received force for calibration

Experimental Setup

(1) RITEC 2500GA: Sinusoidal signal generation (1.8 MHz, 12 cycles)
(2) Lithium niobate transducer: Excitation of longitudinal wave in material, oil-coupled
(3) Material Sample: Aluminum 2024 or Fused Silica
(4) Ultrasonic NCT4-D6 air-coupled transducer: Detection of plane wave
(5) Oscilloscope: Tektronix TDS5034B Digital Oscilloscope

Results and Discussion

Measurement Results

Aluminum Laser Scan Air Transducer Surface

Linear

Nonlinear

Data Fitting and Extraction of \( \beta \)

• Window time-domain waveform to extract steady state signal
• Waveform undergoes FFT to extract amplitudes \( A_1 \) and \( A_2 \), fundamental and first harmonic frequencies
• Plot transducer transfer function
• Employ best fit optimization to calibrate transducer parameters

Conclusions

• Air-coupled transducers can be calibrated inexpensively using a contact transducer and a material with known nonlinear properties
• A computational multiple Gaussian beam model is provided and confirmed by laser interferometer results from material surface vibrations
• Measurement of \( \beta \) matches expected value from literature

References