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Ultrasonic broadband characterization of a viscous liquid: Methods and perturbation factors

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A B S T R A C T

The perturbation factors involved in ultrasonic broadband characterization of viscous fluids are analyzed. Precisely, the normal incidence error and the thermal sensitivity of the properties have been identified as dominant parameters. Thus, the sensitivity of the ultrasonic parameters of attenuation and phase velocity were measured at room temperature in the MHz frequency range for two reference silicone oils, namely 47V50 and 47V350 (Rhodorsil). Several methods of characterization were carried out: time of flight, cross-correlation and spectral method. These ultrasonic parameters are measured at room temperature. For this family of silicone oil, the dispersion of the attenuation spectrum is modeled by a power law. The velocity dispersion is modeled by two dispersion models: the quasi-local and the temporal causal. The impact of the experimental reproducibility of the phase velocity and acoustic attenuation was measured in the MHz frequency range, using a set of ultrasonic transducers with different center frequencies. These measurements are used to identify the dispersion of the ultrasonic parameters as a function of the frequency.

A first experimental and descriptive approach is developed to assess the reproducibility of the normal incidence between the acoustic beam and the viscoelastic material. Thus, the relative error on the measurements of velocity and attenuation are directly related to the angular deviation of the ultrasonic wave, as well as the sampling and signal-to-noise ratio. A second experimental and phenomenological approach deals with the effect of a temperature change, typical of a polymerization reaction. As a result, the sensitivity of the phase velocity of silicone oil 47V50 was evaluated around $-2\ \mathrm{m\,s^{-1}\,K^{-1}}$.

1. Introduction

Ultrasonic techniques in non destructive testing (NDT) or non-destructive evaluation (NDE) have proven to be useful in several material evaluation areas. The measurements of velocity and attenuation dispersions are the most important factors in the monitoring of several properties such as ageing of a structure [1], viscoelastic behavior [2], polymer cure [3–10] and porosity characterization [11]. Reproducibility at normal incidence and temperature sensitivity has an important effect on dispersion acoustic parameters. In this paper, a measurement method is proposed for the ultrasonic characterization of a fluid layer by several methods: time of flight, cross-correlation and spectral method. Their impact is studied in the context of an application on a production monitoring of composite plates by RTM. The dispersion in attenuation characteristic is modeled by power law [12–14]. The velocity dispersion is modeled by Szabo [15] and O'Donnell et al. [16]. In normal incidence, the error of distance measurement, the relative error of time due to the sampling measurement and the relative error of time due to the signal–noise ratio (*SNR*) present a major impact on acoustic parameters. Furthermore, the sensitivity of the phase velocity to temperature is evaluated as an essential parameter. The article is divided into three parts: the first presents the equations for measuring the acoustic properties; the second part describes the proposed experimental setup and the results of reproducibility of the normal incidence and the sensitivity to temperature. In the third part, acoustics parameters were measured using several methods for two reference silicone oils by different center frequency transducers in the MHz range. Viscosity is evaluated using the Cole–Cole model [17].

2. Theory

2.1. Velocity and attenuation calculations

In order to characterize ultrasonic velocity and attenuation in the fluid samples, we placed the fluid in a tank. The measurements were carried out at normal incidence which corresponds to the

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maximum acoustic energy signal. Considering the first round-trip signals $s_1(t)$ and $s_2(t)$, measured at two positions d_{ref} and $d_{ref} + \Delta d_{oil}$ respectively (Fig. 1(a)), the arrival times and maximum amplitudes of the first round-trip echoes are denoted as (t_1, A_1) and (t_2, A_2), respectively.

2.2. Time of flight method

Using the time of flight method, the velocity $c_{oil,t}$ (Eq. (1)) is expressed as a function of $\delta t_{tof} = t_2 - t_1$ and the attenuation $\alpha_{oil,t}$ (Eq. (2)) is related to the echo amplitude ratio A_1/A_2:

$$c_{oil,t} = \frac{2\Delta d_{oil}}{\delta t_{tof}} \tag{1}$$

and

$$\alpha_{oil,t} = \frac{1}{2\Delta d_{oil}} \log\left(\frac{A_1}{A_2}\right) \tag{2}$$

Some alternative are based on those time of flight methods. Particularly, the time of flight δt_{tof} can be estimated using the rising time δt_{10} or δt_{20}, at 10% or 20% of the maximum of the envelope of the round-trip echoes, respectively. In the case of the amplitude ratio A_1/A_2, it can be estimated using the ratio between the maximum of the rectified echoes or the ratio between the maximum of the envelope of the echoes.

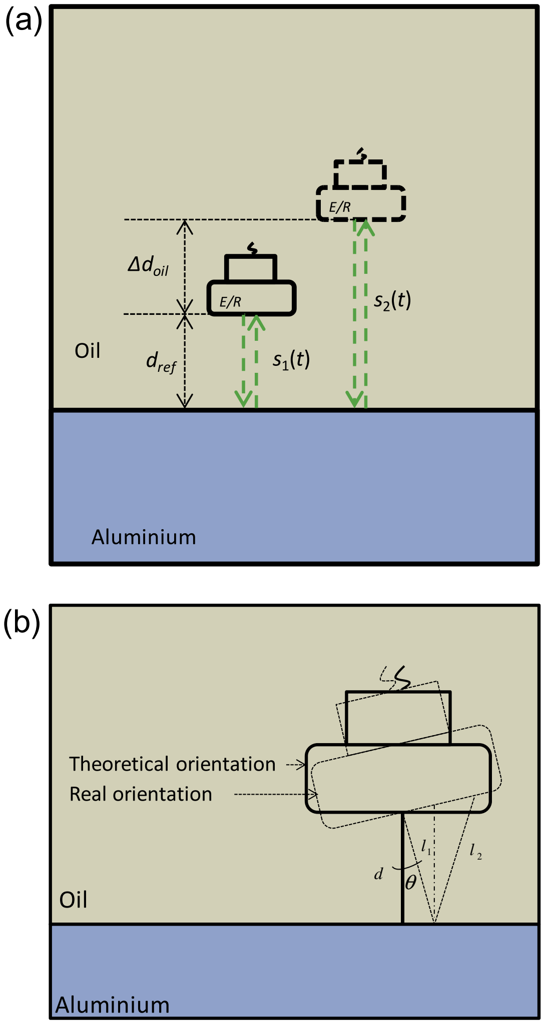

Fig. 1. Experimental setup (a) with the two positioning configurations, and (b) associated incidence discrepancy relative to the normal theoretical case.

2.3. Cross-correlation method

The cross-correlation technique is commonly used to calculate time delay δt_{cor} between two signals supposed to have the same shape (no distortion). The cross-correlation function between the two signals $s_1(t)$ and $s_2(t)$ is written as:

$$cor_{s_1/s_2}(t) = \int_{-\infty}^{+\infty} s_1(\tau)s_2(\tau + t)d\tau \tag{3}$$

The time of the maximum of this cross-correlation function (Eq. (3)) corresponds to the characteristic time delay δt_{cor} between $s_2(t)$ and $s_1(t)$. Using time cross-correlation technique, the phase velocity $c_{oil,t,cor}$ is written as:

$$c_{oil,t,cor} = \frac{2\Delta d_{oil}}{\delta t_{cor}} \tag{4}$$

In addition, the attenuation can be evaluated by the normalized cross-correlation $r_{s1/s2}$ between $s_1(t)$ and $s_2(t)$ (Eqs. (3) and (5)). If there is no frequency dependent attenuation, one can write $s_2(t) = A_2/A_1 \cdot s_1(t + \delta t_{cor})$, and the maximum amplitude of the envelope of the normalized cross-correlation $r_{s1/s2,\max}$ directly gives the amplitude ratio A_2/A_1. This assumption corresponds to the case where the attenuation is considered constant in the bandwidth of the transducer:

$$r_{s_1/s_2}(t) = \frac{cor_{s_1/s_2}(t)}{\max\left(env(cor_{s_1/s_1}(t))\right)} \tag{5}$$

and

$$r_{s_1/s_2,\max} = \max\left(env(r_{s_1/s_2}(t))\right) = \frac{\max\left(env(cor_{s_1/s_2}(t))\right)}{\max\left(env(cor_{s_1/s_1}(t))\right)} = \frac{A_2}{A_1} \tag{6}$$

$$e_k(t) = env(s_k(t)) = |s_k(t) + j \cdot Hilbert\{s_k(t)\}|$$

where the envelope $env(x(t))$ of the signal $x(t)$ is determined using its Hilbert transform $Hilbert\{x(t)\}$ as $env(x(t)) = |x(t) + j.Hilbert\{x(t)\}|$. Thus, the attenuation in the oil $\alpha_{oil,t,cor}$ estimated via the normalized cross-correlation amplitude $r_{s1/s2,\max}$ (Eq. (6)) is illustrated by Fig. 3(b) and given by:

$$\alpha_{oil,t,cor} = \frac{-\log\left(r_{s_1/s_2,\max}\right)}{2\Delta d_{oil}} = \frac{1}{2\Delta d_{oil}} \log\left(\frac{A_1}{A_2}\right) \tag{7}$$

2.4. Spectral method

The spectral method makes it possible to find the ultrasonic dispersion properties with frequency [14,18]. The complex spectra of useful roundtrip signals $s_1(t)$ and $s_2(t)$, denoted $\underline{S}_1(f)$ and $\underline{S}_2(f)$ are given by:

$$\begin{cases} \underline{S}_1(f) = \underline{S}_0(f)e^{-2\alpha_{oil}(f)d_{ref}}e^{-j\frac{4\pi f d_{ref}}{c_{oil}(f)}}\underline{R}_{Al/oil} \\ \underline{S}_2(f) = \underline{S}_0(f)e^{-2\alpha_{oil}(f)(d_{ref}+\Delta d_h)}e^{-j\frac{4\pi f(d_{ref}+\Delta d_{oil})}{c_{oil}(f)}}\underline{R}_{Al/oil} \end{cases} \tag{8}$$

where $\underline{S}_0(f)$ is the spectrum of the emitted signal, $\underline{R}_{Al/oil}(f)$ is the reflection coefficient of the aluminum to the oil, $c_{oil}(f)$ is the phase velocity as a function of frequency and $\alpha_{oil}(f)$ is the attenuation as a function of frequency. The transfer function between these two positions is:

$$\underline{T}(f) = \frac{\underline{S}_2(f)}{\underline{S}_1(f)} = e^{-2\alpha_{oil}(f)\Delta d_{oil}}e^{-j\frac{4\pi f \Delta d_{oil}}{c_{oil}(f)}} \tag{9}$$

The argument of $\underline{T}(f)$ corresponds to the phase difference between the signals $s_1(t)$ and $s_2(t)$ is: