A Technique for Quantitatively Measuring Microstructurally Induced Ultrasonic Noise

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Introduction

In ultrasonic inspections of aircraft engine components, the detectability of critical defects can be limited by grain noise. This is likely to be the case for subtle defects, such as hard-alpha-phase inclusions in titanium alloys, where the difference between the acoustic impedances of the defect and host is small. A sound quantitative description of grain noise in such alloys is essential for accurate estimates of flaw detection reliability. In this work we present a method for quantifying backscattered grain noise by using positional averaging to determine the root-mean-squared (rms) noise level. The measured noise level will depend on details of the measurement system, as well as on inherent material properties of the alloy. We present a preliminary model of the noise measurement process which accounts for system effects, and we compare its predictions with experiment. We then indicate how the rms noise data can be processed to extract a factor which parameterizes the inherent noise severity independent of the measurement process.

Quantification of Grain Noise

Several titanium alloy specimens (Ti-6Al-2Sn-4Zr-6Mo, denoted here as Ti-6246) were supplied to us by aircraft engine manufacturers. The specimens were machined into rectangular prisms, and faces were smoothed using 600-grit sandpaper. The experimental geometries used in our preliminary investigations of ultrasonic grain noise are illustrated in Fig. 1. Pulse/echo (P/E) time-domain noise signals were acquired in immersion at normal incidence using a focussed transducer. The waterpath \( z_{os} \) was chosen such that the beam was focussed in the interior of the specimen. A separate P/E "reference" signal was used for normalization purposes; this was a front surface reflection acquired with waterpath \( z_{os} \) equal to the geometrical focal length (F) of the transducer. The broadband transducer used had a nominal F of 9 cm, a nominal radius (a) of 0.635 cm, and a center frequency of 15 MHz. Auxiliary experiments were carried out to characterize the transducer. By using the Gauss-Hermite beam model [1] to analyze [2] signals reflected from a small spherical reflector in water, we found that, near the focal region, the transducer behaved like an ideal focussed piston probe having \( a=0.61 \) cm and \( F=9.65 \) cm.

Representative A-scans acquired at three transverse locations with common \( z_{os} \) above a Ti-6246 specimen are displayed in Fig. 2. A spike excitation of the transducer was used to produce a broadband ultrasonic pulse, and signal averaging was performed at each transducer position to...
eliminate electronic noise from the backscattered wavetrain. In Fig. 2 the front-surface (FS) echo is centered near \( t = 0.5 \mu s \) and exceeds the vertical range shown. At subsequent times one can observe signal features common to all A-scans which arise from the instrumentation. These include the gradual rise toward zero of the mean voltage on the interval \( 2 \mu s < t < 6 \mu s \), and the small echo near \( t=2.3 \mu s \) which is thought to arise from a reverberation of the FS echo within the transducer housing. Grain scattered noise signals are superimposed on the instrumentation background, and are generally observed to be largest in amplitude near the center of the time interval displayed. By scanning the transducer laterally and spatially averaging such backscattered signals, one can obtain the instrumentation background and the root-mean-square (rms) noise amplitude as functions of time. Let \( V_i(t) \) denote the measured signal voltage at time \( t \) for transducer position \( i \). If signals are acquired at \( M \) transducer positions, then the background voltage \( b(t) \) which would be observed in the absence of grain noise may be estimated as

\[
b(t) = \frac{1}{M} \sum_{i=1}^{M} V_i(t) .
\]  

(1)

The root-mean-squared deviation of grain noise from the background is then:

\[
n(t) = \left[ \frac{1}{M} \sum_{i=1}^{M} (V_i(t) - b(t))^2 \right]^{1/2} .
\]  

(2)

To compute \( b(t) \) and \( n(t) \), it is not necessary to store the entire waveform for each transducer position \( i \). One needs only to store the running sums \( \sum_i V_i(t) \) and \( \sum_i (V_i(t))^2 \) for each discrete time \( t \) at which digitization is performed. In our work, time-domain waveforms are sampled at 100 MHz, and the interval between consecutive time points is consequently 0.01 \( \mu s \). Dimensionless versions of \( b(t) \) and \( n(t) \) are obtained by dividing by \( E_{\text{max}} \), the peak amplitude of the reference signal:

\[
B(t) = b(t)/E_{\text{max}} ; \quad N(t) = n(t)/E_{\text{max}} .
\]  

(3)

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Fig. 3 displays normalized background and rms grain noise functions deduced from A-scans acquired at 500 transducer positions above a specimen of Ti-6246. The time origin in Fig. 3 and all similar figures (Figs. 5, 6, and 7) is chosen such that t=0 in the A-scan occurs at the center of the pulse reflected from the front surface of the metal. Immediately following t=0, there is a time interval during which the trailing half of the front surface echo swamps the grain noise signals. Accurate noise measurements are not possible within this interval. The broad maximum of N(t) seen in Fig. 3 arises from the focussing of the ultrasonic beam within the metal. The vertical arrow in Fig. 3 locates the position of the time-scaled focal point: a metal grain located at the geometrical focus would return an echo that is centered at the time indicated by the arrow. The rms grain noise which is shown as a function of time may also be regarded as a function of depth (d) within the specimen. The speed of longitudinal waves in the metal was 0.609 cm/μs, and time-to-depth conversion is consequently effected using \( d = (0.305 \text{ cm/μs}) t \).

GRAIN NOISE MODEL

In order to extract pertinent material parameters from the experimental data, we require a grain noise model which incorporates the effects of the measurement system. In deriving a first-order model, a number of simplifying assumptions will be made. We assume that the total noise signal is an incoherent superposition of noise signals backscattered by the individual grains of the metal. Only single-scattering events will be considered explicitly; however, the attenuation of the beam with depth will be treated through an effective attenuation constant. To simplify the mathematics, we assume that the interrogating ultrasonic pulse takes the form of a narrow-band tone burst of angular frequency \( \omega_0 \). We further assume that the wavelength of sound in the metal is much greater than the mean grain size. We use the hybrid coordinate system shown in Fig. 1. Subscripts 0 and 1 refer to water and metal, respectively. Subscripts R and S, when used, refer to the reference and noise signal geometries, respectively (the waterpaths are generally different for the two geometries). The waterpath \( z_{os} \) is measured outward from the transducer face along the central ray direction. Coordinates for points in the solid, \((x,y,z)\) - \((x,y,z)\) for short, are measured from the intersection of the central ray and the water/solid interface.
For the pulse/echo front-surface reference signal, let $R(t)$ denote the outgoing (i.e. propagating away from the probe) time-domain voltage signal appearing in the coaxial cable of the transducer. Using the same time origin, let $\delta S(t,x,y,z)$ similarly denote the outgoing voltage signal observed in the noise-measurement geometry due to scattering by a single grain located at position $(x,y,z)$. We assume $R(t) = E(t) \sin(\omega t)$ where the slowly varying envelope function, $E(t)$, is non-zero only over a finite time range. $R'(\omega)$ and $\delta S'(\omega,x,y,z)$ will denote the Fourier transforms of $R(t)$ and $\delta S(t,x,y,z)$, respectively. The ultrasonic measurement model of Thompson and Gray can be used to obtain expressions for $R'$ and $\delta S'$. Following the notation of Ref. [3], we write:

$$R'(\omega) = \beta R_{00} D(\omega) \exp(-2ik_0 z_{0t} - 2a_0 z_{0t})$$

(4)

$$\delta S'(\omega,x,y,z) = \frac{2\beta A(\omega,x,y,z) p_1 v_1}{ik_1^2 \rho_0 v_0} T_{0t}^2 C^2(\omega,x,y,z) \exp(-2ik_0 z_{0s} + k_1 z - 2a_0 z_{0s} - 2a_1 z) \text{ where } \exp(F) = 1$$

(5)

In these expressions, $v$, $k$, $\rho$, $\alpha$ and $a$ denote longitudinal wave velocity, wavenumber ($k = \omega/v$), density, attenuation constant, and transducer radius, respectively. $A(\omega,x,y,z)$ is the scattering amplitude for backscattered sound from the grain in question. $\beta$ is the transducer efficiency, defined as the ratio of the outgoing ultrasonic power to the incident electrical power in the transducer cable. $R_{00}$ and $T_{0t}$ are reflection and transmission coefficients for plane wave velocity fields propagating in the central-ray direction. $C(\omega,x,y,z)$ is a measure of ultrasonic field strength in the metal; if the velocity at each point on the transducer face is $V_0 \exp(i\omega t)$, then $V_0 C(\omega,x,y,z) \exp(i\omega t - 2ik_0 z_{0s} - 2k_1 z)$ is the velocity at point $(x,y,z)$ that would exist in the absence of attenuation and interface transmission losses. $D(\omega)$, which accounts for the effects of diffraction losses in the reference signal, is defined as the integral of the reflected velocity field over the equilibrium location of the transducer face, divided by $\pi a^2 V_0 \exp(i\omega t - 2ik_0 z_{0t})$, again in the absence of other losses. In addition to the explicit dependence on frequency, $C$ and $D$ depend upon transducer characteristics ($a$ and $F$), waterpaths, and speeds of sound. Eqn. (4) is used to eliminate $\beta$ from the expression for $\delta S'$, and the result is inserted into the right-hand side of:

$$\delta S(t,x,y,z) = \int \delta S'(\omega,x,y,z) e^{i\omega t} d\omega$$

(6)

The resulting integral contains $R'(\omega)$ which is sharply peaked near $\omega = \omega_0$. All constants and slowly varying functions of $\omega$ (i.e., all factors except $R'(\omega)$ and the complex phase) are collected into a term $H$, evaluated at $\omega = \omega_0$, and factored outside of the integral. Eq. (6) then takes the form:

$$\delta S(t,x,y,z) = H(\omega_0,x,y,z) \int R'(\omega) \exp(i(\omega t - 2k_0(z_{0s} - z_{0t}) - 2k_1 z)) d\omega$$

$$= H(\omega_0,x,y,z) R(t-t_0) = H(\omega_0,x,y,z) E(t-t_0) \sin \omega (t-t_0)$$

(7)

where $t_0 = \frac{2(z_{0s} - z_{0t})}{v_0} + \frac{2z}{v_1}$

(8)

Here $t_0$ represents the time delay between the reference and grain-scattered signals. For times near $t_0$, $\delta S(t,x,y,z)$ is seen to be a harmonic voltage oscillation of amplitude $|H(\omega_0,x,y,z) E(t-t_0)|$. 1724
Now consider summing over all grains to calculate the total noise signal seen at time $t$. For the incoherent superposition of time-harmonic waves, the square of the amplitude of the sum equals the sum of the squares of the individual amplitudes. Also recall that for a time-harmonic signal, the mean squared value of the signal (averaged over one period) is one half of the square of the amplitude. Thus the mean squared noise voltage observed at time $t$ is
\[
<S^2(t)> = \frac{1}{\sum_{\text{all grains}}} |H(\omega_0, x, y, z)E(t-t_0)|^2
\]
(9)

We now replace the sum over grains by an integral over the volume of the metal. The scattering amplitude $A(\omega_0, x, y, z)$, which varies from grain to grain, is replaced by a spatially averaged counterpart, $\bar{A}(\omega_0)$, and is factored from the integral. Finally, we take the square root of the resulting equation and we then divide each side by the peak value of the reference signal envelop function, $E_{\text{max}}$, to obtain the dimensionless (normalized) signal ratio measured in our experiments. The result is
\[
N(t) = \frac{\sqrt{<S^2(t)>}}{E_{\text{max}}} = n^{1/2}|\bar{A}(\omega_0)||\int_0^T \rho_1 v_1 \exp(-2\alpha_0(z_{05} - z_{02})) \int_0^r \frac{k_0^2 \rho_0 v_0 D(\omega_0)k_1}{R_0^2} d^2dr dz|^2
\]
(10)

where $G(z) = \int_{-\infty}^z |C(\omega_0, x, y, z)|^2 dx dy$
(11)

Thus, the normalized rms grain noise is directly proportional to $n^{1/2}|\bar{A}(\omega_0)|$, where $n$ is the volume density of grains, and $\bar{A}(\omega_0)$ is an averaged grain backscatter amplitude at frequency $\omega_0$. The effects of grain scattering also enter the calculation through the attenuation factor $\exp(-4\alpha_0 z)$ appearing in the integral over $z$. Presumably, $\alpha_0(\omega_0)$ is a function of $n$ and $A(\omega_0)$; however, no effort is made in this work to explicitly include that function. The term $G(z)$ is associated with the scattering from a plane of grains at depth $z$; the integration over $z$, which is weighted by the tone-burst envelope function ensures that all grains contribute to the noise signal at time $t$ except those forbidden by time-of-flight considerations.

**COMPARISON OF THEORY AND EXPERIMENT**

To test the predictions of the model, a series of measurements was carried out on a specimen of Ti-6246. Initial experiments utilizing a planar transducer and multiple back wall echos were performed to deduce the ultrasonic attenuation in the specimen; at $f = 10$, 15, and 20 MHz we found $\alpha_0 = 0.05$, 0.10, and 0.18 nepers/cm, respectively. Noise measurements were then made using the focussed transducer described earlier and incident

![Fig. 4. Pulse/echo reference signals used in three grain noise measurement trials. Here, the separate 15-MHz tone bursts have been shifted in time and concatenated to facilitate comparisons.](1725)
Fig. 5. Measured (a) and predicted (b) rms grain noise, \( N(t) \), in a Ti-6246 specimen using a focussed transducer and 15-MHz tone-burst pulses of lengths 1, 2, and 3 \( \mu \)s. \( F, a, z_{ox} \) and \( M \) are as in Fig. 3.

tone-burst pulses. In each case the waterpaths in the reference and noise geometries were \( z_{ox} = F = 9.65 \) cm, and \( z_{ox} = 2.00 \) cm, respectively, and noise signals were acquired at 500 positions above the specimen. In the first set of measurements, three 15-MHz tone-bursts having similar amplitudes but different durations were used in turn. The associated reference signals are shown in Fig. 4, and are seen to have durations of approximately 1, 2, and 3 microseconds, respectively. \( N(t) \), the measured rms grain noise at time \( t \), normalized by the peak amplitude of the reference signal, is displayed in the left half of Fig. 5 for each of the three pulses. The predicted noise function for each pulse, calculated using Eq. (10), is shown in the right half of the figure. For the model predictions, the material dependent scaling factor \( n^{1/2} |A(\omega, = 2\pi \cdot 15 MHz)| \) has been chosen such that the measured and predicted rms noise functions have the same peak value for the 2-\( \mu \)s tone-burst. The envelope function, \( E(t) \), required by Eq. (10) was deduced by fitting a spline function through the extremal points of the reference signal. The normalized velocity field \( C(\omega_o,x,y,z) \), was evaluated using the Gauss-Hermite beam model [1], and the integrals over the spatial coordinates were calculated numerically. The diffraction loss factor, \( D(\omega_o) \), was evaluated using analytical formulae reported in Ref. [6]. The model is seen to successfully predict the general shape of each noise-vs-time curve, and the location of the maximum. In addition, the model predicts the rise of the noise level with increasing pulse length. The predicted and measured peak rms noise values were nearly identical for the 1-\( \mu \)s tone-burst, and differed by about 15% for the 3-\( \mu \)s pulse. Eq. (10) predicts that the rms grain noise at fixed time \( t \) approximately increases as the square root of pulse duration. This is easily seen by using Eq. (8) to convert the \( z \)-integral in Eq. (10) to an integral over \( t_o \) and then noting that the limits of the \( t_o \)-integral are determined by the duration of the pulse through the envelope function \( E \).

To further test the ability of the model to predict the time-dependence of \( N(t) \), a second set of noise measurements was performed using three tone-bursts of similar duration (1-\( \mu \)s) but differing frequencies (10, 15, and 20 MHz). The measured grain noise was found to increase rapidly with frequency, with \( N(t) \) having peak values of 0.0003, 0.0005, and 0.0023 at the three frequencies, respectively. The measured and predicted time dependences are compared in Fig. (6), where each \( N(t) \) function has been renormalized to a peak value of unity to better compare curve shapes. The time of occurrence of the peak noise is well predicted by the model, and the predicted and measured shapes are quite similar. However, in the tails of \( N(t) \) on either side of the focal maximum, the model curves are slightly lower than their measured counterparts. As the frequency increases, the broad maximum in the measured \( N(t) \) curve is seen...
to narrow, with the peak shifting slightly to later times. This trend is well predicted by the model. It results from a) the sharpening of the beam focus and b) the movement of the focus towards its geometrical value $F$ with increasing frequency. When the attenuation is small, the time dependence of $N(t)$ is principally determined by the degree of beam focussing, as quantified by $G(z)$ in Eq. (11). Ultrasonic attenuation acts to modify the shape of $N(t)$ by raising the early-time tail and lowering the late-time tail relative to the focal maximum.

The factor $n^{1/2}A_0$ may be taken as a figure of merit describing the inherent severity of grain noise in a specimen at angular frequency $\omega_0$. In principle, if the ultrasonic attenuation is known and the transducer is well characterized, Eq. (10) can be used to extract $n^{1/2}A$ from the measured rms grain noise at any one time (or depth). The level of agreement between theory and experiment seen in Figs. (5) and (6), suggests that the extracted value of $n^{1/2}A$ will be approximately independent of depth or tone-burst duration, as desired. If the attenuation is unknown and appreciable, one should be able to estimate the attenuation from the time-dependence of $N(t)$.

As expected, we found the severity of backscattered noise to increase with frequency. In some specimens we also observed that the noise severity was strongly dependent upon the direction of propagation. Fig. 7 displays the measured $N(t)$ functions for focussed probe inspections through three mutually-perpendicular faces of a Ti-6246 specimen. A 15-MHz tone burst of 1-μs duration was used, and all measurement system parameters were identical for the three inspections. The specimen was considerably smaller than those discussed previously, necessitating the use of a longer waterpath. Micrographs taken of the three faces revealed very similar mean grain sizes and shapes. However, longitudinal wave speeds were different ($v_1 = 0.603$, 0.601, and 0.605 cm/μs for propagation perpendicular to faces 1, 2, and 3 respectively), suggesting that texture differences may be partly responsible for the observed differences in noise severity.

SUMMARY

We have presented a method for quantifying backscattered grain noise amplitudes in pulse/echo inspections. The method uses positional averaging to extract the rms grain noise, $N(t)$, as a function of time (or, equivalently, as a function of depth in the specimen). The method has been demonstrated for focussed transducer inspections of titanium alloys. The amplitude and shape of $N(t)$ are determined both by material properties of the specimen (e.g.: grain size and morphology; ultrasonic velocity and
Fig. 7. Measured rms grain noise in a specimen of Ti-6246. The three N(t) curves result from inspections through three mutually perpendicular faces of the specimen. F=9.65 cm, a=0.61 cm, z_{os}=6.6 cm, M=500, 15-MHz 1-µs tone burst.

attenuation) and by measurement system parameters (e.g.: transducer diameter and focal length; pulse shape and duration). A proper theory of the grain noise measurement process would account for system effects, would allow the extraction of pertinent material parameters, and would permit the prediction of mean grain noise for other inspection geometries. Such a theory, when combined with models for predicting UT flaw signals, would be useful in probability-of-detection studies. As a first step toward the development of a comprehensive theory, we have presented a simple grain noise model which assumes incoherent single scattering by the individual metal grains. Our approach is based on the ultrasonic measurement model of Thompson and Gray [3], and employs the Gauss-Hermite model [1] for beam propagation. Our initial implementation of the model assumes the use of near-harmonic tone-burst pulses. Model predictions for N(t) were compared to experiment for tone-burst measurements of grain noise. The model did a good job of predicting the shape of N(t), and the dependence upon pulse duration of the amplitude of N(t). This suggests that the model can be used to extract a material dependent amplitude factor from rms noise data. This factor, which takes the form √nA(ω) in the model, serves to characterize the inherent severity of backscattered grain noise in the specimen. In some specimens, √nA(ω) was found to depend upon the direction of beam propagation, in addition to the expected dependence upon frequency.

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