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Serge Dos Santos, Pierre Marechal, François Vander Meulen, Marc Lethiecq. Time-frequency analysis for surface roughness characterization using backscatter ultrasound. *Quantitative Nondestructive Evaluation*, Jul 2001, Brunswick, Maine, United States. pp.752-758, <10.1063/1.1472873>. <hal-03840911>

HAL Id: hal-03840911

<https://hal.science/hal-03840911v1>

Submitted on 6 Nov 2022

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TIME-FREQUENCY ANALYSIS FOR SURFACE ROUGHNESS CHARACTERIZATION USING BACKSCATTERER ULTRASOUND IMAGING

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Abstract. The determination of a surface roughness with translation velocity was investigated with an ultrasonic backscattered technique based on the Doppler effect. The difficulty of the Fourier analysis to detect with accuracy the changes of roughness induce a time-frequency analysis. We demonstrate that the Doppler spectrum is related to the spatial spectrum of the surface roughness and the velocity of the surface. A accurate detection of roughness has been derived thanks to the spectrogram representation.

INTRODUCTION

Detection of the roughness of a surface in movement is of great interest for the automotive industry if it is performed without contact, at low cost and in the real time. Furthermore, ultrasonic methods based on the measurement of the backscattering signal are widely used in the characterization of materials and biological medias.

Several articles have shown their ability to estimate the number of scatterers in an insonified medium in underwater acoustics[1] or medical ultrasonography[2]. In these experiments, the scatterer concentrations is extracted from: *i* classical statistical parameters (high order moments) describing the amplitude echo[1]; *ii* non classical approach done in the frequency domain but needing both the temporal nature of the data acquisition.

However, a difficulty arise from the characterization of a three dimensional (3D) random scattering structure[3]. This was partially solved by Sleaf[2] which has proposed a stochastic model for backscattered acoustic signals allowing the determination of the number of scatterers per volume unit. Its analysis is based on the speckle pattern generated by the interference between the contributions from a large number of randomly distributed scatterers.

The limitation of statistical technics [4, 5, 6, 7, 8] are due to the non stationarity of signals. Furthermore, the characterization of a surface in a translation add a new variable which increase the complexity of use these statistical approaches. This is one of the reason which leads us to use a time-frequency analysis in order to extract qualitative parameters of the roughness.

Classical Doppler Effect

The classical Doppler theory concerns a monochromatic incident acoustic wave of frequency f_0 . This wave is reflected on the surface in motion and causes the Doppler frequency shift f_D due to the phase difference of incident and reflected wave given by

$$f_D = \frac{2f_0 v \sin \theta}{c}, \quad (1)$$

where c is the sound velocity in air ($c \simeq 340 \text{ ms}^{-1}$), θ is the angle deviation with respect to the normal direction of the surface and v the linear velocity of the surface. In our experiments, where $v \simeq 15 \text{ ms}^{-1}$, the Doppler frequency shift is about $f_D \simeq 2.8 \text{ kHz}$ which is an audible signal.

All parameters in Eq.(1) are supposed to be constant in our experiment. But small variations of the angle θ can induce small variations of the Doppler frequency shift f_D . These variations of θ can be due to the transducers radiation pattern of the non-focalized emitter and receiver, the consequence of which is a global constant broadening of the Doppler spectrum. Nevertheless, this first intuitive approach is based on the fact that the monochromatic wave is completely reflected by the surface and not perturbed by the profile $h(x)$ of the unknown surface.

Influence Of The Profile

Local modifications of the surface will induce small variation of the Doppler shift around its mean value. Lets start our study assuming that the surface profile change instantaneously (step profile). It can be shown that the frequency Doppler shift change in the proportion of the area \mathcal{A} (integral of all paths of acoustic signals (Fig.1)). Then, the effect of instantaneous step variation is only visible if the acoustic emission is done with transducers having a wide diameter (compared with the step width).

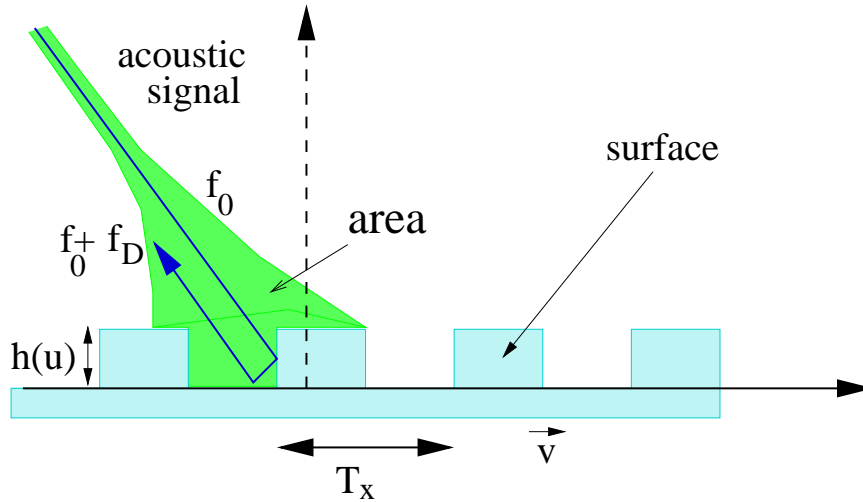


Figure 1. Periodic profile of the roughness surface

Lets consider a periodic profile $h(u + T_s) = h(u)$. The step signature will appear periodically in the temporal Doppler signal. Then, the resulted backscattered signal

through the relation

$$f_D = v f_s, \quad (2)$$

where v is the translation velocity.

More generally, if we have the experimental set-up shown in *figure 2*, the ratio between the emitted signal (V_e) and the received signal (V_r) is given by

$$\frac{V_r}{V_e} = \int_x T_e(x) T_r(x) \exp(-2jkh(x-vt)) dx, \quad (3)$$

where $T_e(x)$ (resp. $T_r(x)$) is the emitter (resp. receiver) transfer function. Thus phase variations of the ratio $\frac{V_r}{V_e}$ gives information about $h(u) = h(x-vt)$ of the profile variations. The Doppler effect, as a result of phase variations, will be dependent of the profile throughout the amplitude (because of the energy of the backscattering effect) and dependent of the spatial spectrum of the roughness.

If we suppose that $h(x-vt) \ll \lambda = c/f_0$, then Eq.(3) becomes

$$\frac{V_2}{V_1} = \int_x T_e(x) T_r(x) (1 - 2jkh(x-vt)) dx, \quad (4)$$

$$\frac{V_2}{V_1} = \int_x T_e(x) T_r(x) dx - 2jk \int_x T_e(x) T_r(x) h(x-vt) dx, \quad (5)$$

which can be seen as the direct reflection and the diffusion components.

Now assuming that $h(x-vt) \simeq h_0 = cte$ over a wide spatial range, we can measure the power ratio between direct \mathcal{P}_r and diffused power \mathcal{P}_d by:

$$\frac{\mathcal{P}_r}{\mathcal{P}_d} = \frac{\left| \int_x T_e(x) T_r(x) dx \right|^2}{\left| -2jk \int_x T_e(x) T_r(x) h(x-vt) dx \right|^2} \simeq \frac{\lambda^2}{16\pi h_0^2}. \quad (6)$$

If the profile has a spatial periodicity T_s , then $h(x-vt)$ can be written as Fourier series *i.e.*

$$h(x-vt) = \sum_{n=-\infty}^{n=\infty} H_n \exp\left(\frac{2i\pi n(x-vt)}{T_x}\right). \quad (7)$$

Then, the ratio between the emitted and the diffused signal is given inserted Eq.(7) into Eq.(5), *i.e.*

$$\frac{V_d}{V_1} = -2jk \int_x T_e(x) T_r(x) h(x-vt) dx \quad (8)$$

$$= -2jk \int_x T_e(x) T_r(x) \times \sum_{n=-\infty}^{n=\infty} H_n \exp\left(\frac{2i\pi n(x-vt)}{T_x}\right) dx \quad (9)$$

$$= -2jk \underbrace{\sum_{n=-\infty}^{n=\infty} H_n \exp\left(\frac{-2i\pi nvt}{T_x}\right)}_{\text{Doppler Spectrum}} \times \underbrace{\int_x T_1(x) T_2(x) \exp\left(\frac{2i\pi nx}{T_x}\right) dx}_{\text{Spatial spectrum with filtering}} \quad (10)$$

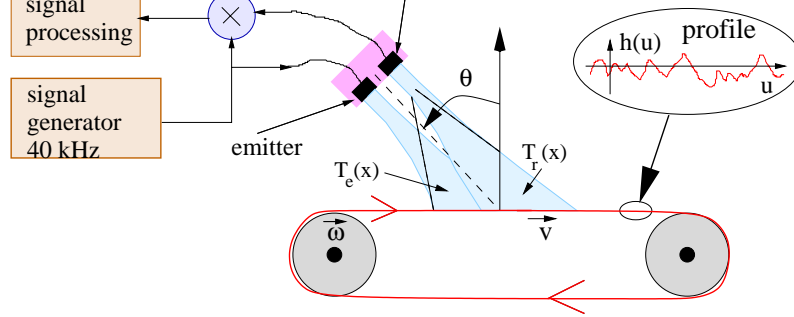


Figure 2. Roughness surface characterization experimental set-up using acoustic backscattering effect. The surface is in translation whereas the transducers are fixed

The general result is that the Doppler spectrum is proportional to the spatial spectrum assuming the mean roughness profile lower than the wavelength of the emitted signal. As a conclusion of this theoretical part, one can see that the Doppler spectrum contains an information related to the spatial spectrum of the roughness because of the translation property. In our application, an instantaneous variation of roughness induces an instantaneous variation of the spectrum requiring accurate signal processing methods.

EXPERIMENTAL SET-UP

In order to characterize the surface roughness, we propose an acoustical experiment where the backscattered Doppler signal of a moving surface is measured (*figure 2*). The surface with the roughness profile $h(u)$ is in translation (\vec{v}) with respect to the fixed emitter and receiver transducers running at $f_0 = 40$ kHz. The translation velocity (supposed to be constant) allow to analyse the Doppler component in a narrow band with a good noise rejection. The Doppler signal is extracted from the received signal with an electronical demodulation.

TIME-FREQUENCY ANALYSIS

The introducing remarks concerning the difficulty of using statistical analysis and the motivation to use this experimental method for non stationary profile $h(x, t)$ has led us to use time-frequency analysis applied to the demodulated backscattering Doppler signal. These choice was adapted thanks to preliminary experimental results which have shown that spectral analysis, and statistics on temporal defect was not satisfying to detect rapid variations of temporal signals. If we suppose that the frequency limit of the Doppler spectrum is lower than 20 kHz which gives $f_T = v/f_D = 8.10^{-4}$ m as the limit of spatial frequency, a PC sound card (with 44 kHz of sampling rate) can be use to record the Doppler signal allowing real time treatment.

Statistical Properties Of Doppler Signals In The Time Domain

Some statistical parameters can be defined. It is well known that these parameters are used for tissue characterization [9]. The classical statistical momentum (during T)

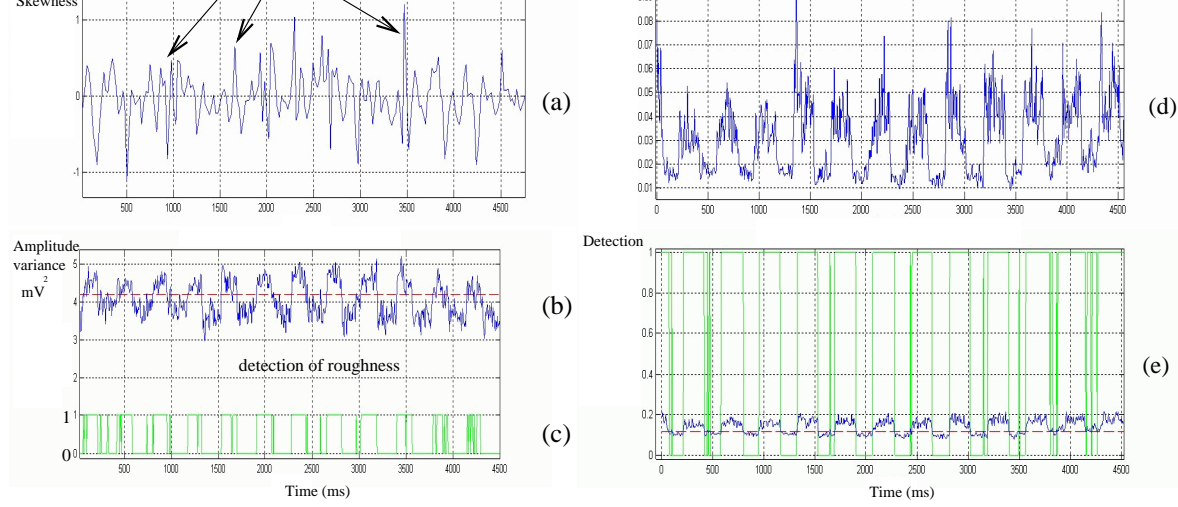


Figure 3. Skewness (a) and variance (b) parameters for the roughness detection (c) on the amplitude of the temporal signal. The skewness present some limitation in the detection. (d) Kurtosis of the temporal signal and the detection result. The Kurtosis allows a better differentiation than the Skewness as seen in the detection result (e)

of order n (and particularly the Skewness and the Kurtosis) defined by

$$E[x^n(t)] = \frac{1}{T} \int_{-\infty}^{+\infty} x^n(t) dt, \quad Skew[x(t)] = \frac{E[x^3(t)]}{E[x^2(t)]^{3/2}}, \quad Kurt[x(t)] = \frac{E[x^4(t)]}{E[x^2(t)]^2}, \quad (11)$$

have been chosen as indicators.

These parameters were used for the determination of the change of roughness as seen in *figure 3*. Each evaluation of the parameters is take on the same measurement with the same number of data (1000 values). The variance give an information of the energy which confirms the fact that the roughness induce a increase of the backscattering energy. The detection is then possible as seen from the (c) and (e) curves where the detection is represented as the binary value (0 : no detection; 1 : detection). The (a) curve showing the Skewness confirm the difficulty to use this parameter for an accurate detection.

Nevertheless, the results concerning the Kurtosis and presented in (d) emphasizes the potentiality of this parameter for the roughness characterization as obtained by Kuc for tissue diagnostic [9]. But the fact that the surface is in movement certainly induce a difficulty of an accurate detection. Indeed, the detection at $t = 1800 \text{ ms}$ where the roughness is present seems to be difficult.

Classical Spectrum Analysis

The classical FFT spectrum is presented at different points which are slightly different if the signal is acquired on the smooth (*figure 4(a)*) or on the roughness (*figure 4(b)*) surface.

The two spectrum are very closely each other in amplitude and spectrum components. The mean Doppler frequency is around 400 Hz. The amplitude of spectrum given in *Figure 4(a)* is slightly different but not sufficient for an accurate differentiation. The broadening of the spectrum is qualitatively verified with the roughness surface. The

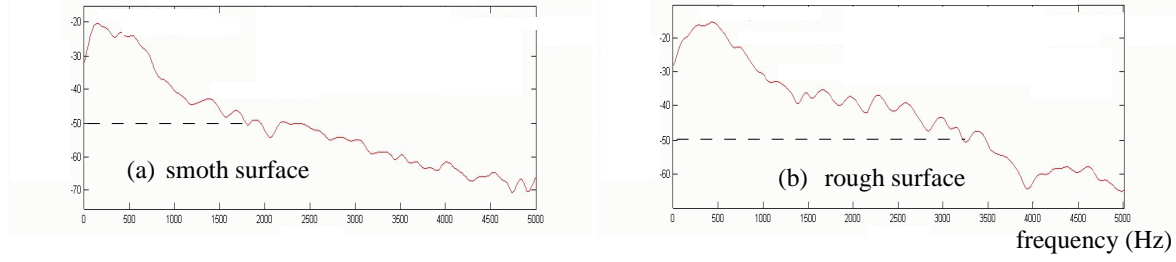


Figure 4. Exprimental measurement showing the limitation of the classical spectrum analysis. (a) FFT of Doppler signal before the roughness surface. (b) FFT on the roughness defect. The broadening of the Doppler spectrum is the result of the presence of the roughness

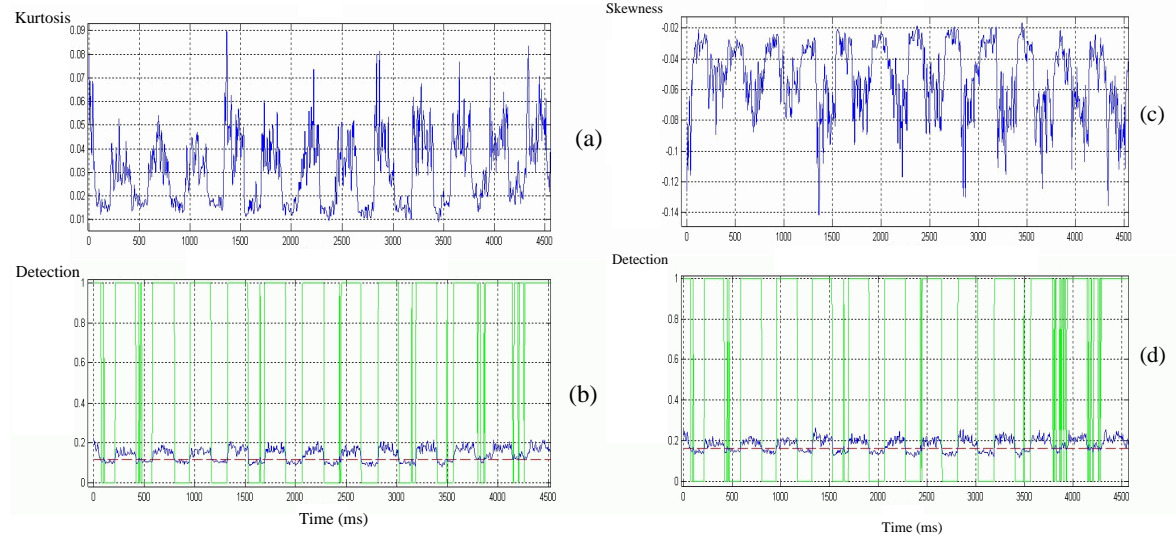


Figure 5. Kurtosis (a) and Skewness (b) parameters for the roughness detection on the FFT of the temporal signal. The detection based on the spectral parameters are more significant that the detection based on time parameters

level -50 dB is located at 1700 Hz for the smooth surface and located at 3200 Hz for the roughness one while the amplitude maximum is constant ($A \simeq -20\text{dB}$). The result is due to the difficulty of the spectrum analysis to consider instantaneous variation of the profile.

Time-Frequency Analysis With Spectrogram

The same statistical study has been done on the Fourier transform $X(\nu)$ of the Doppler temporal signal $x(t)$. The previous statistical parameters Eq.(11) can be either define in the Fourier representation of the Doppler signal, *i.e.*

$$E[\nu^n] = \frac{\int_{-\infty}^{+\infty} \nu^n S_X(\nu) d\nu}{\int_{-\infty}^{+\infty} S_X(\nu) d\nu}, \quad Skew[\nu] = \frac{\int_{-\infty}^{+\infty} \nu^3 S_X(\nu) d\nu}{E[\nu^2]^{3/2}}, \quad Kurt[\nu] = \frac{\int_{-\infty}^{+\infty} \nu^4 S_X(\nu) d\nu}{E[\nu^2]^2}, \quad (12)$$

which are respectively the mean, the variance, the Skewness and the Kurtosis of the spectral components defined from the power spectral density $S_X(\nu)$. Results of this spectral detection are presented in *figure 5*. As a consequence of previous results, the need of a spectral parameter evolution versus time, *i.e.* versus the surface roughness

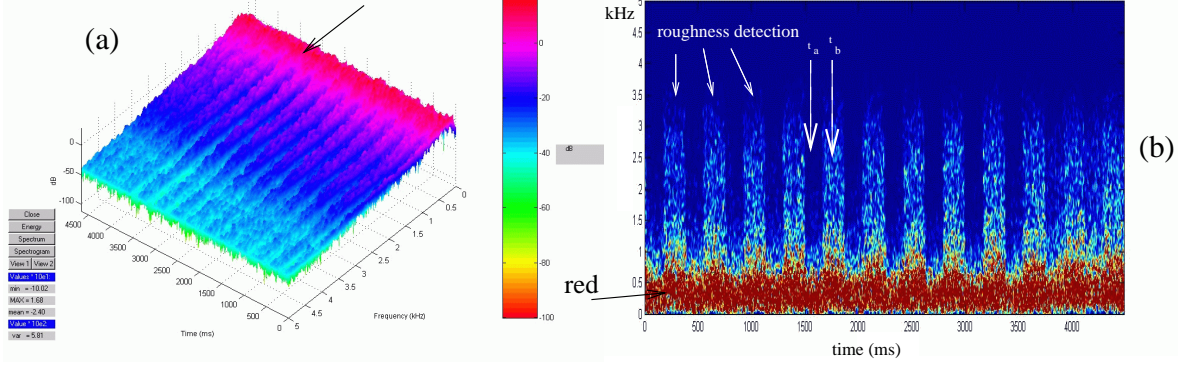


Figure 6. (a) Spectrogram of the Doppler signal visualized in 3D plot. The difference of roughness appears at a frequency analysis around 1 kHz where the roughness contribute to the broadening of the Doppler spectrum. (b) Spectrogram of the Doppler signal visualized versus time. The red component appears at 400 Hz

displacement, leads to use a time-frequency approach.

One of the way to use time-frequency representation (TFR) is proposed in this paper by applying a Short Time Fourier Transform (STFT) to the Doppler backscattered signal $x(t)$ defined by [10, 11]

$$S(\omega, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} x(\tau)h(\tau - t) \exp(-i\omega\tau)d\tau, \quad (13)$$

where $h(t)$ is a window function. The energy density spectrum of a STFT is defined as $E(\omega, t) = |S(\omega, t)|^2$ and called a spectrogram.

The time-frequency resolution of a spectrogram depends only on the window size and type and is independent of frequency. A wide window give better frequency resolution but worsens time resolution, whereas a narrow window improves time resolution but worsens frequency resolution.

The figure 6 where the spectrogram is presented propose a more accurate characterization of the surface profile. The spectrogram mapped is using a colorbar defined from the STFT amplitude of the signal analyzed with a 512 pts window in the time domain. The analysis is performed with all Shannon conditions verified. The red component is associated to the Doppler frequency which is approximately constant in the experiments. The other components (when the surface is more rough) is clearly visible with this time-frequency analysis.

These results obtained with the spectrogram present the advantage to combine both time and frequency domains. As a consequence, the calculus of the Kurtosis and the Skewness is a real time-frequency characterization because of the evolution of frequency domain characteristics versus time. In fact, the coefficient given by Eq.(12) are calculated from the STFT which are time-frequency representations.

CONCLUSION

Ultrasonic backscattered signal has been recorded for an accurate differentiation of roughness surface in movement. The Doppler effect associated to a time-frequency analysis characterization of a change of surface properties. The necessary need of a time-frequency analysis has been progressively argued thanks to: *i* previous work related

stationary effects in the frequency domain, and *iii* preliminary experiments realized for this kind of application. The roughness induces not only a modification in the amplitude of the received electrical signal from the transducer, but also in the spectrum components of this signal. If the roughness has instantaneous non stationary time variations, it is also necessary to introduce it in the analysis and perform it with a time-frequency approach.

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