ANALYSIS OF ACOUSTICS SIGNALS ECHOS FROM CYLINDRICAL ELASTIC SHELLS BY HHT AND THT

Abdelkhalek Bouchikhi[a], Abdel-Ouahab Boudraa[a] and Gérard Maze[b]

[a]IRENav (EA 3634), Ecole Navale, BCRM Brest, CC 600, 2940 Brest, France.
[b]Laboratoire Ondes et Milieux Complexes, FRE CNRS 3102, Université du Havre, place Robert Schuman. BP 4006, 76610 Le Havre, France.

{Bouchikhi, boudra}@ecole-navale.fr, gerard.maze@univ-lehavre.fr

Abstract:
The interest of Time-Frequency Representation (TFR) compared to time or frequency representations, is their ability to quantitatively resolve changes in the frequency content of nonstationary signals such as under water reflected acoustics signals. However, a limit of such TFRs is they produce, in some cases, representations that are meaningless or difficult to explain and to analyze. In this work two new TFRs based on the Empirical Mode Decomposition of Huang, called respectively Hilbert-Huang Transform (HHT) and Teager-Huang Transform (THT) are investigated. The two TFRs are applied to analyze echo signals of cylindrical tube. Resulting TFRs are compared to that of Wigner-Ville distribution. Both HHT and THT give qualitatively and quantitatively better results than the Wigner-Ville distribution and the spectrogram in terms of pertinent and accuracy time-frequency features, used in targets classification.

Keywords: *Time-frequency representation, HHT, THT Underwater signal echoes, cylindrical shells.*

1. INTRODUCTION

Use of underwater sound for detecting and locating submerged targets was introduced more than 80 years ago. The problem of discrimination of immersed targets was initiated by Hoffman [1] who investigated time-domain approaches followed by Chesnut and Floyd who tested multiple frequencies based techniques [2]. Time-frequency (TF) approaches have also been used for target classification [3],[4] and have given high potentiality for discrimination between solid and hollow targets as well as for determining the target material [5]. For example in [5] a Wigner-Ville distribution (WVD) as a TF description is used. WVD has been shown to be a relevant for understanding of echo formation mechanisms and for surface waves that circumnavigate the targets [3],[4]. In [7] a Sonar target classification based on the TF projection filtering [8] has been proposed. The WVD associated to the Impulse response (IR) (acoustic response) of a Sonar target generates a TF plane (image) showing different patterns. These patterns can be classified into two categories 1) Interferences due to the bilinear nature of the WVD [6]. 2) High energy pattern: the first one, non dispersive, is associated with the specular echo on the target and the two following patterns correspond to the arrival of surfaces waves (antisymmetric Lamb waves) that circumnavigate the target [7]. The two pertinent patterns for classification are the specular reflection and the Lamb waves. The function of a TF filter is to extract from the signal to be analyzed the pertinent patterns. The filter is designed from the WVD of a reference signal and more particularly from its TF support R containing the relevant information. This region R is derived manually (isolation of the echoes by an expert operator). A limit of the WVD is the severe cross terms as indicated by the existence of negative power for some frequency ranges. Although most of these difficulties can be avoided by using proper kernel functions, the method is still Fourier based; therefore all complications associated with Fourier transform still exist. To circumvent this difficulty two new TF methods based both on the Empirical mode decomposition (EMD) of Huang [10] called Teager Huang Transform (THT) [9] and Hilbert Huang Transform (HHT) [10] are investigated to analyze IR of Sonar target. The EMD does not make any assumption about the stationnarity or the non-linearity of the analyzed signals, and avoids the interference problem of the WVD. The EMD decomposes a signal into oscillatory modes called Intrinsic Mode Functions (IMFs). The aim is to determine IMFs that characterize the Sonar target. In this paper we investigate the THT and HHT to analyze echoes signals scattered from cylindrical object. We examine their ability for characterising Lamb waves, which can propagate in the object. We compare the results of TF representations of HHT and THT to those of the WVD and spectrogram.

2. EMD-BASED APPRAOCHES

2.1. Hilbert-Huang Transform:

This TFR is based on the EMD and the Hilbert transform (HT). The EMD is defined by an algorithm, called sifting process, which decomposes any time series to a set of IMFs that are conform to HT [10]. Using HT, IMFs produce IFs and Instantaneous Amplitudes (IAs). The resulting energy-TF representation, called HHT, is comparable to WVD. The interest of EMD based methods is that IMFs are derived from the signal itself. This means that no artificial basis functions are used and so the extracted IFs are physically meaningful. The

EMD can be seen as a type of wavelet decomposition, whose sub-bands are built up as needed, to separate the different components of a signal $s(t)$. Each IMF replaces the signal detail, at a certain scale or frequency band [12]. The EMD picks out the highest frequency oscillation that remains in $s(t)$. An IMF satisfies two conditions:

1) Numbers of extrema, and of zeros crossings, may differ by no more than one;
2) Mean value of the envelope defined by the local maxima, and the envelope defined by the local minima, is zero.

To be successfully decomposed into IMFs, $s(t)$ must has at least two extremas, one minimum and one maximum. The sifting is repeated in order to get a true IMF that fulfills conditions (1) and (2). The result is that $s(t)$ will be decomposed into IMFs and a residual:

$$s(t)=\sum_{j=1}^{N} IMF_j(t)+r_N(t) \tag{1}$$

HT is applied to each IMF and associated analytic signal, $s_a(t)$ is formed. IF and IA of the IMF are given by

$$f(t)=\frac{1}{2\pi}\frac{d\phi(t)}{dt},\ a(t)=\sqrt{\Re s_a(t)+\Im s_a(t)} \quad \text{where } \phi(t)=\arctan\left[\frac{\Im s_a(t)}{\Re s_a(t)}\right] \tag{2}$$

2.2. Teager Huang Transform:

THT is a combination of the EMD and the Teager operator. This operator is applied to each IMF, $\psi[IMF(t)]$. To demodulate an IMF, the Energy Separation Algorithm (ESA) based on Teager operator is used [13]. ESA estimates the IF and the IA of $s(t)$ as follows:

$$\psi[s(t)]=\dot{s}(t)-s(t)\ddot{s}(t) \tag{3}$$

$$f(t)\approx\frac{1}{2\pi}\sqrt{\frac{\psi[\dot{s}(t)]}{\psi[s(t)]}},\quad a(t)\approx\frac{s(t)}{\sqrt{\psi[\dot{s}(t)]}} \quad \text{where } \dot{s}(t)=\frac{\partial}{\partial t} \tag{4}$$

3. TFRs OF ECHOES FROM CYLINDRICAL SHELLS

TFRs from echoes of cylindrical shells are presented. A tube characterized by a material and radius ratio b/a (a, outer radius; b inner radius) is used. Usually specular echo is a broad band signal with high amplitude compared to Lamb waves. Since associated TFR is not easy to analyze, specular echo is cancelled before analysis. The tube of aluminium is immersed in water filled full of air with $b/a=0.95$, $a=1\,\text{cm}$. Sifting results of echo $s_1(t)$ is given in Fig. 1 and the associated TFRs are shown in Figs. 2-5. These TFRs show that circumnavigate waves around and inside the tube are globally detected. However, for Smooth Pseudo WVD (SPWVD), these waves are not evidenced on the TF plan. Indeed, in SPWVD the filtering used for smoothing the representation could badly affect this last [6]. These waves can be recovered using convenient parameters which are in practice difficult to determine. As for SPWVD we can draw the same conclusions for spectrogram. TF features (Fig. 2) are not well evidenced. Except the time localisation, spectrogram features do not give pertinent information. In contrast HHT and THT give accuracy frequency values and represent

correctly the circumnavigate waves in TF plan. More particularly, HHT reveals different laws frequency for each wave packet, corresponding to different IMFs of $s_1(t)$. IMFs are shown in figure 1. The first one is noise dominant mode; its frequency is the highest one. IMFs are presented from the highest frequency mode to the lowest one. As can be seen in Figs. 6 and 7, a zooming region in time interval [1.54ms, 1.57ms] of both HHT and THT show different frequency laws, characterizing the echo. Figures 8 and 9 show spectrogram and SPWVD of signal echo, $s_2(t)$, of steel tube with, $a/b = 0.97$, respectively. As for Figs. 2 and 3, these TFRs do not provide interesting features. Thus, good window parameters adapted to the analyzed signal are necessary to improve the resolution of these TFRs to get pertinent information. For HHT and THT this problem is systematically resolved by EMD which decomposes the signal with no a priori. From a zooming on HHT and THT in time interval [1.29ms, 1.37ms] one can observe different frequency laws corresponding to $s_2(t)$.

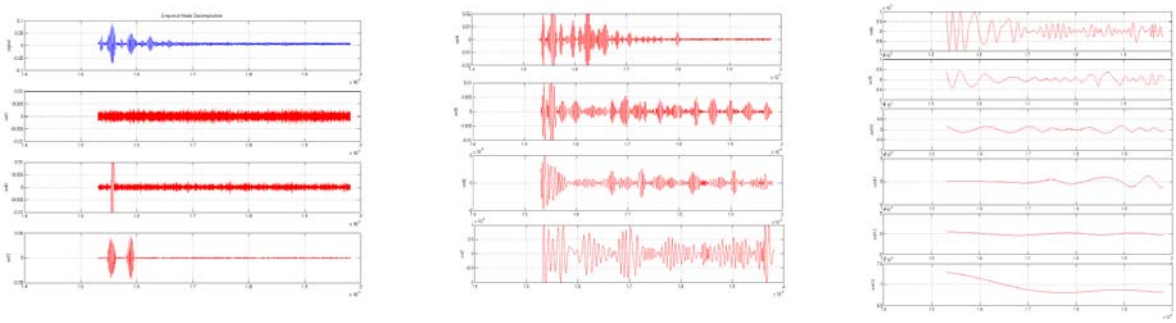

Fig.1: Sifting results of Results of signal, $s_1(t)$, of tube of aluminium with $a/b = 0.94$. The signal $s_1(t)$ (left up in blue), IMF1-IMF12 (from the second line at left to the before last line right) and the residue (the last line, right)

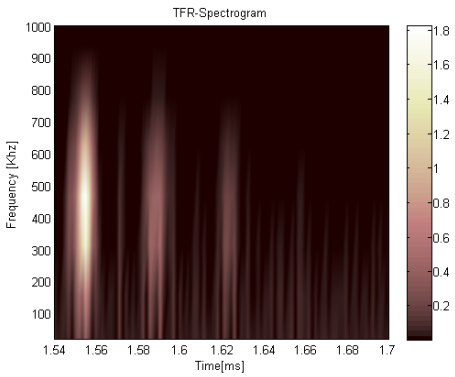

Fig.2: Spectrogram of signal $s_1(t)$ divided into segments equal to 64, with overlap of 32 and nfft of 128.

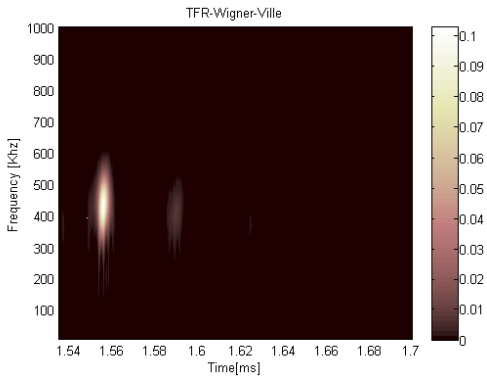

Fig.3: SPWVD of $s_1(t)$ (filtering window is 'Kaiser', with larger 3 and 127 for time and frequency).

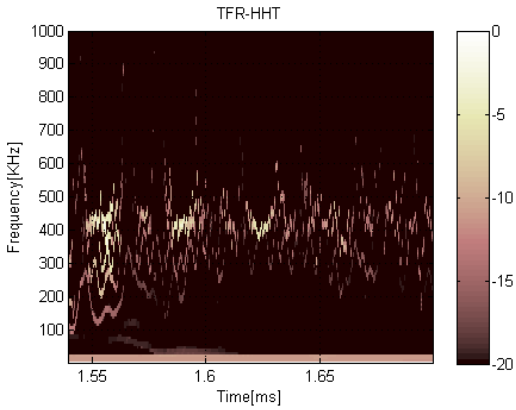

Fig.4: HHT of scattering signal, $s_1(t)$.

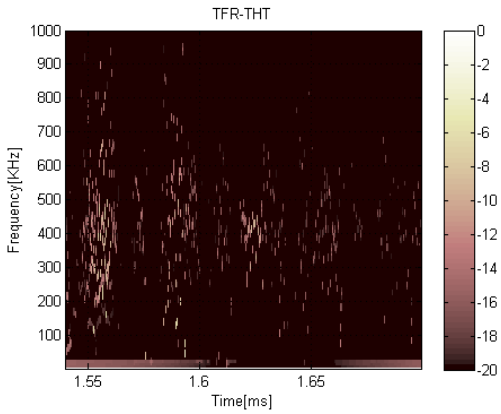

Fig.5: THT of scattering signal, $s_1(t)$.

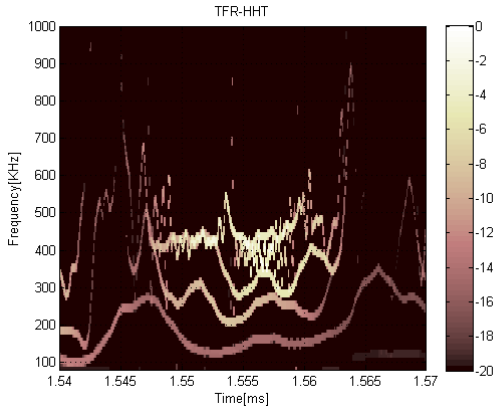

Fig.6: A zooming in 1.54ms to 1.57ms time interval on HHT

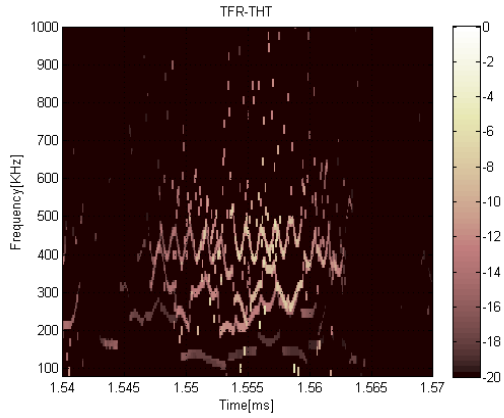

Fig.7: A zooming in 1.54ms to 1.57ms time interval on THT

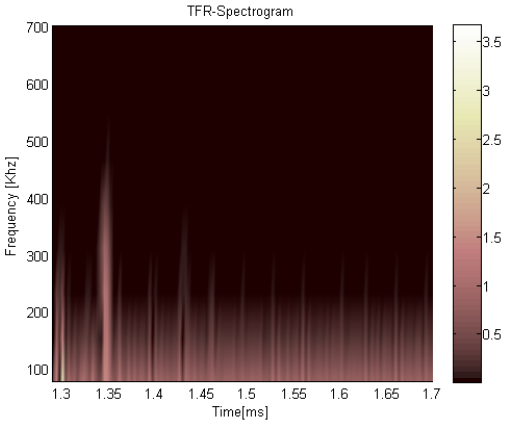

Fig.8: Spectrogram of signal $s_2(t)$ *divided into segments equal to 64, with overlap of 32 and nfft of 128.*

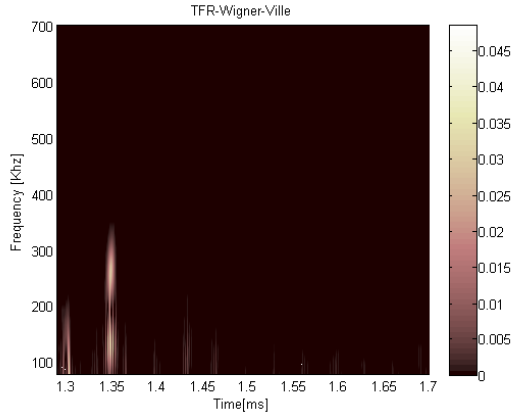

Fig.9: SP WVD of $s_2(t)$ *(filtering window is 'Kaiser', with larger 3 and 127 for time and frequency).*

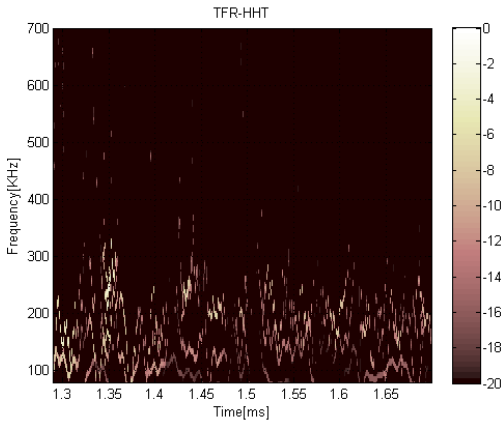

Fig.10: THT of scattering signal, $s_2(t)$.

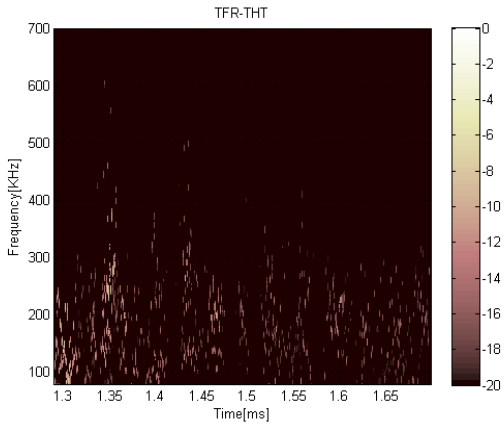

Fig.11: THT of scattering signal, $s_2(t)$.

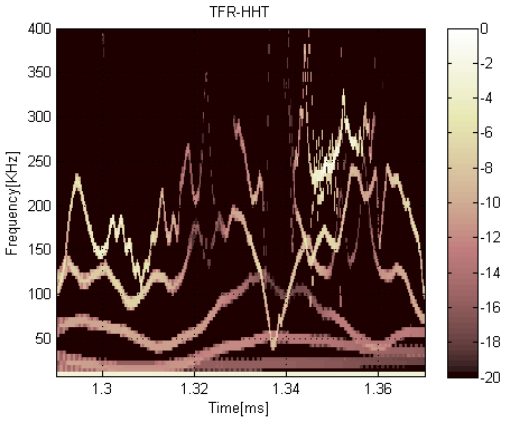

Fig.12: A zooming in 1.29ms to 1.37ms time interval on HHT

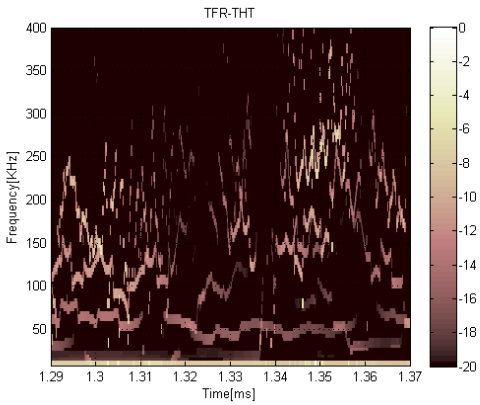

Fig.13: A zooming in 1.29ms to 1.37ms time interval on THT

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