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► **To cite this version:**

Manell Zakharia, Bertrand Dubus, Philippe Plantevin. Time-frequency characterization in support of broadband sonar transducer design. e-Forum Acusticum 2020, Dec 2020, Lyon, France. pp.1575-1579, 10.48465/fa.2020.1016 . hal-03231996

HAL Id: hal-03231996

<https://hal.science/hal-03231996>

Submitted on 25 May 2021

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Time-frequency characterization in support of broadband sonar transducer design

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ABSTRACT

Commonly used in ultrasonic pulse imaging, wideband transducers are becoming more and more popular in sonar area in various areas of application where the time resolution is a paramount issue such as: estimation of time of flight, communication, high resolution imaging, impedance and attenuation measurements, fine echo analysis....

While, for most ultrasonic transducers, the power involved is rather small (about ten watts), for sonar transducers the power may exceeds several tens of kilowatts.

Thus, for power efficiency considerations, sonar transducers are conventionally designed, at a given frequency, to convert the energy of an electric source into the acoustic energy without paying much attention to the fine temporal structure of transducer response. This has been satisfactory as long as narrow band systems are involved but becomes a limitation for wideband systems. In this paper, we are interested in wideband high-power systems. We will show how time-frequency approach can be used from the early design stage up to full system characterisation.

1. CONVENTIONAL SONAR TRANSDUCER CALIBRATION

Conventional transducer calibration is achieved in term of Transmitting Voltage Response (TVR) which represents the power spectrum of the acoustic pressure radiated in the far field, in the axis, at a reference distance when submitted to a unit drive voltage (figure 1) [1]. TVR amplitude spectrum is usually widely discussed and optimized but TVR phase spectrum is most of the time ignored despite the fact that it includes relevant information on the impulse response and thus time (axial resolution). In order to improve temporal resolution, transducer bandwidth increase is usually achieved in two ways: damping the mechanical system (high frequency dampers) or adding extra mechanical resonances (“camel” type or Janus Helmholtz transducers broadening the bandwidth up to one octave [2], [3]). Both methods increase the effective bandwidth as far as energy is concerned, but also lead to phase distortions. Thus, although increasing the bandwidth (B) leads to an improvement of time resolution, phase spreading leads to the opposite effect and the expected resolution ($1/B$) is hardly achieved.

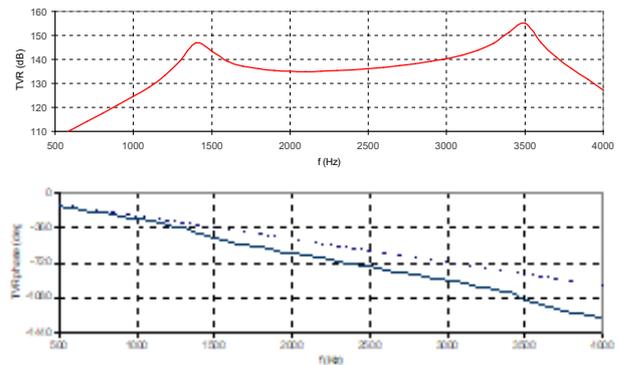


Figure 1. Transducer calibration: Transmitting Voltage Response (TVR); top: amplitude, bottom: phase.

Even when provided (rarely), the phase information can only be used for characterisation but not for mechanical design improvement as several mechanical phenomena can occur on a given frequency (including harmonic generation) and the phase information is a global information that does not allow to characterise (and correct) each phenomenon individually. Thus, a joint time-frequency approach (3D) is needed in order to separate, in the time-frequency plane, phenomena that could not be separated in time or frequency axis (2D).

2. TIME-FREQUENCY REPRESENTATION, TFR

For a wideband transducer, the impulse (in the axis) characterises the transducer. Nevertheless, the superposition of various physical phenomena at each date does not allow an easy detailed interpretation. Pseudo Wigner-Ville Distribution, PWVD has been used since a while for characterising either loudspeakers [4] or ultrasonic transducers [5] impulse response and to overcome the limitation of time or frequency representation. The major advantage of this time-frequency representation (PVWD) that it allows a separate time and frequency smoothing and that it can give direct estimation of group delay independently from the dispersion of group velocity [6], [7].

The impulse response of an ultrasonic transducer is commonly characterised by three major parameters as shown in figure 2:

- Peak amplitude
- d_6 : time duration of response at -6 dB
- d_{20} : time duration of response at -20 dB

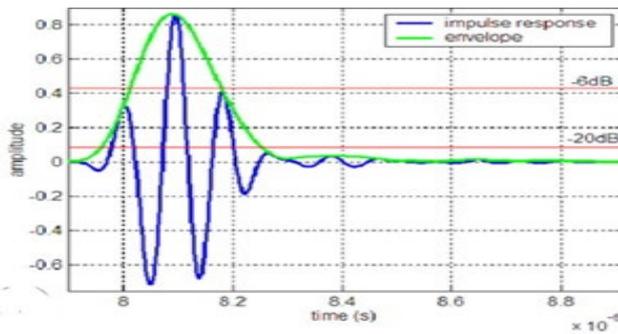


Figure 2. Impulse response of an ultrasonic transducer.

Such a characterisation may be sufficient for users but is definitely incomplete for designers whose aim is to improve the transducer: higher efficiency in a wide band, reduction of the “ringing” effect, increase of the bandwidth...

Increasing a transducer bandwidth (i.e. reducing its response in time) can be achieved by digitally correcting for bandwidth variations (envelope and phase).

As shown in figure 3, from an original power spectrum, we define the “target power spectrum (with zero phase) defined by the so-call “weighting function”.

The deconvolution (or pre-accentuation) procedure can be achieved either in post-processing or by transmitting a pre-computed signal integrating the corrections.

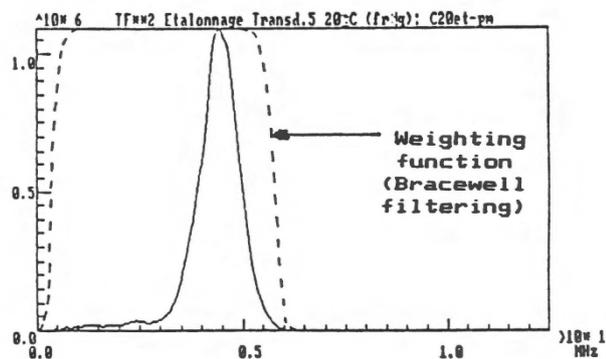


Figure 3. Target bandwidth for deconvolution [5].

An example of deconvolution result is given in figure 4 for an ultrasonic transducer. The figure shows the “flattening of power spectrum as well as the reduction of the ringing in the time domain. The time-frequency representation shows that for the corrected response, all frequencies are transmitted at the same date and that both ringing and velocity dispersion are corrected [5], [6].

Deconvolution methods are limited by several technical issues:

- Signal to noise ratio during the calibration procedure.
- Dynamic range of the digital system.
- Power efficiency (inefficiency will lead to oversizing of power amplifiers).
- High voltage limitation mainly due to cables and connectors (<1 000 V)

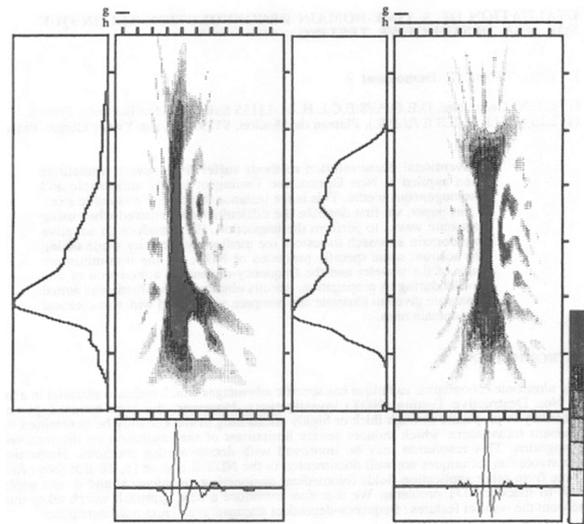


Figure 4. Characterisation of deconvolution in the time-frequency plane. Horizontal axis: 1 μ s/div, vertical axis: 400 kHz/div, 4 dB/grey level.

3. WIDEBAND TONPILZ TRANSDUCER DESIGN

The major concern in wideband and high-power transducer design is to optimise conversion of input electrical energy into radiated acoustic energy over a wide frequency range [8], [9]. As stated in [2], “*The desired performance from a projector is usually high power or intensity, high efficiency and broad bandwidth, usually with limitation on size and weight.*”

In this work, we report the design and test a super-wideband Tonpiliz transducer: 500 Hz - 10 kHz i.e. about 4.5 octaves.

This transducer was specifically developed for sub-bottom imaging and characterization.

The design must find a compromise between output bandwidth, power efficiency and weight considerations.

The design process steps are the following:

- Define the target performance requested.
- Design and simulate a conventional “camel Tonpiliz”.
- Characterise its response into the time-frequency plane.
- Modify the design in order to improve performances and reduce weight. At this stage, the geometry of the transducer is changed in order to add additional mechanical resonances.
- Characterise the wideband transducer in the time-frequency plane.

The last two steps were iterated until obtaining a solution satisfying the requirements on source level, mass and time frequency response. The optimised transducer was then built up, calibrated and tested at sea.

The **target performances of the ultra-wideband system** are the following:

- TVR: **> 132 dB** ref 1 μ Pa/V @ 1m over all band
- Bandwidth: **1 to 8 kHz**
- Weight: **< 30 kg**

Figure 5 shows the simulation result for a conventional Camel Tonpilz using Atila finite element software developed at ISEN [10].

Conventional design leads to a heavy weight transducer: 48 kg (>30 kg). As shown clearly in the figure, the TVR is insufficient below 1 kHz and between 3.9 and 5.2 kHz

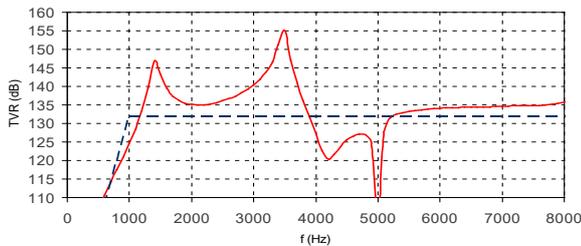


Figure 5. TVR of Camel Tonpilz transducer (simulation).

Figure 6 represents the TF representation of the impulse response of such a transducer (that integrates both amplitude and phase of the TVR).

In the time domain, the impulse response shows a “ringing” effect due to the resonance of the Camel Tonpilz at two frequencies. Both resonances are clearly visible in the time-frequency representation in the form of energetic horizontal lines (ringing).

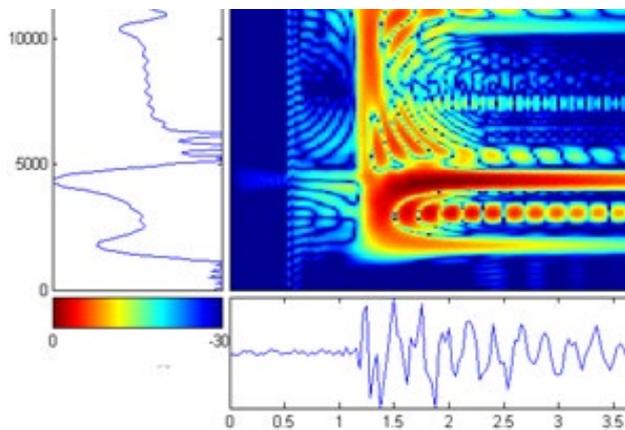


Figure 6. Time-frequency representation PWVD of simulated impulse response for Camel Tonpilz transducer. Horizontal axis: time in ms, vertical axis, frequency in Hz, logarithmic colour scale.

Figure 7 shows the TVR for the new ultra-wideband transducer developed that integrates a broadening of both resonance frequencies by introducing adequate additional resonances.

It clearly shows that the new transducer fits the prerequisite performances. In addition, the predicted weight is 29 kg.

Figure 8 shows the improvement of performance in the time frequency plane (when compared to figure 6).

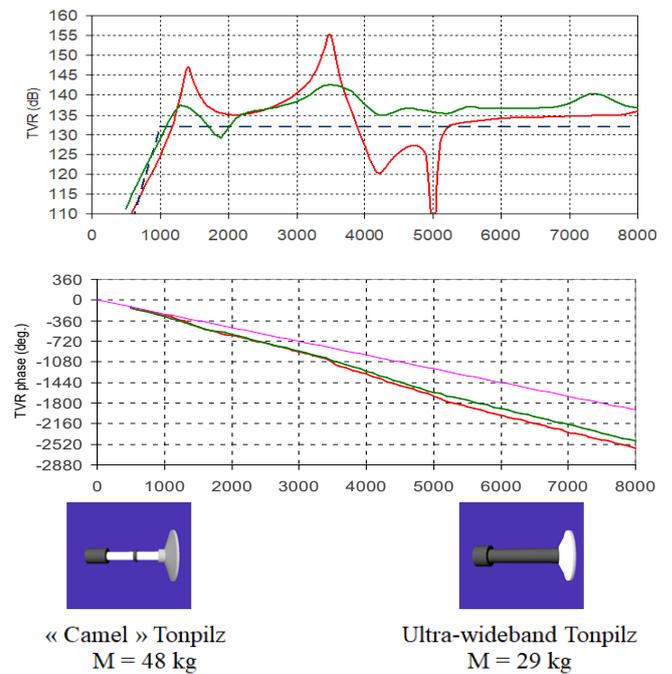


Figure 7. TVR for the new ultra-wideband transducer (simulation). Top: amplitude; bottom: phase.

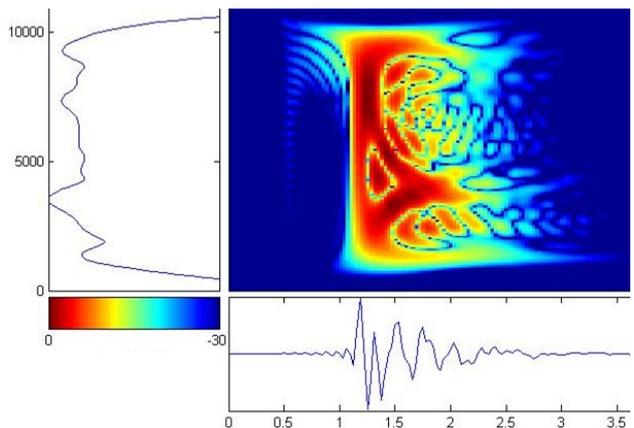


Figure 8. Time-frequency representation PWVD of simulated impulse response for the developed transducer (simulation). Horizontal axis: time in ms, vertical axis, frequency in Hz, logarithmic colour scale.

The built transducer is shown in figure 9.



Figure 9. Photography of the ultra-wide band transducer.

As for simulations, the PWVD has been used for fine localisation and characterisation of time-frequency events. Events were then associated to mechanical components that were optimised in order to obtain better performances.

Figures 10 illustrate this approach. Both represent the PWVD of experimental impulse response. The left one (a) represent the calibration of the prototype before any additional correction. The right figure (b) represents the final response obtained after fine tuning of mechanical components.

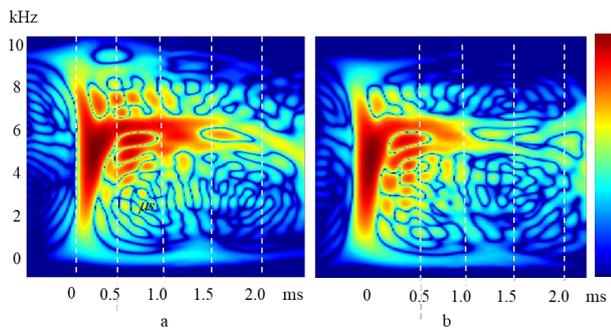


Figure 10. Time-frequency representation PWVD of experimental impulse response for the ultra-wideband transducer. Horizontal axis: time in ms, vertical axis, frequency in kHz, logarithmic colour scale (0-30 dB). a) before correction, b) after final tunings.

4. SEA TRIALS

Sea trials were conducted in the bay of St Tropez (FR). The figure 10 displays the experimental set-up used at sea.



Figure 11. Experimental set-up at sea: ultra-wideband transducer (red arrow) installed on a surface ROV. Receiver (blue arrow) consists into 11 hydrophone linear array of 1.7m.

Sea trials were achieved in shallow water zone (13-15m) with a muddy bottom covered with Posidonia. Surface ROV was towed at 3-4 knots and was positioned with both GPS and motion reference unit.

The main characteristics of the sonar system are the following:

- Transmitted signal: chirp modulated from 0.5 to 10 kHz. Duration: 10 ms
- Source level at 0.8 kHz.: 180 dB ref 1 μ Pa @ 1m
- Echoes were pulse compressed prior to envelope computation and display.

An example of sonar image is provided in figure 12a.

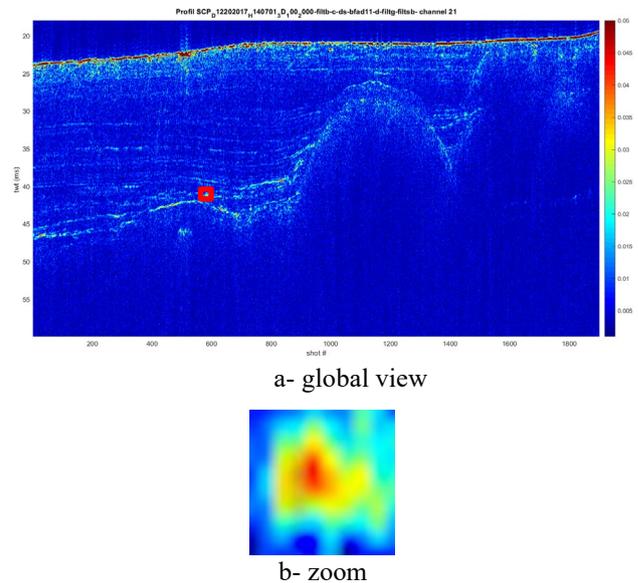


Figure 12. Sub-bottom imaging using the ultrawideband transducer at sea.

- Top; horizontal axis: ping number (0-2000, corresponds to about 350 m) and vertical axis: time (15-60 ms).
- Bottom: zoom on the red square area; horizontal range: 8 pings (about 1.5 m), vertical range: 0.5 ms (propagation in the sediment).

In order to evaluate the overall axial resolution at sea, a zoom around the area marked by a red square in fig 12a was computed and is shown in figure 12b. Measuring the size of the red spot in fig. 12b leads to an axial resolution of 0.12 ms that corresponds roughly to the inverse of the bandwidth ($0.10 = 1/9.5$ kHz).

5. CONCLUSION

There is an increasing need for ultra-wideband transducers for various civilian and naval applications: high resolution imaging, communication, target recognition....

While in ultrasonic range, digital deconvolution techniques may be sufficient, they may be limited when low frequency and high-power systems are concerned.

The time-frequency representation of transducer impulse response (PWVD) has proved to be an efficient tool to understand complex wideband signal and separate in the time-frequency plane phenomena that could be separated neither in the time nor the frequency axis.

This approach was used for designing an ultra-wideband Tonpilz transducer ranging from 1 to 8 kHz with severe design constraints: TVR > 132 dB ref 1 μ Pa/V @ 1m and weight less than 30 kg.

At every step of transducer design, time-frequency representation has been used for physical phenomena understanding and for fine tuning of mechanical components.

The prototype built has been tested at sea and predicted performances were checked in real conditions.

Remaining ripples on TVR are now small enough to be easily corrected by deconvolution using a reasonable dynamic range for digitising.

Future works include the use of an array of such transducers and control the directivity pattern over such a wide range of frequency (frequency variable array shading).

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