ESTIMATION OF SURFACE REFLECTION PROPERTIES BY MEANS OF A NEW FREQUENCY SHIFT TECHNIQUE

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Peter Holstein[1], Roland Müller[1], Gerhard Fischer[1], Jörn Huebelt[2], Felix Franck[3]
[1] *SINUS Messtechnik GmbH,*
Föpplstr. 13,
04347 Leipzig
Germany
Tel: 0049 341 2442919
Fax: 0049 341 2442999
E-mail: hol@sinusmess.de
[2] *Technische Universität Dresden, Institut für Akustik und Sprachkommunikation*
[3] *Hochschule für Technik, Wirtschaft und Kultur, Leipzig*

ABSTRACT

The *in-situ* estimation of reflection properties is of interest for many practical situations.
A new technique will be presented which can be used to measure acoustic reflection. The procedure exploits *Doppler* effects in order to differentiate between incident and reflected waves by means of very small frequency shifts. There are many possible applications of the technique. The high resolution of frequencies will be explained and demonstrated by means of a real-time *zoom FFT* experiment. Multiple reflections, originating from the slow motion of the apparatus, will be shown and transferred into the frequency range (*acoustic pulley*).

INTRODUCTION

Estimations of reflection coefficients are carried out by comparison of incident and scattered (reflected) waves, beams or particles. In acoustics, some peculiar problems and limitations arise. An acoustic signal cannot be focused to a similar extent as optical or molecular beams. The reflected component provides a further spatial dispersion. This yields to consequences regarding the technical equipment and procedures because the aim of all techniques is the differentiation of incident and reflected components because the signal contains the transmitted and the received signal as well at the same frequency. The complications are impressively illustrated by the recent developments to overcome this problem by the use of sophisticated techniques such as MLS (Maximum Length Sequences) in combination with substraction techniques. All such techniques, which exploit the comparison of definite signal patterns, are performed in the time domain. Classical techniques, e.g. Kundt's Pipe, require special equipment and a predefined geometry of the sample material. These techniques are often only suitable for laboratory work. The reflection and absorption coefficients obtained as a result of such experiments are important acoustic characteristics for a variety of materials such as porous road surfaces or foam absorbers [Hue].
It is well known that the motion of a direct or reflecting acoustic source influences the frequency which is measured by a stationary observer (receiver) or vice versa. The Doppler effect in acoustics is an everyday experience, e.g. when fast-moving vehicles pass an observer. The effect can be neglected for slow relative motion of transmitter and receiver. That means, in terms of the Fourier spectroscopy, that the Doppler shift is often much smaller than the spectral resolution which is normally used for real-time applications (e.g. 51,2 kHz sampling rate and 1 .. 4 k data blocks). On the other hand, the

physical effect occurs independently of the numerical resolution and would provide a tool to discriminate a slowly-moving reflector with respect to its surroundings by means of a frequency change. The term *zoom* is used in the DSP-literature [Thr, Hol, Por]. This does not mean a simple expansion of the information of a spectrum in order to increase the resolution on a computer screen or a graphical plot, but rather the real-time realisation of frequency band narrowing without changing the physical sampling rate. It is not the aim of this article to describe the algorithms, numerical solutions and problems in detail; however, it should be mentioned that the technique is not limited to the frequency ranges which are used for the examples. Normally, long-term recording of data requires identical sampling rates for the complete recording range. Typical sampling rates ($1/t_s$) in acoustics are e.g. 44.1 / 48 / 51.2 kHz. Consequently, the resolution given by the sampling theorem (½ sampling rate ÷ block size) can only be improved by using larger file blocks, which entails disadvantages concerning the computing performance and accuracy. Often, only information within a narrow frequency band is of interest. Therefore, obtaining spectra with enhanced resolution from spectra with high sampling rates just by increasing the block size yields unnecessarily large FFT sizes, which are in many cases impracticable or impossible for real-time applications. To achieve the same frequency resolution by means of non-decimated data, the acquisition duration must be prolonged by the factor *d,* which would require a much higher signal stability and is impracticable in many cases. Using zoom techniques, however, there is no need to change the density (t_s) of data acquisition points: this is of importance when either the factor *d* is not known in advance or there are different superposed problems which cannot be recorded using only a single sampling rate.

EXPERIMENTAL AND METHODOLOGY

An acoustic bench has been constructed in order to improve the reproducibility of mechanical situations. The two principal set-ups of the experiments are exemplified in Figure 1.

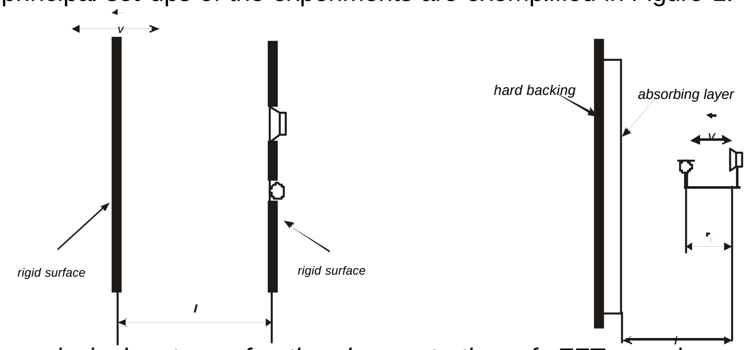

Figure 1 *The two principal set-ups for the demonstration of FFT-zooming and the estimation of reflection properties by means of the Doppler-effect experiment. The object (reflector) moves very slowly (around 0.001 ..0.002 ms^{-1}). In order to observe frequency-resolved multiple reflections, source and receiver are assembled in one (e.g. in the non-moving) reflector. The second reflector can be moved with the velocity v. The other type of experiment is designed to prevent multiple reflections. Acoustic source and receiver have a (fixed) distance r_1 . Both have the common velocity v. The variable length is denoted as l.*

The enhancement of the spectral resolution can be calculated from the decimation rate *d*. The zoomed spectral width is $1/\{(2\times t_s)/d\}$. All samples contribute to the calculation of the zoomed spectra, resulting in a large overlap (up to 1024) of the spectral information. The interplay between decimation and spectral resolution overlap is illustrated in Figure 2. The control of the experiment and post-processing tasks were performed using a MATLAB™-Toolbox written by the authors.

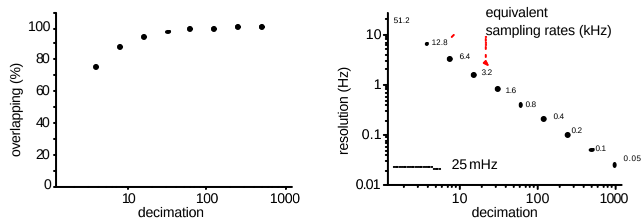

Figure2 *Dependence of spectral resolution on the decimation rate (*left*) and overlapping of decimated data blocks for the FFT calculation (*right*)*

The zoom-FFT was used to obtain narrow bands at high resolutions from data with high sampling rates. As usual, the signal passes through a general anti-alias filter which reduces the effective bandwidth to about 20 kHz. The signal is then mixed with a carrier frequency which defines the centre frequency for the expanded range. The sine and cosine values are obtained from real-time tables which provide an efficient and highly accurate calculation of the mixing frequencies. Furthermore, this results in a very effective suppression of the carrier frequency to below -90 ... -100 dB (under the noise level). One advantage is that the signal becomes complex. Therefore, positive and negative frequencies relative to the carrier frequency can be distinguished. This technique has some similarities e.g. with frequency modulation (FM) techniques or the data acquisition in NMR (Nuclear Magnetic Resonance). A decimation of 2 would yield a +/-12.5 kHz range. Therefore, the first usable decimation level is 4. The inverse transformation can be done by means of algorithms which are known from FM techniques (or digitally as a Hilbert transformation). A further advantage of the modulation technique is that it enables the use of decimation filters which are independent of the frequency range of interest. Only one filter design is necessary for each decimation level, which allows the convenient implementation of efficient real-time DSP tasks. As mentioned above, despite the decimation of the original samples, all data are used for the calculation of the spectra. The time-signal treatment overlaps according to the decimation rate. One beneficial effect is that a huge averaging rate of the signal becomes possible. The signal recording (for one data block) is prolonged by the decimation rate. To acquire a data block for the zoom-FFT calculation needs $1k \times t_S \times d$ recording time. Consequently, the higher the decimation rate, the more the spectra overlap, which can be used to average the decimated spectra with an accumulation rate analogous to that of the non-decimated original data. This results in a good signal-to-noise ratio which cannot be achieved by simply using large data sets for non-decimated data. In contrast to increasing the block size, accumulation of data yields the advantage that the influence of the statistical noise can be reduced. An other way to enhance the resolution is to increase the number of data points for the calculation of a spectrum. Large data sets (e.g. of the length d×1k) provide the same frequency resolution as "identically" decimated spectra, but they do not have the advantage of noise reduction. The numerically equivalent treatment using the large FFT sizes would require much more computing performance and calculation time which remains impracticable or simply impossible in many real-time applications, despite the availability of faster PC's. Furthermore, the numerical noise is drastically reduced. Beside the prolongation of the calculation time of a spectrum, some numerical problems (precision) can arise when extremely large data sets are used. Let us consider the identical experiment repeated with a decimation rate *d* of 1024. That means the spectral range is now 25.6 Hz compared to 25600 Hz without decimation. For comparison, estimations of the power spectral density of large files giving identical spectral resolution have been performed with the standard high precision of MATLAB (IEEE double precision format with 52-bit mantissa). In contrast, the DSP calculations with the real-time algorithms are based on a 24-bit mantissa. Nevertheless, the signal-to-noise ratio around the carrier frequency of the zoomed data is of the same order, although only 0.1 % of data points compared to the real-time DSP data are used.

The calculation of a spectrum with an equivalent resolution from non-decimated data requires in the order of 1 min. (500 MHz PC), and is therefore not suitable for real-time use or for the post-processing of large data sets. The frequency resolution (50 mHz) is still worse than in the case of the 1k data blocks with the high decimation rate of 1024. The original signal was sampled at 51.2 kHz, giving a resolution of 25 Hz in the frequency range at a block size of 1 k for real-time processing. The resolution can be increased by means of decimated data (here for *d*= 256, 1024) up to 25 mHz, which is equivalent to the spectral resolution of relative motion below 0.001 ms^{-1} with t_d^{-1} = 51.2 kHz and 1 k samples. The highest possible decimation rate for the recording software is 1024 (2048 for the DSP board used). High decimation rates would enable, at least in principle, the detection of speeds below 0.001 ms^{-1} (at 19 kHz). The use of the maximum resolution (25 mHz) requires a high signal stability during a detection period of at least 1024×1k×20µs ≈ 20s. It is important to note that the digital filters in real-time applications must have a filter response time which scales with the decimation rate in order to cope with transient states. The source signal has a frequency of 19 kHz (sine) and is reflected by a very slowly moving real object (reflector) which serves as the secondary source for the demonstration.

RESULTS AND DISCUSSION

The Doppler shift (Hz) of the reflecting source is

$$f_d = 2 f_0(\nu / c)\cos(\theta) \qquad (1)$$

where f_0 is the frequency of the transmitted signal, ν is the speed of the reflector, c is the sound velocity and θ is the axis between signal direction and motion (0° in our set-up). Constant low speeds

(for the acquisition time) of an acoustic reflector are of particular importance for the experiment. Constant minimum velocities of about 0.001 ms^{-1} could be realised, which was in good agreement with the requirements of the frequency resolution (Figure 1). A consequence of the in-line arrangement is that the angle θ is 0 for all positions of the reflector. This results in a constant Doppler shift independent of the distance between transmitter and receiver. However, an off-axis arrangement of reflector and/or microphone would result in a $\cos(\theta)$ dependence on the Doppler shift. This effect has been clearly observed. In a modified experiment, the change of sign of the Doppler shift can be observed (pass-by of a moving source). The situation is further complicated if the reflector passes the source at a certain distance. However, this distance and the vector properties of the velocity of the reflector can be obtained by use of the multiple-channel facilities of the data acquisition system.
For two reflectors, the sound pressure can be expressed as the sum of the multiple reflected orders of the sound wave (the $+j\omega t$ convention is used) :

$$p_t(\omega) = \frac{A|_{\omega_0}}{r_1} \cdot e^{-j\omega_0 \frac{r_1}{c}} + \sum_{i=1}^{n} R|_{\omega_0} \cdot \frac{A|_{(\omega_0 + i\Delta\omega)}}{r_{i+1}} e^{-j(\omega_0 + i\Delta\omega)\frac{r_{i+1}}{c}} \qquad (2)$$

where $\Delta\omega$ denotes the Doppler shift (angular frequency, $\Delta\omega=2\pi f_d$), A the amplitude at the given frequency, R the reflection coefficient, and p_t, p_1, p_2 the sound pressures.

Equ. 3 reduces for a single reflection (i=1) to:

$$p_t(\omega) = \frac{A|_{\omega_0}}{r_1} \cdot e^{-j\omega_0 \frac{r_1}{c}} + R|_{\omega_0} \cdot \frac{A|_{(\omega_0 + \Delta\omega)}}{r_2} \cdot e^{-j(\omega_0 + \Delta\omega)\frac{r_2}{c}} \qquad (3).$$

From the linearity theorem of the Fourier theory, the amplitude ratios in the time domain and in the frequency domain remain unchanged. We obtain:

$$p_2|_{(\omega_0+\Delta\omega)} = R|_{\omega_0} \frac{A|_{(\omega_0 + \Delta\omega)}}{r_2} \cdot e^{-j(\omega_0 + \Delta\omega)\frac{r_2}{c}} \qquad (4),$$

$$p_1|_{\omega_0} = \frac{A|_{\omega_0}}{r_1} \cdot e^{-j \cdot \omega_0 \frac{r_1}{c}} \qquad (5)$$

and

$$A|_{(\omega_0+\Delta\omega)} = A|_{(\omega_0)} \qquad (6)$$

The reflection coefficient ($R(\omega)$) can be calculated if the intensities of emitted and reflected waves (of multiple orders) can be distinguished (which is the basic aim of the presented technique):

$$|R(\omega)| = \left(\frac{2(l - N \cdot t_s \cdot v)}{r_1} - 1 \right) \frac{\left| p_2|_{(\omega_0+\Delta\omega)} \right|}{\left| p_1|_{\omega_0} \right|} \qquad (7)$$

The equation could be applied for all orders.
Let us now consider reflector speeds producing Doppler shifts which would not be detectable with the original sampling rate. A recording of spectra (DSP-calculated) equidistant in time for a motion of the reflector toward the source (upper spectrum), which produces higher frequencies, and for motion away from the source (lower spectrum) resulting in a low-frequency shift is given in Figures 3 and 4.

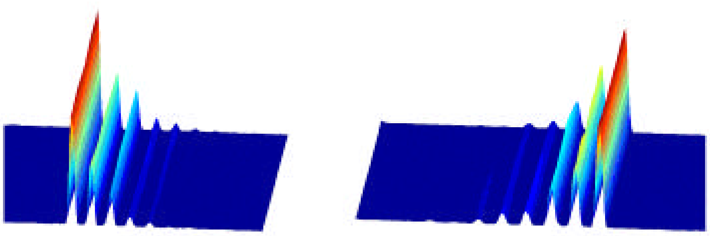

Figure 3 *Highly resolved zoom-FFT spectra (100 spectra) of a slowly-moving reflector (about 0.002* ms^{-1}*). Left: (19kHz – 2.5 Hz …19 kHZ + 8.7 Hz) moving away from the source, right: (19kHz – 8.7Hz …19kHZ + 2.5Hz) towards the source. The spectral resolution is 25 mHz. The largest intensity originates from the 19 kHz carrier frequency.*

The relative speed is identical. The pilot source and the microphone are fixed on one reflector side (Figure 1 left). Clearly resolved are the different orders of the reflection. The first order is the "normal" Doppler-effect, as expected. However, there some additional orders in the spectra which are caused by multiple reflection. The zooming technique enables a real-time observation of an "*Acoustic Pulley*" over several orders. The number of orders observable depends on the reflection properties of the reflecting material and on the geometry of the experiment.
The number of observable orders is only influenced by the reflection properties of the set-up and the materials used. Three different relative speeds are compared in Figure 4.

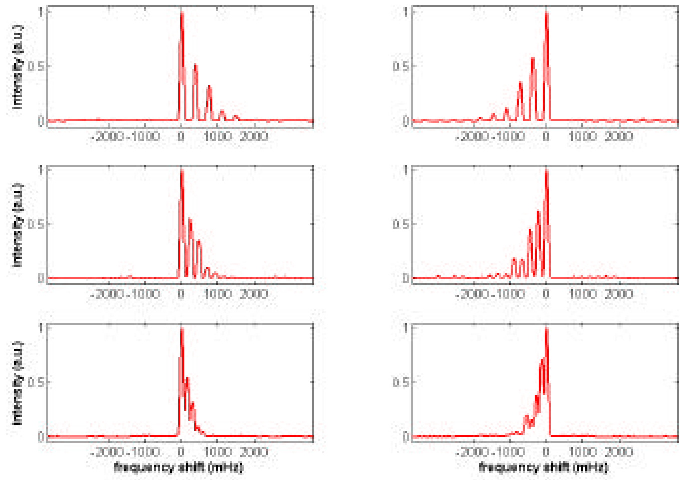

Figure 4 *Comparison of the Doppler shift for three different speeds of the reflector relative to the sound source.*

The spectra shown in Figures 4, 5 and 6 are averaged (100 spectra) in order to improve the signal-to-noise ratio. In combination with the use of the overlap, this results in a further drastic improvement of the signal quality, enabling the detection of very weak signals. The ratio of intensities of the resolved orders are mainly influenced by the geometry of the experimental set-up and by material properties. An example is shown in figure 5 in logarithmic form for the case of an acoustically hard material. The decay corresponds well with the theoretical predictions of equ. 2. It should prove worthwhile to verify and exploit the effect for the estimation of reflection properties such as reflection coefficients.

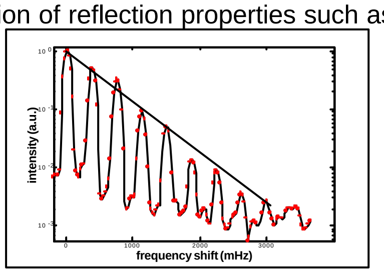

Figure 5 *Logarithmic plot of the intensity (left spectrum of the first row in Figure 4). At 19 kHz, the aluminium surface of the reflector is acoustically hard. Equation (2) predicts a factor of 0.5 between the orders for a reflection coefficient R»1, which can be observed to a good approximation.*

Some preliminary experiments have been carried out in order to estimate reflection or absorption coefficients. In order to avoid multiple reflections from environmental sources, this experiment was performed in an anechoic room.

f / [kHz]	v / [mm/s]	r_1 / [mm]	r_2 / [mm]	p_2/p_1	R	α
19	7	550	4830	0.112	0.98	0.04
19	4	550	4150	0.126	0.95	0.09
6	6	550	2150	0.250	0.98	0.04
6	6	550	1040	0.067	0.13	0.98

Table 1 *Reflection and absorption coefficients for an acoustically hard material (rows 1 … 3) and an absorbing material (open-cell foam, row 4).*

The Doppler shift is smaller for 6 kHz but still well-resolved. The reflection properties have been estimated using equation 7. The results are summarised in Table 1. The technique could be applied down to 1 kHz using the experimental set-up without further modifications. However, there is no limitation in principle with respect to the carrier frequency. The reduced Doppler shift at lower relative speeds and/or lower carrier frequencies can be partly equalized by using larger data blocks in the DSP (or post-processing) calculations.

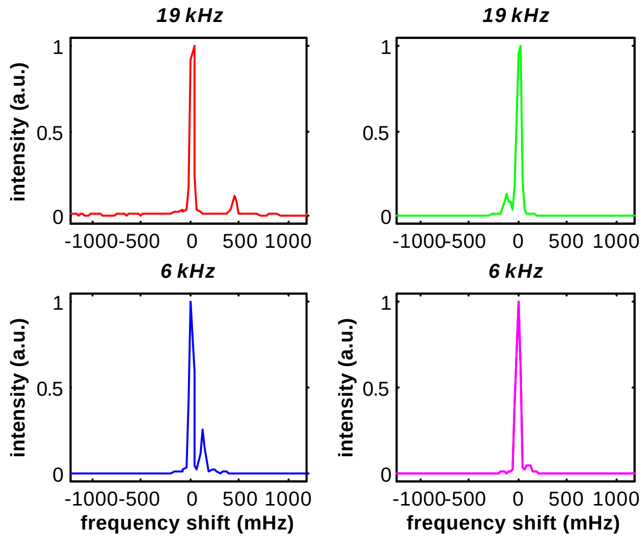

Figure 6 *The Doppler shift experiment for different carrier frequencies, directions of the source and materials (top left: 19 kHz, moving towards acoustically hard surface, top right: 19 kHz, moving away from acoustically hard surface, bottom, left: 6 kHz, moving towards acoustically hard surface, bottom right: 6 kHz moving towards open-cell foam source)*

CONCLUSION

The value of decimation techniques is often underestimated. It should be possible to extend the field for real-time applications and post-processing techniques as well as demonstrated above, e.g. by means of the resolution of small Doppler shifts and very closely-spaced beat-frequencies. The so-called zoom-FFT can be applied to achieve an enhancement of the spectral resolution around a centre frequency. There are several advantages compared to the use of very large data blocks in order to achieve comparable frequency resolution. As well as its high frequency resolution, a similar improvement can also be achieved for phase glitch and small phase differences. Applications are possible wherever higher frequency resolution is needed. When more than one detector is available, the vector of the source velocity can be estimated. When the conditions for sound reflection can be geometrically optimised, the Doppler shift can be used for the direct estimation of frequency-resolved reflection properties of materials. The procedure can be used not only for laboratory work but also under rough outdoor conditions. There is a wide area of applications such as high accuracy frequency estimation, adjustment and calibration purposes or an enhanced frequency resolution either in real-time or by post-processing of data as exemplified for the investigation of reflection properties.

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ADDRESS:

Dr. Peter Holstein, SINUS-Messtechnik GmbH,Föpplstr. 13, 04347 Leipzig, Germany
e-mail: hol@sinusmess.de