On the Experimental Validation of Parametric Transmission Systems

Karsten Wiedmann and Tobias Weber
Institute of Communications Engineering, University of Rostock
Richard-Wagner-Str. 31, 18119 Rostock, Germany
Email: {karsten.wiedmann}{tobias.weber}@uni-rostock.de

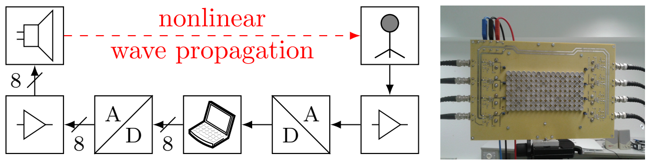
Introduction

In parametric transmission systems, a low frequency acoustic wave with a high directivity and a high relative bandwidth is generated by making use of the nonlinear wave propagation in fluid media. To this purpose, an appropriately modulated and intense ultrasonic wave is radiated by a small aperture transducer. During the wave propagation in the fluid, nonlinear distortions occur at all points where the ultrasonic wave is intense. This yields a virtual large aperture source radiating the intermodulation products (IM products) of the ultrasonic wave.

For technical purposes, particularly the second-order low frequency IM products are of interest. These components can cover the audible range so that parametric acoustic loudspeakers [1] or virtual microphones [2] can be realized taking advantages of the high directivity. Furthermore, the reduced channel attenuation at low frequencies plus the high directivity while using small aperture transducer arrays and the high relative bandwidth motivate the use of parametric transmission systems in underwater acoustics for SONAR [3] and communication applications [4]. Further applications are reported in [5, 6].

A key problem in the experimental investigation of corresponding systems arises from the high transmit power, which is required to sufficiently generate IM products in the fluid. First, IM products due to nonlinear distortions originating from the non-ideal hardware may be of the same order as the components being nonlinearily generated in the fluid. Secondly, the active source region is typically large and its extend is a priori unknown, making farfield measurements in conventional measurement chambers problematic.

This paper discusses methods for the experimental validation of parametric transmission systems. This includes methods which aim at assessing the origins of the observed nonlinear effects. The underlying idea for the methods is to examine specific characteristics of the observed IM products, which may indicate or exclude a certain origin of the generation. For instance, transmitter side generated intermodulation products (Tx-IM products) are already transmitted by the transducer and will therefore exhibit the typical characteristics of a linear radiation. Air generated intermodulation products (air-IM products) exhibit a 12 dB gain, when its frequency is doubled, see [7] for details. Increasing the intensity of the ultrasonic wave by some amount at the microphone, the receiver side generated intermodulation products (Rx-IM products) will exhibit twice the gain.



(a) (b)

Figure 1: Measurement setup under investigation (a) and utilized ultrasonic transmitter array (b).

Furthermore, some of the methods enable an extend estimation of the virtual source and partly can be used to adjust the system setup.

The methods will be distinguished between adaptations at the transmitter, at the receiver and measurements in the acoustical axis. Methods, which are discussed in the literature for this purpose, will be illuminated and developed. Additionally, new methods will be presented. The discussed methods will be illustrated by means of an experimental validation of a generic parametric transmission system in air, which will be introduced next.

Measurement Setup

A block diagram of the parametric transmission system under investigation is shown in Fig. 1(a). The signal generation and processing is done by a PC equipped with an eight channel D/A-converter and a one channel A/D-converter. The D/A- and the A/D-converter sample at a rate of 250 kHz and are synchronized to enable coherent measurements.

The signals to be transmitted are amplified separately and transduced by an acoustic transducer array, see Fig. 1(b), consisting of 8×16 PROWAVE 400ST100 array elements, having a center frequency of $f_0 = 40\,\mathrm{kHz}$. Each row, i.e., 16 array elements, can transmit a separate signal. The maximum achievable sound pressure level (SPL) is $\approx 150\,\mathrm{dB}(1\,\mathrm{m}, \mathrm{re}\ p_0)$.

At the receiver side, a condenser microphone of the type Microtech Gefell MK301 and a corresponding microphone preamplifier of the type Microtech Gefell MV210 are used. A lowpass filter with an integrated amplifier of the type Alligator Technologies USBPGF-S1 is implemented for anti-aliasing filtering and signal conditioning. This way, acoustic waves can be captured up to 100 kHz. Absorber panels are positioned behind the microphone to reduce the influence of the room.

Within this paper, only a two tone excitation is consid-

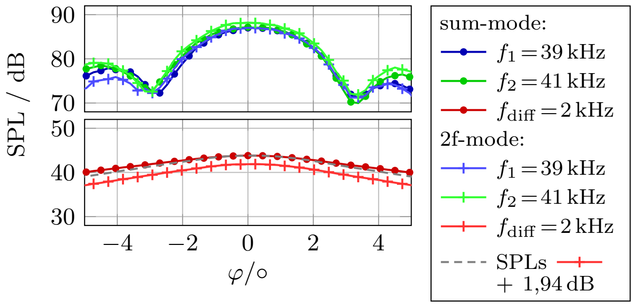


Figure 2: Comparison of the 2f-mode and the sum-mode.

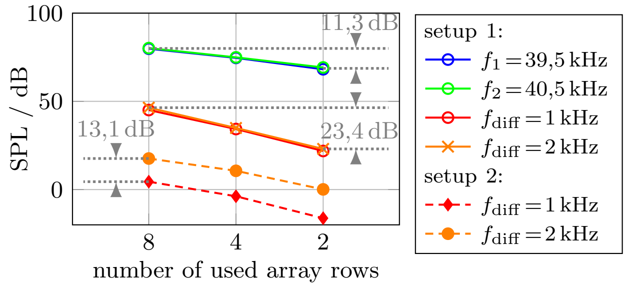


Figure 3: Assessment of the predominate intermodulation products by changing the active radiating transducer array and the difference frequency.

ered, i.e., only two high frequency sinusoids having the frequencies f_1 and f_2, respectively, with $f_2 > f_1$ are transmitted. Among others, this nonlinearly creates a low frequency IM product at $f_{\text{diff}} = f_2 - f_1$. Other IM products, e.g., at the sum frequency or due to higher order nonlinearities are not discussed in the following investigations.

Furthermore, it will be distinguished between two measurement setups, where setup 1 equals the above mentioned setup. In setup 2, the microphone capsule is additionally muffled in a foam. The foam introduces ≈ 30 dB attenuation at the ultrasonic frequencies but the attenuation below 4 kHz is negligible.

Transmitter Side Methods

An assessment of Tx-IM products is redundant, if the sinusoids are transmitted via separate output channels, denoted as '2f-mode' in the following. This way, only harmonics of the sinusoids are generated at the transmitter which will not harm the investigations of parametric systems. This approach is reported in [6], where a hexagonal array comprising two separate output channels is used.

However, this operating method will create a slightly different virtual source in comparison to the transmission of the sum signal via each output channel, denoted as sum-mode in the following. The impact on the performance of a parametric system is not negligible as illustrated by the experimental result shown in Fig. 2. Here, in the 2f-mode, sinusoids of frequency f_1 are radiated via the array rows $\{1, 3, 5, 7\}$ and sinusoids of frequency f_2 are radiated via the remaining rows. The SPLs are measured vs. the azimuth φ, where $\varphi = 0°$ points in the direction of the transducer array's acoustical axis. As can be seen, the conversion efficiency is reduced by ≈ 2 dB in the 2f-mode due to a shortened active source region. Further, the 2f-mode achieves a higher directivity, where the 3 dB beam width is ≈ 1,5° smaller in comparison to the sum-mode in this experiment. A more serious broadening of the beam in the sum-mode is reported in [6].

Note that the 2f-mode cannot be used in most applications, because typically some form of modulation is used in the ultrasonic wave. However, measurements using the 2f-mode can be applied in order to estimate the system performance.

In the sum-mode, the radiation of Tx-IM products has to be investigated. Note that Tx-IM products are radiated linearily from the transmitter. Thus, varying the radiating transmitter area yielding some gain in the ultrasonic waves will cause the same gain in the IM products given that the observed IM products are predominately Tx-IM products. Contrarily, if the nonlinear generation occurs predominately in the air or at the receiver, the nonlinear distortions occur after the coherent superposition of the transducer element's contributions so that observed IM products will experience twice the gain as the ultrasonic wave. For the IM product at the frequency $f_{\text{diff}} = 1$ kHz, Fig. 2 indicates that the observed IM product is not due to the transmitter nonlinearity in both experimental setups, i.e., with and without the foam.

Repeating the experiment and varying the frequency f_{diff} of the IM product enables a further distinction. Due to the highpass characteristic of the parametric effect, air-IM products are expected to show a 12 dB gain per frequency doubling, which may be not the case for Rx-IM products. Applying this method, Fig. 2 indicates that the air-IM product is predominately observed with the foam and the Rx-IM product without the foam.

Moreover, different radiation patterns are expected for the different IM products. Since the Tx-IM products are linearly radiated by the transducer array whose aperture is typically small in comparison to the wavelength of the (low frequency) IM products, basically a low directivity is expected. For reason of comparison, the radiation pattern of a piston source of an equivalent aperture to the utilized transducer array is exemplarily depicted for a $f_{\text{diff}} = 500$ Hz sinusoid in Fig. 4. Furthermore, measuring the radiation pattern, i.e., rotating the transducer array versus its azimuth φ, changes the intensity of the ultrasonic waves at the microphone position. Note that the intensity of the IM products at the difference frequency is

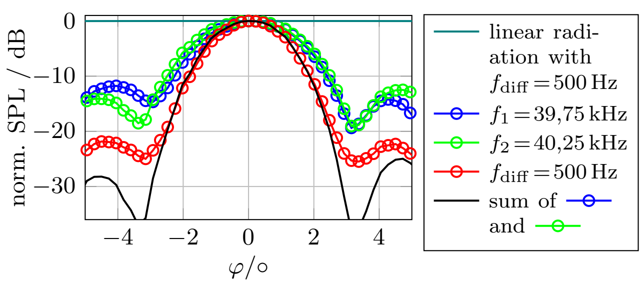


Figure 4: Investigating the radiation patterns of the intermodulation products using setup 1.

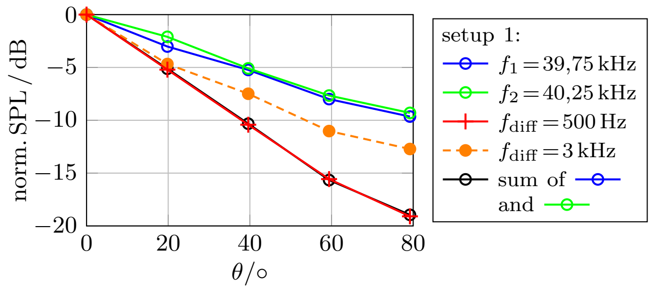


Figure 5: Exploiting the microphone directivity for an assessment of the predominate intermodulation products.

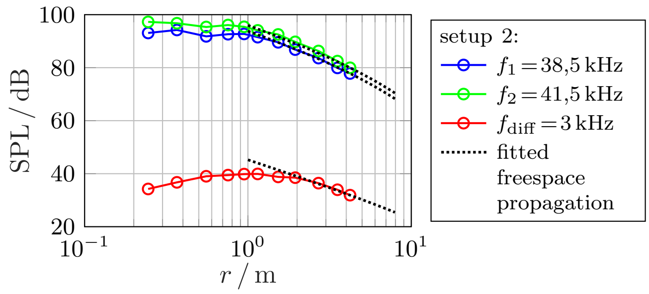


Figure 6: Measured SPLs in the acoustical axis.

proportional to the intensity of the product of the ultrasonic waves. Consequently, in a logarithmic scale, Rx-IM products can be figured out by comparing the measured radiation pattern of the IM product with the sum of the ultrasonic radiation patterns. Exemplarily using setup 1, Fig. 4 shows the radiation pattern of an IM product at $f_{\mathrm{diff}} = 500\,\mathrm{Hz}$, which is predominately generated at the receiver for the azimuths $-3° \leq \varphi \leq 3°$. It can be deduced from this investigation that also an attenuation of the ultrasonic waves at the microphone by $-15\,\mathrm{dB}$ will not be sufficient to reduce the Rx-IM products for an analysis of air-IM products. Accordingly, this method can support the system adjustment.

Receiver Side Methods

Here, as in the investigation of the radiation patterns, the basic idea is to attenuate the ultrasonic waves at the microphone and to investigate the behavior of the observed IM products. This can be done by embedding the microphone in a foam revealing a lowpass characteristic as done in [8, 9] or by employing the frequency dependent directivity of the microphone as done in [6]. The latter is done for the example of the $f_{\mathrm{diff}} = 500\,\mathrm{Hz}$ IM product using setup 1, see Fig. 5. The microphone is rotated in its azimuth θ, where $\theta = 0°$ is the direction of the transducer array. Again, the IM product match the sum of the normalized ultrasonic SPLs so that the receiver nonlinearity dominates in this case. Contrarily, the observed IM product at $f_{\mathrm{diff}} = 3\,\mathrm{kHz}$ show this behavior only for small azimuths θ, i.e., for a low attenuation of the ultrasonic waves. It looses this behavior for larger azimuths θ so that it can be deduced that an ultrasonic attenuation of $10\,\mathrm{dB}$ is sufficient to decrease the Rx-IM product in this case. Accordingly, this method can be used to adjust the system setup as well.

Acoustical Axis

IM products due to the air nonlinearity are generated within the virtual source region. As a result, the intensity in the acoustical axis is expected to increase with the distance r to the transducer array until absorption and spherical broadening dominates the nonlinear generation and the intensity starts to decrease. Beyond the active source region, nonlinear contributions are negligible and freespace propagation will be observed. An appropriate system setup will reveal this characteristic, when the SPLs in the acoustical axis are measured, see Fig. 6.

Again, Rx-IM products can be figured out by comparing the gains of the ultrasonic waves and the gains of the IM products. But Tx-IM products may hardly be distinguishable from air-IM products especially if the active region is short. Consequently, the aforementioned methods have to be applied in addition for a clarification. Alternatively, as done in [9], the transmitter array can be covered by a foam. This hinders the ultrasonic waves to propagate so that air- and Rx-IM products are decreased and an investigation of the Tx-IM products can be done. However, this method strongly depends on the characteristics of the applied foam and feedback due to reflections cannot not be surely avoided.

Besides an assessment of the observed IM products regarding their origin, this method can obviously be used to estimate the extend of active source region given that the system is properly adjusted and air-IM products predominate. The extend may be reasonable estimated as the beginning of the observable freespace propagation.

Unfortunately, measurements of the SPLs in the acoustical axis over several meters are required for this assessment and appropriate measurement chambers of this extend are often not available. Experiments in labs may suffer from significant multipath propagation so that the freespace assumption is invalid. In order to handle multipath propagation, a time-gating approach can be realized by generating a chirped IM product, compare [7]. Regarding this IM product as the response of a linear system, which is excited by a corresponding low frequency chirp at the input, the impulse response of the linear system can be obtained by a deconvolution. The magnitudes of the pulses that correspond to the direct path can be used for the analysis, see Fig. 7. Here, the magnitudes are scaled to the overall measured maximum. Since the pulse magnitude is proportional to the acoustical intensity in the acoustical axis, an increase can be observed

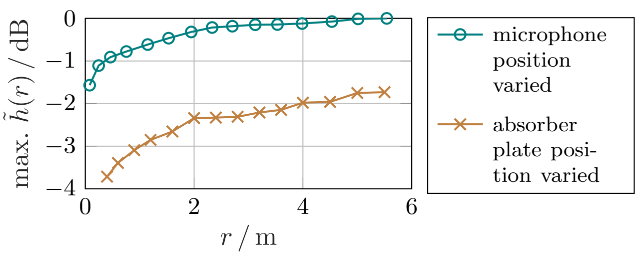


Figure 7: Scaled magnitudes of the pulses corresponding to the direct paths.

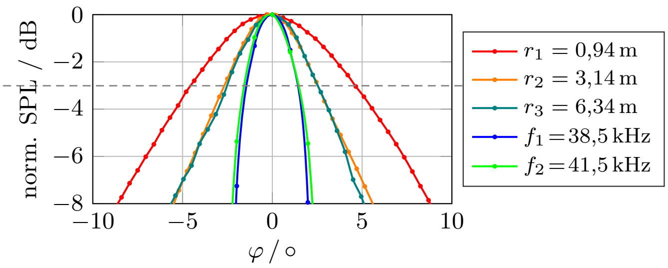


Figure 8: Measured directivity patterns at different distances with $f_{\mathrm{diff}} = 3\,\mathrm{kHz}$ using setup 2.

within the active source region. But in comparison to Fig. 6, the active source region seems to be significantly larger. It is reported in [9] that the extend of the active source region increases with a decrease in the difference frequency, which is owed to the frequency dependence of the parametric effect, the channel attenuation and the nearfield length of the transducer array. Since the time-gating approach measures over some bandwidth, this may consequently lead to an over estimation of the active source region for the high difference frequencies.

Another experiment in order to estimate the extend is reported in [8, 9]. Here, the active source region is artificially limited by an absorber plate for the ultrasonic waves. The position of the absorber plate is varied on the acoustical axis, whereby the microphone position is fixed. A stagnation in the measured air-IM products indicates the end of the active region. The result of a corresponding experiment is shown in Fig. 7, using again the time-gating approach. Both results shown in Fig. 7 indicate that the main part of the intermodulation takes place up to $r \approx 3\,\mathrm{m}$.

Results

An experimental validation for the difference frequencies $500\,\mathrm{Hz} \leq f_{\mathrm{diff}} \leq 4\,\mathrm{kHz}$ by means of the discussed methods reveals for both measurement setups that Tx-IM products are negligible. Rx-IM products are primarily observed in setup 1, especially when low difference frequencies are applied, e.g., $f_{\mathrm{diff}} = 500\,\mathrm{Hz}$. Contrarily, the 30 dB attenuation of the ultrasonic waves introduced by the foam in setup 2 is sufficient to reduce the Rx-IM products below the air-IM products. Thus, setup 2 is appropriate to observe the air-IM products.

The extend of the active source region is estimated to be $\approx 3\,\mathrm{m}$. To validate this, radiation patterns using setup 2 are measured and shown in Fig. 8 for different measurement distances r. As can be seen, the radiation patterns at $r = 3{,}14\,\mathrm{m}$ and $r = 6{,}34\,\mathrm{m}$ coincide, whereas the pattern measured at $r = 0{,}94\,\mathrm{m}$ is significantly broader. Measured 3 dB beam widths are reported in Tab. 1 for the IM product at $f_{\mathrm{diff}} = 3\,\mathrm{kHz}$. For this IM product, a conversion loss of $\approx 45\,\mathrm{dB}$ is measured at a distance $r = 4{,}5\,\mathrm{m}$. Note that no optimization regarding the conversion efficiency is done at this point so that the conversion loss has to be regarded as a lower estimate.

Table 1: Measured 3 dB beam widths.

frequency	value / kHz	3 dB beam width / °
f_1, f_2	38,5/41,5	3/2,5
f_{diff}	3	5 ($r_1 = 6\,\mathrm{m}$)
linear radiation	3	22

Conclusions

This paper discusses methods, which aim at assessing the origin of observed nonlinear effects in parametric transmission systems. The underlying idea is the examination of the observed intermodulation products regarding characteristics, which indicate or exclude certain origins of their generation. Since there is not one overall method, especially the combination of different methods seems to be promising.

Tough focused on air systems, the methods can be accordingly utilized for underwater parametric systems.

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