EVALUATION OF METHODS TO MEASURE ACOUSTIC TRANSER FUNCTIONS IN CAVITATION TUNNELS

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The interest for cavitation noise studies and prediction is increasing in the field of naval architecture, mainly because of attention to environmental issues. Model scale tests in cavitation tunnels are commonly considered as one of the most effective tools for cavitation noise studies. However, despite being carried out since long time, model scale experiments still present many challenges. These are mainly related to scale effects on propeller hydrodynamics, cavitation behaviour and scale effects on noise generation and propagation. Besides these phenomena the effect of the confined environment in which tests are carried out may be of great importance.
In present work, an acoustic characterization of the SSPA large cavitation tunnel section #3 is presented, with the aim to obtain suitable transfer functions in order to take into account (at least partially) this phenomenon. The acoustic characterisation is performed considering two different underwater transducers and different signals and post processing techniques.
The obtained transfer functions are shown and discussed in order to analyse advantages and shortcomings of the different procedures and to generally identify main problems related to this kind of activity.

1. Introduction

The problem of propeller underwater radiated noise has been addressed by naval architects since long time, being of utmost importance for naval ships and special purpose ships, e.g. research vessels. In the last years, however, due to the increased attention to environmental issues (anthropogenic noise impact on marine fauna), this issue is gaining more interest also for merchant ships and the possibility to introduce limits is being discussed in the maritime community.
Due to this, it appears very important to improve and validate the instruments and procedures for a correct prediction of radiated noise in the design phase. Despite the great advances of CFD in the last decades, the direct numerical evaluation of radiated noise is still extremely demanding, very expensive in terms of computational effort and limited in frequency range. Therefore model scale radiated noise measurements in different facilities still represent the most viable solution.
Also in this case, however, radiated noise measurements (and their transfer to full scale) present different problems, among which scale effects and confined environment effects.
A detailed summary of main issues regarding propeller noise measurements in model scale facilities has been presented by Blake and Sevik [1], analysing different facility typologies, setups and instrumentation, discussing also the possible influence of confined environment and boundaries on

measured noise. From this point of view, the calibration of the model scale facilities confined environment evaluating of transfer functions has been suggested by ITTC in [2], [3] and [4].
The importance of this aspect may obviously vary significantly depending on facilities characteristics and in general larger facilities are less affected by these problems. Nevertheless, at least for the lower frequency range, some effects are always present. As a consequence to this, the usual spherical propagation law often adopted in order to take into account the effect of distance may not be correct [5].
The present work is focused in particular on this problem. Even if the confined environment effect has been discussed for long, with efforts in order to establish a procedure; only limited examples exist in literature about application of these approaches and each facility still performs tests on the basis of its own experience.
Relevant examples are those presented in [2][3] regarding the determination of transfer functions for the tunnel of the Shanghai Chiaotung University and for the Tokio SRI Large Cavitation Tunnel.
The problem was also addressed by Bark in his thesis [6] for different cavitation tunnel test sections and different experimental setups adopted at SSPA.
One of the possible problems encountered during the acoustic characterisation of the different facilities is related to the choice of the noise transducers to be adopted. In principle the transducer should be omnidirectional and with limited dimensions.
Actually, when focus of the experiment is on cavitation noise, the sources may be represented by pulsating sheet cavities, vortices and collapsing bubbles. As a consequence the propeller could be schematised as a distribution of point sources, more or less spread in space (not only on the propeller blades but also downstream) depending on the cavitation extensions under study.
Due to this, transducer dimensions should be preferably lower than propeller dimensions and, if possible comparable with typical dimensions of cavities.
On the other hand the transmitting voltage response (TVR) of a transducer at low frequencies usually decreases with decreasing dimensions of the source.
As a consequence a compromise solution between limited dimensions and transmitting capabilities has to be found.
This problem may depend also on the type of signal adopted for calibration as it will be discussed also in the following.
A further problem is represented by source localization during calibration, actually, as it will be shown also in present work, transfer functions may vary significantly for different source positions.
In principle each noise component radiated by the propeller should be transferred to the ideal free field conditions with respect to the position where it is generated.
However the identification of the regions where noise is generated and corresponding intensity is a complex task, especially for extended cavities like developed vortices.
If cavitation occurs mainly in a limited region it is reasonable to consider that region for locating the noise source during transfer function measurements. Thus the most suitable source positions may be defined from expected or observed cavitation extensions.
From a different point of view the knowledge of transfer functions for different hydrophones and for a large number of source positions may allow to localise noise source for the propeller as reported in [7].
In the present work, recent experiences gained at SSPA and UNIGE are presented, analysing some issues related to this topic, considering different signals for the evaluation of the transfer functions, including white noise, pure tones and sweep signals and different transducers allowing to discuss the problem and present merits and shortcomings evidenced. Results obtained for the characterization of UNIGE cavitation tunnel have already been presented in [8], here attention will be focused on the more recent measurements carried out in the SSPA large cavitation tunnel.

2. Adopted techniques

The adoption of the system model characterized by a transfer function is quite diffused in many engineering fields and also in acoustics.
Thus the output of the system is represented by a deterministic function of the input summed with the noise. The knowledge of this function could be useful both to equalize the output of the system and to determine the system input when the output is known from a measure.
Under the hypothesis of linearity and time invariance of the system, the transfer function is represented by the convolution product among the input signal and the system impulse response:

$$y(t) = x(t) \otimes h(t) + n(t) \tag{1}$$

When considering otherwise a non-linear system the problem becomes much more difficult to be analyzed. Moreover when dealing with a signal emitted by a noise transducer (as performed during cavitation tunnel characterizations here presented) nonlinearities assume often the form of initial distortion. After this initial distortion, the system could be considered as linear because the sound propagation into surrounding is characterized by linear phenomena such as reflections, echoes and reverberation.
The effects of these latter phenomena are the object of present work, which is the determination of the linear response of the system.
Considering linear systems, it is usual practice to determine their transfer function by exciting the system with a particular known input signal and measuring the output. The signal to noise ratio is usually enhanced performing averages of the output in order to reduce the random noise.
This idea is the same suggested in ITTC [2]: an underwater transducer with known emitting characteristics should be used to emit noise in the cavitation tunnel.
This generally means that the noise radiated by the source should be measured also in a situation approximating free field condition in order to measure the transducer transmitting voltage response.
Most commonly used input signals for such applications are periodic, deterministic and wideband signals such as white noise, chirp and sine sweeps but also pure tones are commonly adopted.
Usually measurements are carried out with long sequences or with a certain number of repetitions in order to perform a certain number of averages to remove noise.
In general, neglecting the random noise (removed by averages) it is possible to deconvolve the transfer function h(t) using direct and inverse Fast Fourier Transforms as in the following:

$$\mathrm{h(t)} = \mathrm{IFFT}\left[\frac{\mathrm{FFT(y(t))}}{\mathrm{FFT(x(t))}}\right] \tag{2}$$

This operation is called circular deconvolution and it is affected by the risk of time aliasing. However this may be acceptable when interest is mainly focused on the system impulse response (the term between square brackets).
The deconvolved impulse response may also be affected by the nonlinearity of the system (related to the electro-mechanical transducer) appearing as anomalous peaks in time domain.
Finally the adoption of the circular deconvolution may be rather problematic when signal to noise ratio is not sufficient over all the frequency range of interest because of the transducer limitations.
A possible alternative approach is the one proposed in [9][10] and already considered at UNIGE cavitation tunnel, as presented in [8].

This procedure consists in performing a linear deconvolution in the time domain instead of the circular deconvolution. This is possible by defining an inverse filter f(t) as:

$$f(t) \mid x(t) \otimes f(t) = \delta(t) \tag{3}$$

Where δ(t) is the Dirac's delta.

Thus by definition the inverse filter of a certain signal is a signal which, if convolved with the original one, produces a Dirac's delta. In the case of sweeps signal it is the sweep itself reversed in time.

As shown in (4) the impulse response of the system can then be obtained convolving the measured output with the inverse filter and exploiting commutative and associative properties of the convolution:

$$y(t) \otimes f(t) = x(t) \otimes h(t) \otimes f(t) = \delta(t) \otimes h(t) = h(t) \tag{4}$$

One of the advantages of this procedure is that the convolution of the output signal with the inverse filter results in shifting forward the distortions in the time domain, as demonstrated in [11] for the linear sweep.

In addition the signal to noise ratio achievable with this procedure is higher, being all the energy emitted for a rather long period packed into a short impulse.

In present work the sine sweep technique is adopted with the above described procedure. In particular the logarithmic sine sweep is considered because of the enhanced signal to noise ratio at low frequencies. From this point of view also pre-equalization is considered for sweep signals, in order to further enhance signal to noise ratio where the transducer response is low. Actually the sweep may be simply equalized by adding an amplitude modulation derived from the source transmitting voltage response measured in free field conditions. Alternatively the same operation was performed also by exploiting the method developed by Kirkeby [10][12].

In addition more conventional signals are considered, as linear and logarithmic sweeps with circular deconvolution, white and pink noise.

3. Experimental setup

Signals and techniques described in the previous chapter have been applied for the measurement of transfer functions for the SSPA large cavitation tunnel.

The activities have been carried out considering two different underwater transducers, with different emitting-acquiring chains.

The first transducer, shown in Fig. 1, is the ITC1001 which is a spherical broadband omnidirectional transducer. The second transducer is a Gearing & Watson UW-60 loudspeaker, Fig.2.

As already mentioned for impulse response measurements the emitted signal has to be known (and maybe equalized) and thus the transmitting voltage response has to be measured through dedicated tests.

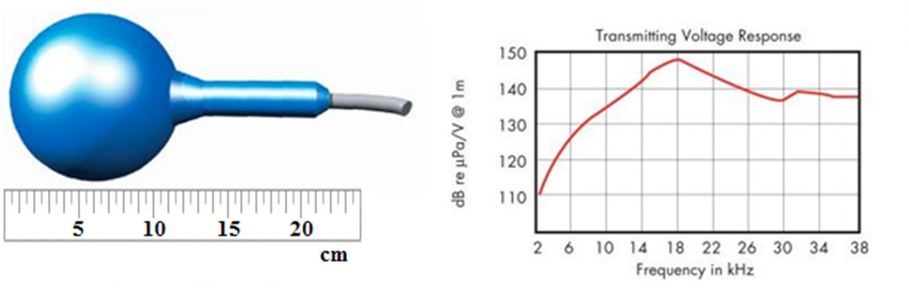


Fig. 1 – ITC 1001 underwater transducer

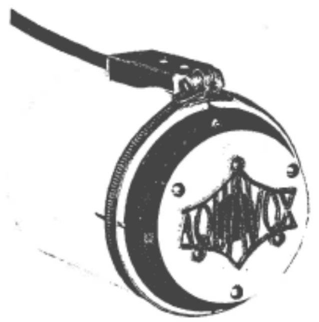


Fig. 2 – Gearing & Watson UW-60 underwater loudspeaker

3.1. Emitters free field calibration

The two transducers have been calibrated by UNIGE and SSPA through separated tests.
The free field calibration of the transducer is a rather complex task for this kind of activities. Main problems are related to difficulty in simulating free field radiation conditions. Generally this is done performing measurements in an environment as large as possible. Nevertheless, reflections from the boundaries are almost always present (unless a perfectly anechoic chamber is adopted).
In order to avoid reflected waves it could be necessary to consider only a very short time signals correspondent to the time necessary for the acoustic waves to reach the nearest boundary and come back to the hydrophone. This of course may consist in a further low frequency limit for adopted signals.
The experimental measurements carried out by the two institutions are rather similar, consisting in measurements carried out in a lake (SSPA) and in open sea (UNIGE), emitting signal with the underwater source and simultaneously acquiring the noise with a calibrated hydrophone.
Anyway problems have been differently faced, complying with respective instrumentation characteristics and limits, and with the different signals adopted.

3.1.1. ITC 1001 calibration (UNIGE)

The first calibration of ITC 1001 transducer was performed in 2013 and it has been already presented in [8]. A second similar campaign has been recently carried out with the aim to enlarge the frequency range for the successive tests at SSPA. The procedures adopted are identical as well as results (minor deviations have been observed only in correspondence of the lower frequencies), thus only the second campaign is presented here.
Tests have been carried out from a boat in open sea with a sea depth of more than 10 meters. However the closer boundary during these tests was the free surface, being source and hydrophone suspended in the water at 4 meters from the free surface.
The hydrophone (Reson type TC4013) and the transducer were kept at the fixed relative distance of one meter by a thin steel rod, The emitting/acquiring chain adopted is schematically represented in Fig. 3.
The rather low depth, determined by the limited length of the hydrophone cable, limited the duration of the direct signal to about 4.7 milliseconds, considering a sound speed of 1490 m/s. This short duration of the direct wave may represent one of the main issues of present work, especially when moving to low frequency. Actually it is already planned to repeat tests at higher depth.
The direct signal was extracted from the deconvolved impulse response, thus allowing to disregard the reflections.

Different sweep signals have been adopted in order to enlarge the explored frequency range, especially for what regards the low frequency limit. Actually three sweeps were mainly considered, with the following features:

1) Low frequency sweeps: F_{MIN} = 80 Hz; F_{MAX} = 2500Hz; F_S = 96000Hz; T = 10 or 20 s.
2) Medium frequency sweeps: F_{MIN} = 400 Hz; F_{MAX} = 30100Hz; F_S = 96000Hz; T = 10s.
3) High frequency sweeps: F_{MIN} = 5000 Hz; F_{MAX} = 95000Hz; F_S = 192000Hz; T = 30s.

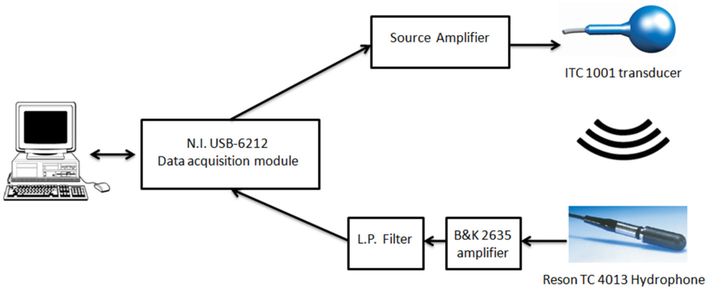


Fig. 3 – UNIGE emitting acquiring chain

Where F_{MIN} and F_{MAX} define the sweep frequency range, F_S is the sampling frequency and T is the duration.
Results obtained with all sweeps have been exploited in order to generate pre-equalized sweeps by using the Kirkeby method [12]. Also equalized signals have been emitted and measured at sea.
The frequency range for which signals are characterized by their nominal amplitude is slightly reduced by the presence of 0.2s fade-in and fade out, added in order to reduce impulsive noise.
The transmitting voltage response (TVR) has been measured considering also the amplifier.
It has to be remarked that the adopted amplifier is equipped with a low pass filter at about 44kHz, as a consequence a large portion of the high frequency sweep is dampened by this filter. Actually the high frequency sweep should be considered mainly to extend the TVR up to 44kHz and confirm results obtained with the medium frequency sweep in correspondence to the large overlapping range.
The measured response is reported in Fig. 4, on the left side the transmitting response is shown while on the right side signals coherences are reported.
As it can be seen results are reasonable, even if some issues are present. The medium and low frequency sweeps clearly show some coherence deficit at their respective lower frequencies. However, due to the short time interval available for the direct signal results below 200Hz should be considered meaningless independently from the coherence.
These problems are mainly related to the difficulties in obtaining a good signal to noise ratio over large frequency ranges in correspondence to which the source response varies of 40÷50dB.
For what regards overlapping frequencies the signal with the better coherence should be considered.
It has to be remarked that during the free field calibration weather conditions were unfortunately not optimal, with relevant wind and consequent motions of the small boat. This resulted in higher background noise levels, preventing the possibility to find the optimum setup in terms of gains and signal amplification. Also for this reason it is already planned to repeat tests in future.
Concluding the transmitting voltage response of the ITC 1001 transducer has been measured for a rather large frequency range obtaining useful results for the following activities.
It is however believed that these results may be improved by repeating tests at higher sea depth and with better weather conditions.

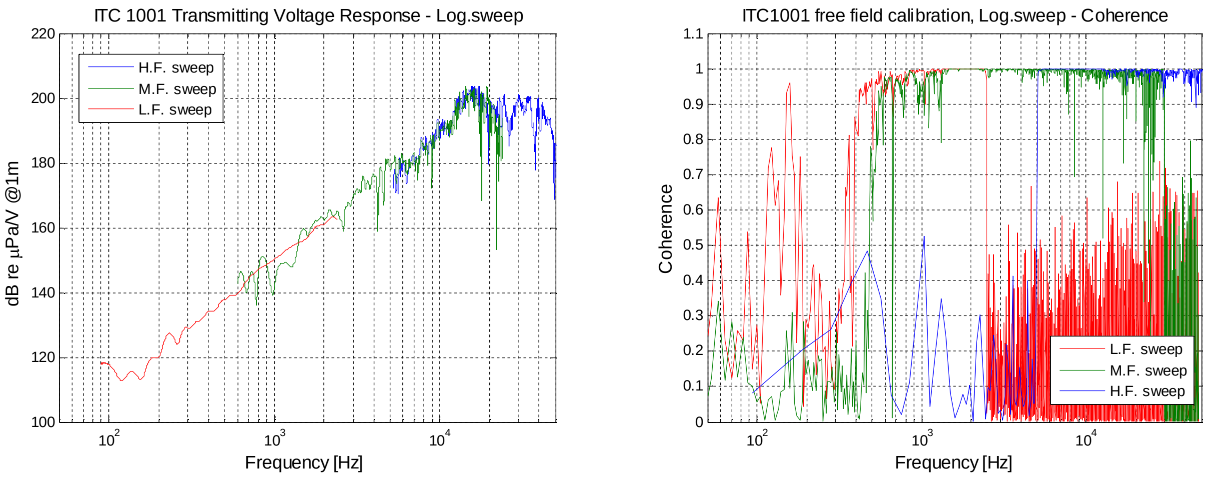


Fig. 4 – ITC 1001 measured Transmitting Voltage Response and signals coherences

3.1.2. Gearing & Watson UW-60 calibration (SSPA)

The Gearing & Watson UW-60 loudspeaker was calibrated through dedicated tests performed by SSPA at the freshwater lake Östra Nedsjön, near Gothenburg. The site was located far away from the shore in a large area with a dept greater than 50m. Transducer and hydrophone were mounted on a custom-made underwater rig made of PVC pipes filled with water. Due to its acoustic impedance, similar to that of water, the rig should not reflect acoustic waves.
Reference hydrophone for these tests was a recently calibrated Bruel & Kjaer 8103 hydrophone.
The instrumentation adopted is schematically represented in Fig. 5. As it can be seen the equipment comprehended also three Sparton PHOD-1 hydrophones which were to be calibrated during the same tests. The output signal sent to the transducer is also sampled by the ADC, as a consequence the transmitting voltage response of the loudspeaker alone was measured.
The rig was suspended at 20m depth while the distance between hydrophone and source was 1.38 m. Given a water temperature of approximately 10° the sound speed results to be about 1447 m/s. According to this the available time for the direct signal is 26.7ms.

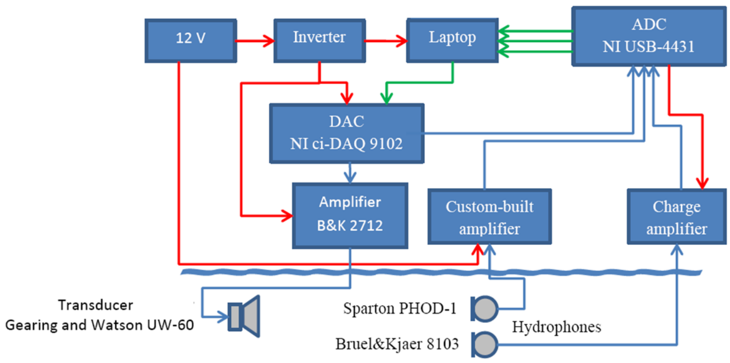


Fig. 5 – Instrumentation setup. Red lines indicate power, blue lines analogue signals and green lines digital signals.

The calibration has been carried out transmitting a series of constant amplitude tones at fixed frequencies with a duration of 10s. With this method it was not possible to separate the direct wave from reflections, however the first reflecting surface is significantly farer from the loudspeaker than the

hydrophone, as a consequence reflections should be rather weak, and negligible. Anyway this assumption was verified transmitting a series of short tone bursts (pings) of 15ms at 9kHz.
The signal was recorded for 200ms, results (omitted for brevity) showed that the power of reflections and noise is about 30dB lower than the power of the direct wave. Finally two additional measurements were carried out, a series of detailed measurements at 1-8kHz and one where the loudspeaker was oriented 30 degrees away from the hydrophone in order to check its directivity. During theses tests only a 30° angular sector was considered, being of interest from the point of view of sea trials transmission loss measurements.
Measured transmitting voltage response is reported in Fig. 6. As it can be seen the frequency response of the G&W loudspeaker seems significantly flatter than that of the ITC 1001 transducer down to about 225Hz where resonance occur. At lower frequency the transmitting capability of the loudspeaker decreases quickly.

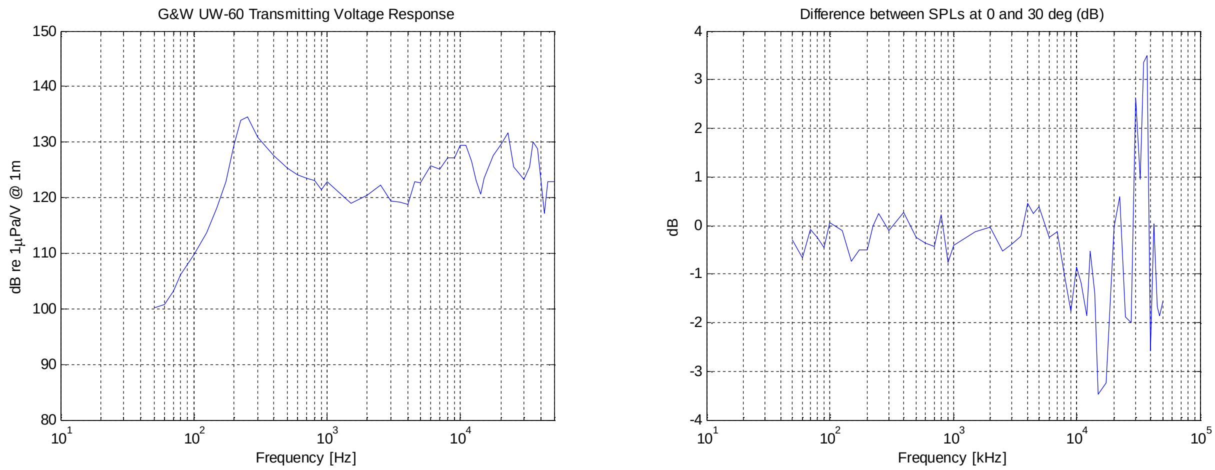


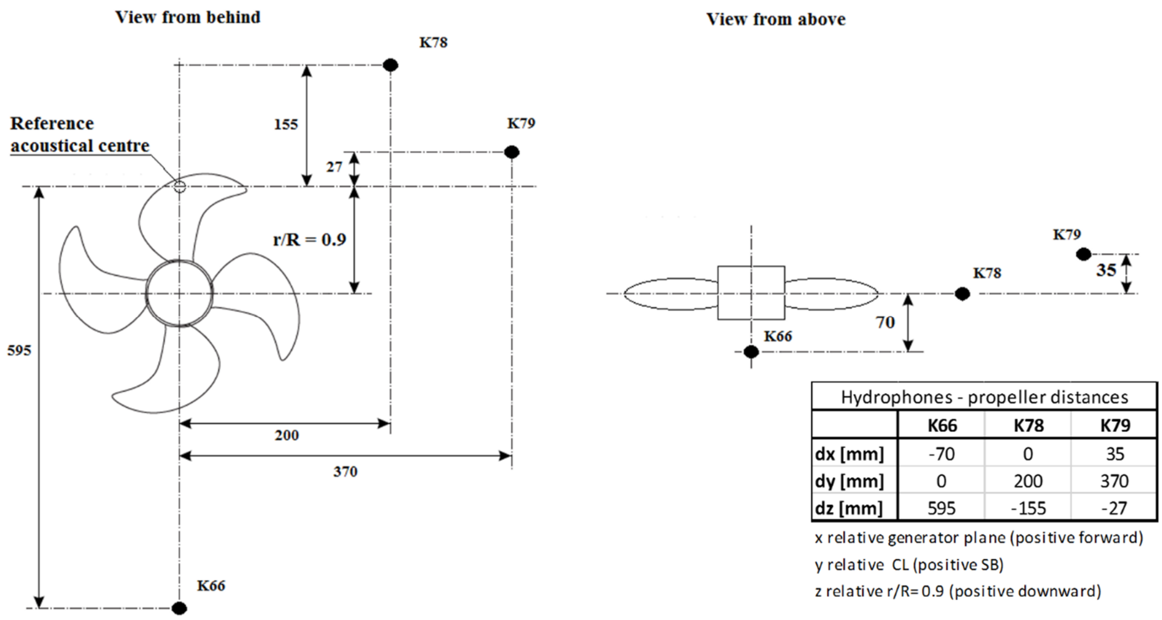
Fig. 6 – Gearing & Watson UW-60 Transmitting voltage response at 0° and 30°.

For what regards the directivity check, differences between the two measurements are below one dB at frequencies below 8 kHz while at higher frequencies some directivity effects are observed.

3.2. Cavitation tunnel setup

The measurement of transfer functions for the cavitation tunnel has been performed reproducing, as far as possible, the configuration adopted for cavitation tests. The propeller is replaced with the transducers and the calibrating signals are emitted in the tunnel and acquired by the same hydrophones adopted for experiments with the propeller.
Measurements at SSPA large cavitation tunnel have been carried out adopting the setup of an ongoing test on a single screw vessel, thus with the propeller placed behind the full hull model (photographs are omitted for confidentiality reasons). Three hydrophones have been employed, located as shown in Fig. 7. The K66 hydrophone is hold on a traversable sword while the K79 is protruding from a thicker fin. Finally the K78 Hydrophone is flush mounted on ship hull, rather close to the propeller. This latter sensor is usually considered to measure non-cavitating propeller noise exploiting its low distance from the propeller.
Different positions were considered for tests with the ITC 1001, corresponding approximately to tip radial position (r / R = 0.9) and five angular positions (-50°, -30°, 0°, 20°, 50°) around the top disk position where the largest cavitation extension is expected.

The G&W loudspeaker has been placed at 0°, with the centre of the emitting membrane at r/R = 0.9. In order to check the possible effects of directivity tests with this transducer were repeated with two different orientations, the first pointing in the aft direction, the second pointing forwards.



Hydrophones - propeller distances			
	K66	K78	K79
dx [mm]	-70	0	35
dy [mm]	0	200	370
dz [mm]	595	-155	-27

Fig. 7 – SSPA cavitation tunnel hydrophones setup

Tests with the ITC 1001 were performed emitting the same sweeps considered for its calibration while a larger number of signals were considered for the G&W transducer, comprehensive of pure tones, white and pink noise and sweeps, both equalized and not equalized, as already mentioned in section 2.

4. Results

In this section results are shown in terms of narrowband transfer functions and signal coherence.
As it will be seen narrowband transfer functions are almost always characterized by a rather irregular pattern, with a large number of spikes, peaks and hollows. This features are only partially related to random errors in the FFT operation, removable by averages. Actually the irregularity are in most cases rather repeatable, thus not related to random processes. These phenomena are probably connected with deterministic acoustic phenomena like the presence of standing waves, wave summation and cancelling. Assuming the acoustical behaviour of the cavitation tunnel to be the same during tests, these peaks and hollows should be present also in the propeller noise measurements. On the contrary these measurements are usually characterized by smoother spectra, without peaks and hollows. This may be explained by the different nature of the noise sources; actually a cavitating propeller may be schematized by a distribution of uncorrelated sources emitting noise from different and time varying positions. As a consequence it is reasonable that deterministic phenomena observed during calibration tests are not present during cavitation tests.
Due to this it could be necessary to smooth somehow the transfer functions before applying them to a propeller measurement. However in present work transfer functions are presented without any further processing, in order to preserve all information present in the measurements.

First measured performed with the ITC 1001 transducer are considered, comparing results obtained with the slightly different source positions. In addition tests for the first considered position corresponding to 12 o'clock were repeated six times for hydrophone K66, three times for the other two hydrophones in order to check repeatability. For example Fig. 8 reports evaluated transfer functions for hydrophone K66 and for the low and medium frequency equalized sweeps.

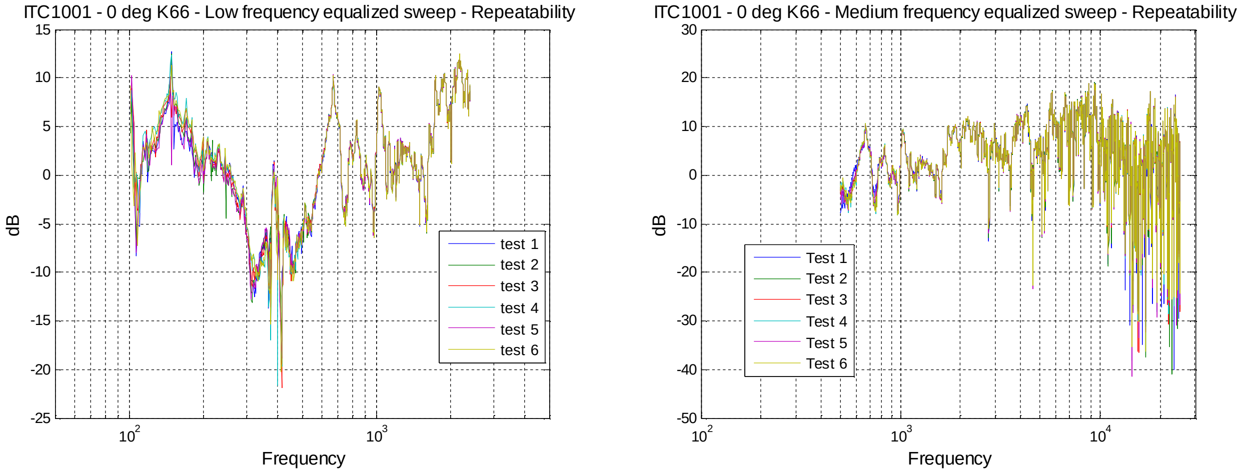


Fig. 8 – K66 transfer function measurements with ITC1001, repeatability

Repeatability is rather good, with larger differences near to the lower frequency limits of the two signal, larger in the case of the most critical low frequency sweep but still acceptable.
As already mentioned transfer functions presented in Fig. 8 are "raw" transfer functions, a further processing can be done considering also the coherence of the measured signals.
If the measured output corresponds well with the digital input signal the coherence should be equal to 1, otherwise lower values may be obtained. Signals and related transfer functions are considered consistent only when the coherence is higher than 0.9.
For lower values the signal is disregarded and the transfer function is computed by means of linear interpolation. This because, as observable in Fig. 9, the coherence falls below the 0.9 threshold only at the limits of the frequency ranges interested by sweep, other low values observed in the middle frequencies are constituted by local negative spikes, and thus it is reasonable to interpolate transfer functions in correspondence to these frequencies instead of considering a $20 LogR$ scaling which could lead to inconsistent results.
Looking more in details the coherence plots, main problems seem to be related to frequencies below 300÷400 Hz for the low frequency sweep (but values are still good), frequencies higher than 40÷50 kHz for the high frequency signal in accordance with the presence of the low pass filter. Finally the coherence seems a bit worst for the medium frequency sweep. Anyway considering the frequency overlap between signals it is almost always possible to select a signal with a good coherence.
As a consequence total transfer functions have been built for each source position, results are reported in Fig. 10 for hydrophones K66 and K79, results for K78 are similar to those for K79 for what regards dependency on source position.

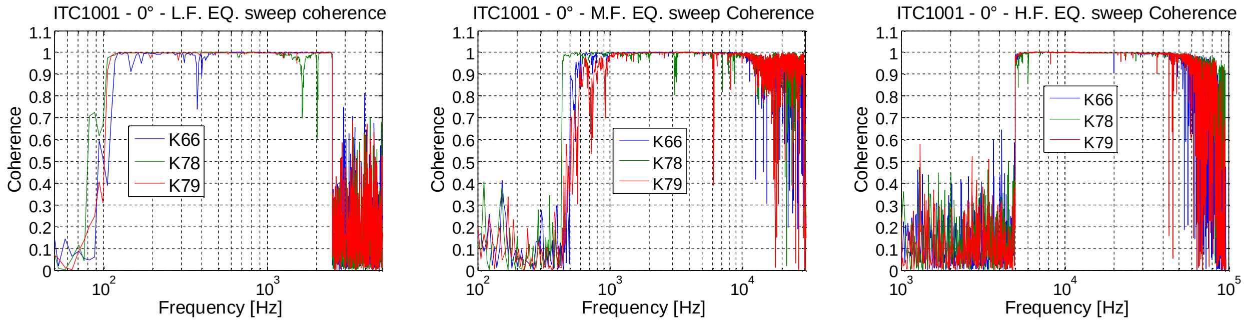


Fig. 9 – Measurements with ITC 1001, signal coherence

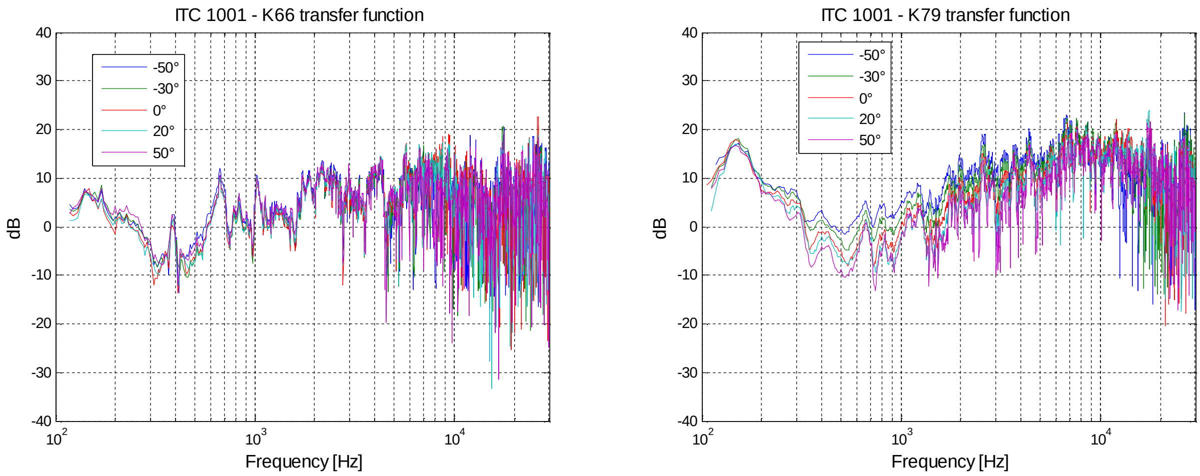


Fig. 10 – Transfer functions measured with the ITC1001 transducer in different positions.

As it can be seen the shape of the transfer function for the three hydrophones does not vary significantly moving the source around the reference position at 12 o'clock (0°).

On the contrary significant differences are observed for what regards levels. These differences seem in agreement with the varying distance between hydrophones and source. Actually in the case of sensor K66, positioned about 60 cm below the reference position, the distance between sensor and transducer does not vary significantly, accordingly transfer functions are very close to each other. Considering instead hydrophone K79 (and K78) the distance from the source increases monotonically passing from −50° to 50°, source – hydrophones distances and corresponding scaling factors computed according to traditional spherical propagation are reported in Table 1. The transfer functions behave accordingly for frequencies below 7÷8 kHz, while at higher frequencies reverberation seems to dominate and levels seem not clearly dependent from the distance from the source. However it has to be remarked that variations observed at medium low frequencies are rather large if compared with variations predicted by the spherical propagation.

Finally a large number of negative spikes are observed at high frequencies, these seem to occur for different frequencies moving the source. As already remarked these features are not suitable to describe noise propagation in the case of a cavitating propeller thus should probably be disregarded. In addition it has to be remarked that propeller cavitation occurs in different positions, in present case it is expected to occur around 0°. Moreover, cavitation moves through the domain, as a consequence it is reasonable to estimate a final transfer function as the average of considered positions.

Table 1 – Source – hydrophones distances.

Θ [°]	R [m] K66	R [m] K78	R [m] K79	20LogR K66	20LogR K78	20LogR K79
-50	0.569	0.227	0.302	-4.9	-12.9	-10.4
-30	0.588	0.225	0.324	-4.6	-12.9	-9.8
0	0.599	0.253	0.373	-4.4	-11.9	-8.6
20	0.594	0.284	0.407	-4.5	-10.9	-7.8
50	0.569	0.336	0.452	-4.9	-9.5	-6.9

For what regards tests carried out with the Gearing & Watson UW-60 underwater loudspeaker, measurements are summarized in Table 2.

Table 2 – Gearing & Watson UW-60 measurements.

Test ID	Signal type	Freq. range	EQ.	Source direction	Test ID	Signal type	Freq. range	EQ.	Source direction
09-39-04	log sweep	30:16000	No	Aft	14-05-07	log sweep	500:16000	No	Aft
09-45-05	log sweep	30:16000	Yes	Aft	14-06-03	log sweep	500:16000	Yes	Aft
09-53-43	log sweep	30:16000	No	Aft	14-12-14	lin sweep	30:16000	Yes	Aft
10-13-30	log sweep	500:16000	No	Aft	14-14-01	lin sweep	30:16000	No	Aft
10-14-21	log sweep	500:16000	Yes	Aft	14-20-29	Pink noise	50:12000	No	Aft
10-17-13	log sweep	500:16000	No	Aft	14-37-32	White noise	50:12000	No	Aft
10-21-22	lin sweep	30:16000	No	Aft	07-53-16	log sweep	30:16000	No	Fwd
10-25-04	lin sweep	500:16000	No	Aft	07-56-17	log sweep	30:16000	Yes	Fwd
11-07-06	log sweep	400:30100	No	Aft	07-57-44	log sweep	500:16000	No	Fwd
11-07-58	log sweep	80:2500	No	Aft	07-59-27	log sweep	500:16000	Yes	Fwd
11-50-28	log sweep	80:2500	Yes	Aft	08-02-00	lin sweep	30:16000	No	Fwd
11-51-32	log sweep	400:30100	Yes	Aft	08-03-37	lin sweep	30:16000	Yes	Fwd
13-51-51	log sweep	400:30100	No	Aft	08-13-11	log sweep	400:30100	No	Fwd
13-53-54	log sweep	80:2500	No	Aft	08-15-29	log sweep	80:2500	No	Fwd
13-55-37	log sweep	80:2500	Yes	Aft	08-36-48	White noise	50:12000	No	Fwd
14-02-58	log sweep	30:16000	Yes	Aft	09-06-30	Pink noise	50:12000	No	Fwd
14-03-57	log sweep	30:16000	No	Aft					

Results obtained with the different signals have shown to be consistent in almost the totality of cases. A selection of results is shown in Fig. 11. Transfer functions have been processed together with signal coherence as in the case of ITC1001, adopting interpolation for those points where the coherence was lower than 0.9. As visible in the plot some differences can be observed between the transfer function evaluated using white noise and other signals, with main differences in the range 200÷400Hz. However, in this frequency range the coherence is generally better for sweep signals which, as a consequence are deemed more reliable.

In general the signal to noise ratio achieved with the Gearing & Watson loudspeaker is very good with all signals employed, thus leading in all cases to consistent results. However the sweep signals allowed to slightly enlarge the useful frequency range resulting also in better coherence values. In addition it has to be remarked that the white noise signal had a duration of 10 minutes in order to reduce noise by averages, thus from this practical point of view the sweeps allow to obtain a significant reduction of measuring time. This advantage may become of utmost importance if the measurement is performed with slightly variant environmental conditions (for example with tunnel depressurization), or if they have to be repeated for a larger number of configurations.

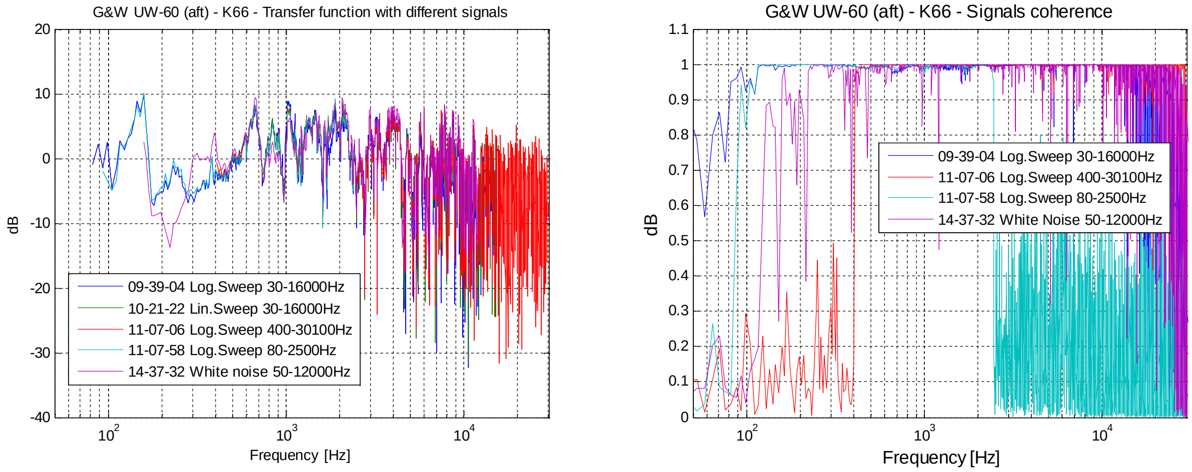


Fig. 11 – Transfer functions and signal coherence measured with G&W UW-60 loudspeaker with different signals

Finally results obtained with the loudspeaker pointing in aft and fore direction are compared with ITC1001 transfer functions measured at 0°, hydrophone K78 is again omitted for brevity. For these final curves a median filter was applied for better clarity.

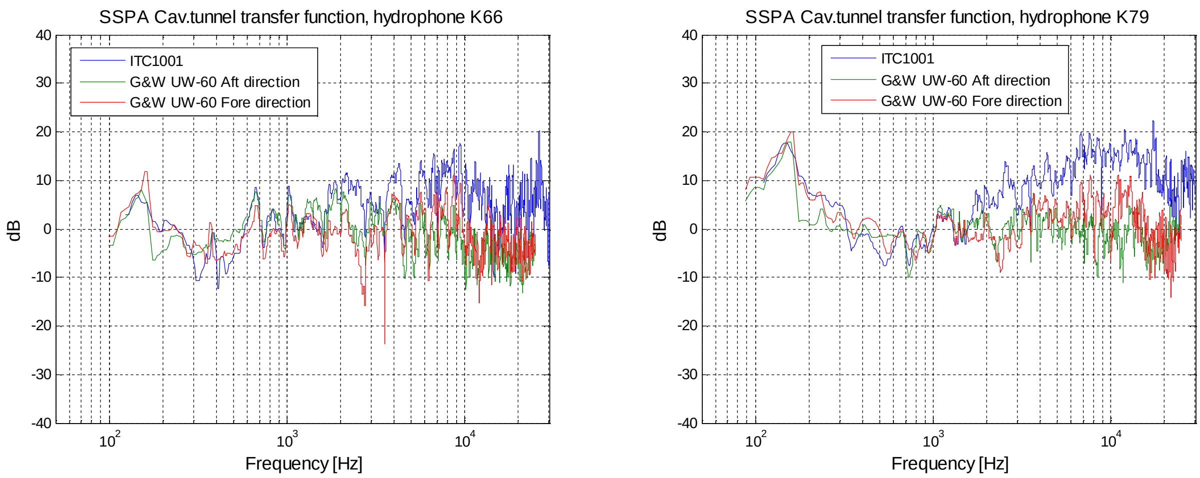


Fig. 12 – Comparison between Transfer functions measured with different transducers/techniques

As a first comment significant discrepancies are observed between functions estimated with the ITC1001 transducer and functions measured with the Gearing & Watson UW-60 loudspeaker. These discrepancies are relevant especially at medium high frequencies, (above 1÷2 kHz), and they reach their maximum around 10 kHz. Comparing T.F. measured with the loudspeaker in the two opposite directions some clear effects are observable even if the two curves are still rather similar. Also in this case differences are largest around 10 kHz. The simplest possible explanation for these dissimilarities may consist in differences in the directivity of the two transducers. Actually, due to its spherical shape, and according to producer specifications, the ITC1001 should be closely omnidirectional. However this was not verified for present transducer, therefore it has been decided to carry out directivity tests in future work in order to check it. For what concerns the UW-60 Loudspeaker, effects of directivity were evidenced during free field calibration. These effects seemed significant above 8 kHz, thus in only partial agreement with what observed at cavitation tunnel. However it has to be remarked that, due to the lower distances between source and hydrophones and to the higher angle, directivity effects during cavitation tunnel tests could be more relevant. Actually the angle between the transducer main emitting direction and the sensors in the tunnel was about 90°, while during free field tests directivity was checked only for 30°. Finally also the confined environment may influence somehow the effect of directivity on final results.

Of course observed discrepancies may be also related to other source of uncertainties, for example the calibration of the ITC1001 at low frequencies was affected by signal to noise ratio problems at low frequencies and, as already mentioned, should be repeated.

In general also transfer functions measured with the loudspeaker point out a different behaviour with respect to what predicted by the spherical propagation model, actually transfer functions for hydrophones K66 and K79 are mainly around 0dB. More complex transfer functions shapes are measured for the K78 hydrophone, which however is characterized by the most complex configuration, with possible effects related to the close distance from the hull model.

5. Conclusion and future work

In present work a summary of the recent experiences gained at UNIGE cavitation tunnel and SSPA in the field of acoustic characterization of different measuring facilities has been presented.

In particular results of the transfer function measurements carried out for the SSPA large cavitation tunnel are presented and discussed.

These measurements have been performed with two different transducers and slightly different techniques and adopted signals. Main differences between transducers regard the low frequency transmitting capability, significantly better for the G&W loudspeaker, and directivity reasonably more critical for the loudspeaker.

For what regards adopted techniques their effectiveness may not be compared in a complete way because they have been applied with different transducers. The adoption of sine sweeps seems to always to improve results in terms of signal to noise ratio and signal coherence. However in the case of the loudspeaker signal to noise ratio was always rather good while some problems were present at low frequency during free field calibration for the ITC1001. Anyway in such case only the sine sweep technique with linear convolution in the time domain was adopted thus a direct comparison with other techniques is not available at the moment.

Obtained results give important information on noise propagation inside the cavitation tunnel but are also characterized by significant differences depending on which transducer is considered.

In both case it is evident that the spherical propagation model does not describe consistently the real situation. A certain dependency from the frequency is observed, larger when considering the ITC1001.

This means that scaling to 1m by means of the standard $20LogR$ formula may lead to errors of several dB. As a result the importance of measuring the transfer function is underlined; however, the problem of how to measure it appears clear. Discrepancies observed adopting the two noise sources are deemed not acceptable and should be justified.

For what regards the largest discrepancies at medium high frequencies these may be related to the different directivity characteristics of the transducers, further tests are needed in order to better assess the possible influence of this aspect.

As a first conclusion results at medium high frequencies may be more consistent in the case of the ITC1001 transducer, because of its omnidirectionality. Of course further tests are needed in order to verify this conclusion, measuring more in details transducers directivity and considering other possible source of errors.
On the contrary at frequencies below 300÷400 Hz results obtained with the G&W loudspeaker may be more reliable, because of the enhanced transmitting voltage response of the transducer and the advantages related to the calibration tests carried out at in deeper water.
As a further step obtained transfer functions will be applied to cavitation noise tests carried out in similar configuration, possibly comparing model scale data with results from sea trials in order to check the effectiveness of estimated transfer functions.
From this point of view it could be necessary to analyse more deeply the nature of local features of the transfer function in order to assess if it is necessary to apply the transfer functions as it is or if it is better to consider only its general behaviour, neglecting by smoothing all local fluctuations of functions.
Finally it has to be remarked that presented work is a summary of activities which are currently ongoing, further analysis and calibration tests of the transducers may allow to obtain more consistent and reliable results and to better justify presented results.

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