OCTAVE-BANDWIDTH TRANSDUCERS FOR ULTRA-BANDWIDTH ECHO-SOUNDING SYSTEM

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ABSTRACT

The BASS system developed under the European MAST 3 program contract number MAS3-CT95-0031 is used to measure the Broadband Acoustic Scattering Signatures of fish and zooplankton (BASS)[1,2]. The system covers a frequency-range from 25 kHz to 3.2 MHz. The BASS system is equipped with seven separate transducers, each transducer covering an octave band.

This paper provides a general description of the physical composition of the BASS system including a description of the seven transducers and their acoustical performance. A more detailed description is given for two of the seven transducers which cover the extremes of the frequency range. This paper also serves as background for the paper "Measuring the frequency response function of octave-bandwidth transducers", KG Foote et al [3].

1. GENERAL DESCRIPTION OF HARDWARE

The BASS system is used to measure the broadband acoustic scattering of fish and zooplankton over a frequency range of 25 kHz to 3.2 MHz. The objective for the design of the BASS system was to build a technology demonstrator that could show the potential of such a system in the field of fisheries research by characterizing the broadband acoustic scattering of fish and zooplankton. The objective was not to build a high-efficiency, high-speed and robust working tool. This fact affects the way the system was designed and constructed, and the operational handling of the system. Handling and deployment of the system requires a minimum of three people to launch the system and one to control the cable winch. The actual number of people to deploy it in a secure way depends on the prevailing conditions during deployment such as the sea state and the wind speed. The hardware for the system was build as a joint venture between the University of Birmingham, IMR (Institute of Marine Research, Norway) and Reson A/S.

A drawing of the BASS system is shown on Figure 1. The outline drawing does not show the support frame placed around the system. The purpose of the support frame is to improve the operational handling of the unit and to protect the system from slamming against the side of the vessel during deployment in rough sea conditions. During deployment the system operates as a fixed position probe, although it is possible to move the vessel during deployment but only at very low speed, typically less than 0.5 knots. The BASS system was designed and constructed to withstand an operational water pressure of 25 bar equivalent to an approximate water depth of 250 m.

The seven transducers are mounted on a transducer bracket attached to the lower end of the cylindrical pressure housing containing the wet-end electronics of the system. The frequency range and position on the bracket is shown for each of the seven transducers in Figure 2.

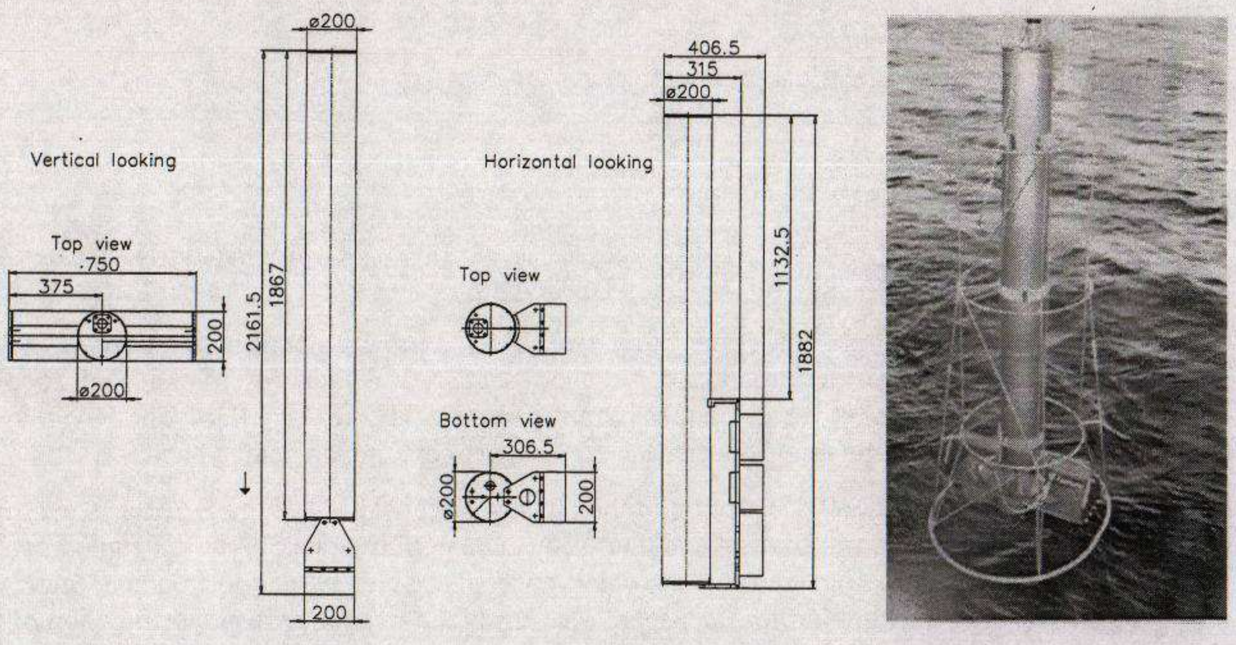

Figure 1. Outline dimension drawing of the BASS system. The drawing on the left shows the BASS system in the vertical-looking configuration. The drawing in the middle shows the BASS system in the horizontal-looking configuration. The picture on the right shows a launch of the system. For each type of deployment the system is used as a probe.

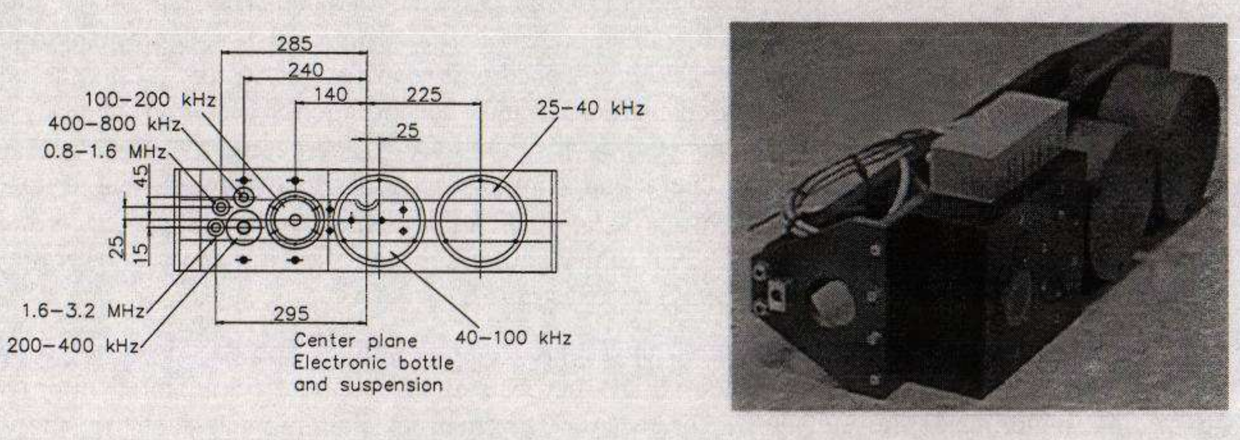

Figure 2. Transducer bracket and arrangement of transducers.

2. TRANSDUCER DESIGN

In the following a description of each of the seven transducers located in the BASS transducer array is given, starting from the low frequency end. More detail is given for the two transducers covering the frequency range from 25 kHz to 40 kHz and the range from 800 kHz to 1.6 MHz. All of the seven transducers are pressure-rated and pressure-tested to a 250 m operational depth.

2.1 The transducer for the frequency band 25 to 40 kHz

The first transducer of the seven covers the band from 25 kHz to 40 kHz. This frequency band is deliberately designed to cover less than an octave. The reason for this results from the order in which the transducers were designed at Reson A/S during the work on the BASS project. The band 2 transducer was the first to be designed and covers the range from 40 to 100 kHz, more than an octave band, and thereby only a smaller range was needed for the lowest frequency band transducer.

The transducer is based on seven identical tonpilz transducer elements placed in a planar polar array. The tonpilz transducer element is designed to have two separated and distinct modes of resonance. The first of the modes of resonance is the thickness mode. The thickness mode dominates the transducer behaviour in the frequency range from 25 to 30 kHz. The second mode of resonance in the element is the flapping mode of the front mass. The flapping mode dominates the transducer behaviour in the frequency range between 31 and 40 kHz. The carefully controlled interaction between the closely spaced elements serves to provide an overall transducer frequency response with a minimum of amplitude ripple.

Figure 3 shows a drawing of a cross-sectional view of the transducer.

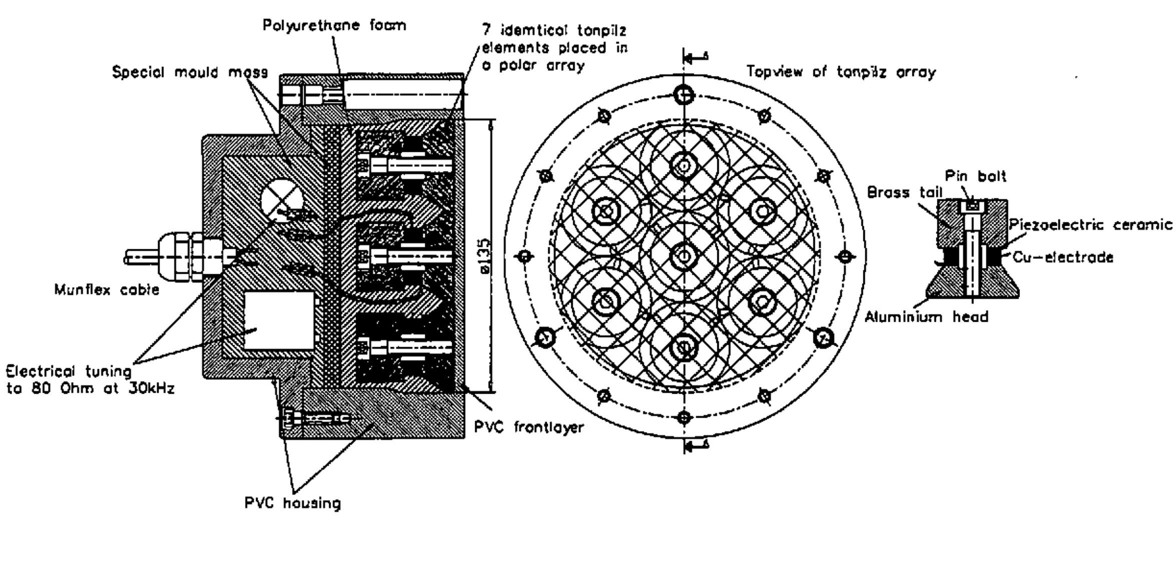

Figure 3. Cross-sectional and front-face view of the transducer covering the frequency range from 25 kHz to 40 kHz. The front-face view (middle) shows the polar array of the seven tonpilz transducer elements without the protective cover. The dimensions shown are in millimetres.

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The tonpilz element design is based on a conventional design approach incorporating a simple finite element (FE) formulation. The design aim was to achieve a high power handling capacity combined with a high electrical-to-acoustical power conversion for the element. The efficiency of the transducer is 45% at 30 kHz. The beam width of this transducer is 22.5 degrees at 30 kHz. The transducer is provided with electrical tuning that transforms the impedance at 30 kHz into 80 Ω.

2.2 Transducer for the frequency band 40 to 100 kHz

The construction of the second transducer of the seven is similar to that of the previous design and is based on a group of simple multiple resonance transducer elements placed in a planar array. The basic element shape for this transducer is that of a horn. Due to the multiple resonances of the sub transducer elements this transducer covers the frequency range from 40 to 100 kHz closely approximating the desired –3 dB amplitude specification. The design aim of this transducer was to achieve a wide bandwidth combined with a high power handling capacity and a high electrical-to-acoustical power coupling. The efficiency of this element is higher than 50% at 50 kHz.

The outline dimension drawing of this transducer is shown on Figure 4. The transducer housing is identical to the housing of the previous transducer. This transducer is also provided with an electrical impedance-matching network in order to achieve an impedance of the transducer of 80 Ω at 50 kHz. The beam width varies from 16.6 degrees at 45 kHz to 7.3 degrees at 100 kHz.

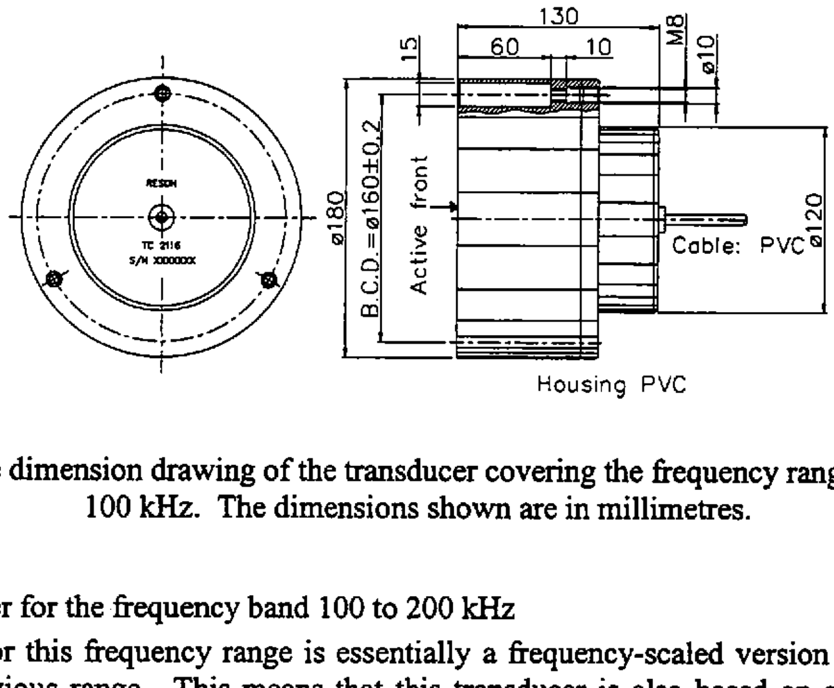

Figure 4. Outline dimension drawing of the transducer covering the frequency range from 40 kHz to 100 kHz. The dimensions shown are in millimetres.

2.3 Transducer for the frequency band 100 to 200 kHz

The transducer for this frequency range is essentially a frequency-scaled version of the transducer covering the previous range. This means that this transducer is also based on a group of simple multiple-resonance elements placed in a planar array. The design aim for this transducer was purely to achieve a good bandwidth specification at the expense of power handling capability. This transducer handles 50 W in the range from 100 to 200 kHz at a duty cycle of 1%. A higher power handling capacity was not necessary for the BASS system according to the experimental nature of the system.

The housing for this transducer is machined from PVC. The depth rating of the PVC housing is upgraded by the use of a high-density foam backing for the transducer elements. The beam width of this transducer varies from 13.6 degrees at 100 kHz to 6.8 degrees at 200 kHz.

The outline dimension drawing of this transducer is shown Figure 5.

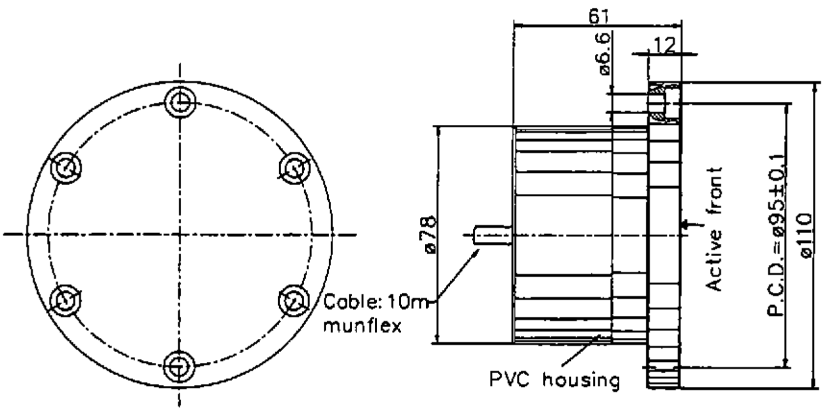

Figure 5. Outline dimension drawing of the transducer covering the frequency range from 100 to 200 kHz. The picture on the left shows the acoustical active front area. All dimensions shown are in millimetres.

2.4 Transducer for the frequency band 200 to 400 kHz

For this medium frequency range it is no longer possible, or at least very expensive, to build a broadband transducer based on a group of multiple resonance sub-transducer elements placed in a planar array. The size of each sub-element will be very small due to the required inter element spacing of less than half a wavelength. The use of multiple resonance elements will also require a very small sub-element structure in order to work in this frequency range. Alternative design approaches based on a thin disk are beset by implementation problems as the operating frequency is not really high enough. This means that a different design approach is needed.

Due to these facts, this transducer was built based on a single 1-3 composite piezoelectric disk drive. The matrix for the composite was of the high-loss, soft polyurethane type in order to gain bandwidth. The centre frequency of the 1-3 composite disk is 290 kHz. In addition to the use of a soft matrix 1-3 composite drive, the performance and bandwidth was improved by providing the 1-3 composite with a high-loss impedance-matched backing and two-quarter wave front matching layers.

Based on the centre frequency of the composite, the thickness and the density, it is possible to determine the characteristic impedance of the composite. The value obtained by measuring and averaging of 5 identical disks is 7.4 MRayl. A tungsten/aluminium oxide loaded epoxy was used as a backing material for the 1-3 composite piezoelectric drive. The characteristic impedance of the solid backing for this transducer is 7.1 MRayl, which is sufficiently close to the characteristic impedance of the composite. The damping-versus-frequency function of the backing material is shown on Figure 6.

The composite transducer is shown on Figure 7. The acoustic active area of this transducer is ø29 mm equal to the diameter of the composite disk drive. The beam width ranges from 15.3 degrees at 200 kHz to 7.6 degrees at 400 kHz.

The solid materials for the two quarter-wave front matching layers were chosen using the approximations [4]:

$$Z_{matchingI} = \sqrt[4]{Z_{ceramic}^3 \cdot Z_{water}} = 4.97 \text{ MRayl}$$
$$Z_{matchingII} = \sqrt[4]{Z_{ceramic} \cdot Z_{water}^3} = 2.2 \text{ MRayl} \qquad (1)$$

Layer I is the layer closest to the piezoelectric driver. Layer II is the layer closest to the water.

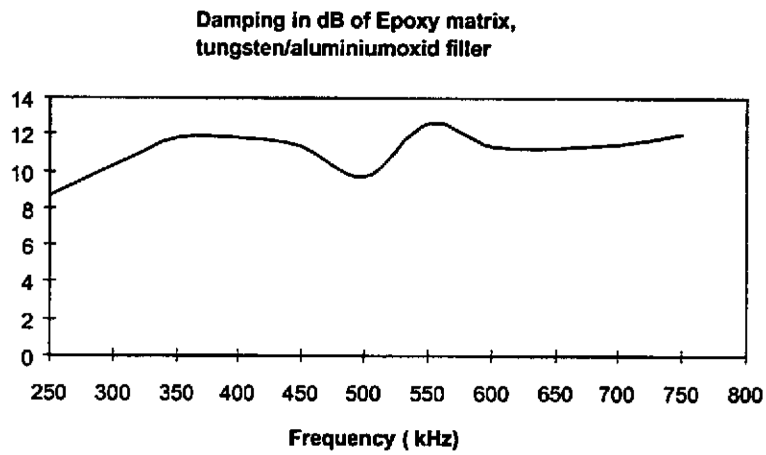

Figure 6. Damping characteristic of the solid epoxy tungsten backing. The damping is shown in dB.

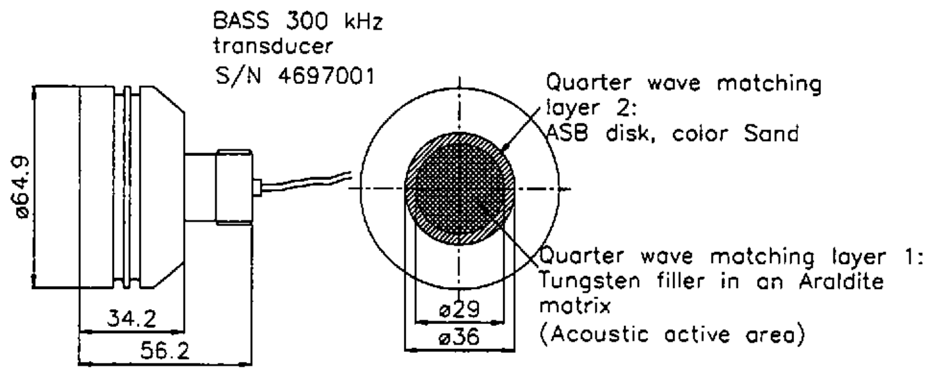

Figure 7. Sketch of the 1-3 composite transducer, 200 to 400 kHz. Dimensions all in millimetres.

2.5 Transducer for the frequency range 400 to 800 kHz:

The transducer for this frequency range and the following are constructed on the thin disk design approach. The thin disk transducer design for these transducers includes the use of multiple matching front layers and a solid backing attached to the ceramic disk drive. Normally it is possible to build octave-band, or at least very broadband, thin disk transducers with an air-backed piezoelectric drive [5]. The reason why all of the thin disk transducers for the BASS system have been provided with a solid backing is a combination of the improved bandwidth, increasing depth rating and the elimination of unwanted modes of resonance in the transducer structure. All of the thin disk transducers built for the BASS system have a relatively small diameter-to-drive thickness ratio. All solid materials for the front matching layers are chosen based on equation 1.

The transducer for this frequency range is shown on Figure 8. The transducer is based on a ø18 mm 500 kHz dense ceramic disk. The thickness of each of the two matched front layers is close to ¼ λ at 500 kHz. The first quarter-wave matching layer is manufactured from aluminium. The ceramic disk was glued directly on to the aluminium front matching layer under a high compressive load. The aluminium front layer is part of the transducer housing. The metal part of the housing is insulated from the seawater. The aluminium is used as an electrical ground for the ceramic. The second quarter-wave matched front layer is made from epoxy.

The manufacturing procedure used to determine the optimum thickness of each of the front layers was to reduce the thickness of each layer in small steps, and at each step measure the admittance of the transducer in order to detect the thickness creating the largest transmitting bandwidth.

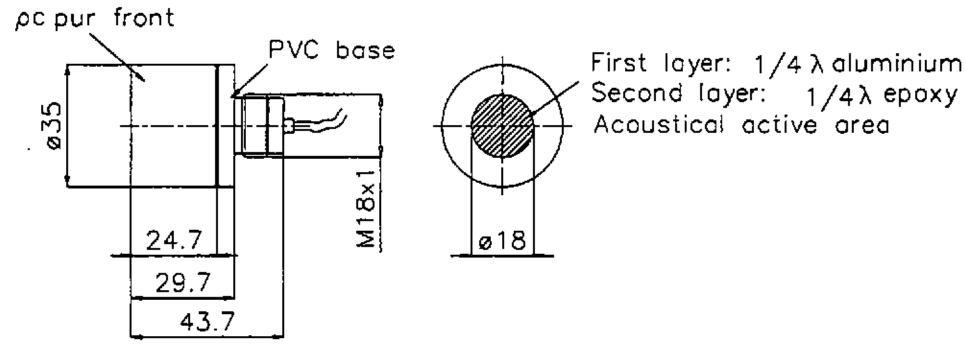

Figure 8. Sketch of BASS transducer for the frequency range 400 to 800 kHz.

The solid backing is an impedance-matched epoxy and tungsten compound. The backing is needed to damp and control unwanted resonance of the transducer housing. The directivity of the transducer is 8.1° at 500 kHz.

2.6 Transducer for the frequency range 800 to 1600 kHz:

This transducer is the second transducer where the transducer design will be shown in more detail. The design follows the classic thin disk approach, although the ratio of the radial dimension of the disk to its thickness is smaller than is commonly encountered in thin disk transducers. The reason for this is the desired beam width of 8 degrees at the centre frequency. The transducer is a solid-backed, thin-disk, dense-ceramic structure provided with two impedance-matching front layers. The housing for this transducer is made of PVC. A cross sectional view of the transducer is shown on Figure 9.

The impedance-matched solid backing of the piezoelectric drive is a tungsten-epoxy compound. The backing is manufactured as a separate component. After the moulding process of the backing, the component is machined to a perfect cylinder where the top and bottom surfaces of the cylinder are perpendicular to the centre axis of the cylinder. The ceramic is glued directly to the machined backing cylinder. During the glueing and curing processes, the ceramic and backing was exposed to a large axial compressive load. As a result of this procedure the thickness of the glue interface was controlled and minimised. The same procedure was used when mounting the quarter wave aluminium front matching layer on to the ceramic disk. It is essential for this design that all the interface layers between the different solid materials in the transducer are controlled and minimised with respect to acoustical influences. The glue layer will add compliance and mechanical damping to the system. Glue is in general soft and a high-loss material compared to aluminium and piezoelectric ceramic. From the results achieved during the early stages of the project, the control of the glue interface between the different parts in a multiple-matching-layer thin disk transducer would appear to be very important in order to maintain the desired performance. At high frequencies the glue interface becomes relatively large compared to the other components of the transducer.

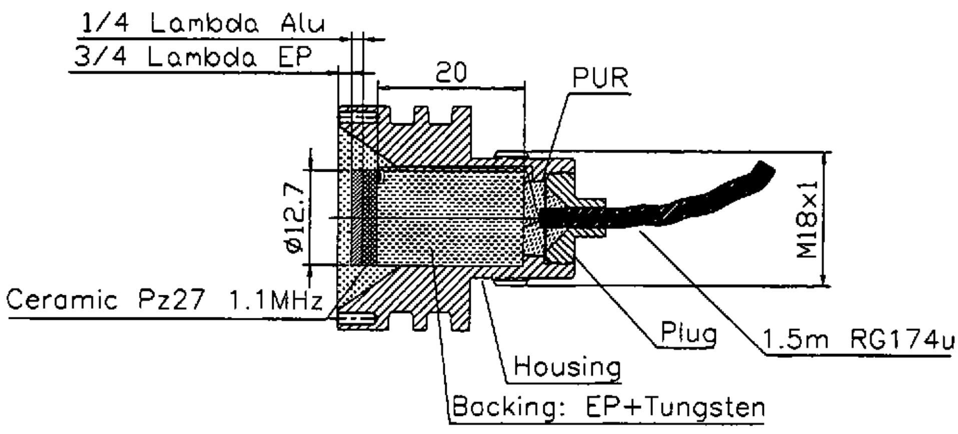

Figure 9. Transducer for frequency range 800 to 1600 kHz, S/N1797011. All dimensions in mm.

The final matching front layer, which is epoxy, was moulded directly onto the aluminium matching-layer. Later the epoxy was machined to a thickness of ¾ λ. The reason the thickness of the front layer was ¾ λ instead of ¼ λ was that a ¼ λ layer of epoxy is extremely thin at the high centre-frequency of this transducer. It was simply not possible to machine the thin ¼ wave layer accurately enough. A number of prototypes of this transducer had to be manufactured before the machining process could be perfected.

One of the manufacturing problems associated with this transducer results from the small radial dimension of the disk. Normally a thin disk transducer uses a piezoelectric disk drive that has a diameter that is much larger than the thickness of the disk. The ratio was only 6.5 for this

transducer. The small ratio requires a very efficient, high-loss backing in order to eliminate unwanted modes of resonance in the transducer structure.
During the early stages of the BASS project, Phoebe, a Boundary Element / Finite Element program developed by the University of Birmingham [6,7], was used to determine the effect of the disk shape with particular emphasis on the diameter-to-thickness ratio.

At 1100 kHz the beam width of this transducer is 7.2°.

2.7 The transducer for the frequency range 1600 to 3200 kHz:

The transducer for this frequency range is similar to the previous two and is based on a multiple matching layer, thin-disk transducer with a solid backing. The housing for this transducer is made of PVC. The two front matching layers of this transducer are ¾ λ layers rather than ¼ λ because of the manufacturing problems associated with very thin quarter-wave layers. The piezoelectric ceramic disk drive used for this transducer is a ø20 mm 2 MHz disk. The solid backing of the disk drive is a tungsten-epoxy compound and is matched to the impedance of the ceramic. The backing is manufactured using the same procedure as the ones used for the transducers for the previous frequency range.

The transducer is shown on Figure 10. At 2000 kHz the beam width of this transducer is 2.3 degrees.

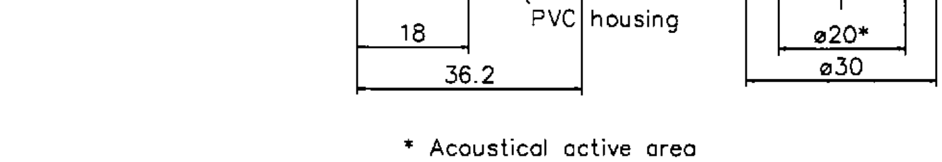

Figure 10. Sketch of transducer for the frequency range 1600 - 3200 kHz. All dimensions are in mm.

3. METHODS

3.1 Acoustical calibration of transducers

The acoustical calibration of the seven transducers was performed on the Computer-Aided Transducer Calibration system (CATC) located at and developed by Reson A/S. The CATC system is calibrated and is traceable to international references.

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The dimension of the water tank used for the calibration is 3 m deep, 2.5 m wide and 4 m long. The tank contains stabilised freshwater kept at a constant temperature of 20°C. The speed of sound of the water in the tank is 1475 ms^{-1}.

All of the transducers for the BASS system were calibrated in the far field. The standard calibration method using a reference hydrophone is used for the calibration. Pulse gated measurements are used to avoid disturbance by sound reflections from the walls of the tank. Voltage, current and impedance are all measured within the same gated pulse.

Table 1, Reference hydrophone / projector used for transducer calibration:

Frequency band	Type of reference	Serial number on reference	Duration of pulse	Comments
25 to 40 kHz	TC4033	301001	15cycles	
40 to 100 kHz	TC4033	301001	25cycles	
100 to 200 kHz	TC4034	349204	25cycles	
200 to 400 kHz	TC4034	349204	35cycles	
400 to 800 kHz	OSTE RØD	423001	25cycles	
800 to 1600 kHz	TC3022	230818	35cycles	
1600 to 2500 kHz*	TC3021	441008	25cycles	* Limitation in frequency on calibration system

All of the reference transducers used for the calibration are calibrated by a reciprocity calibration procedure [8].

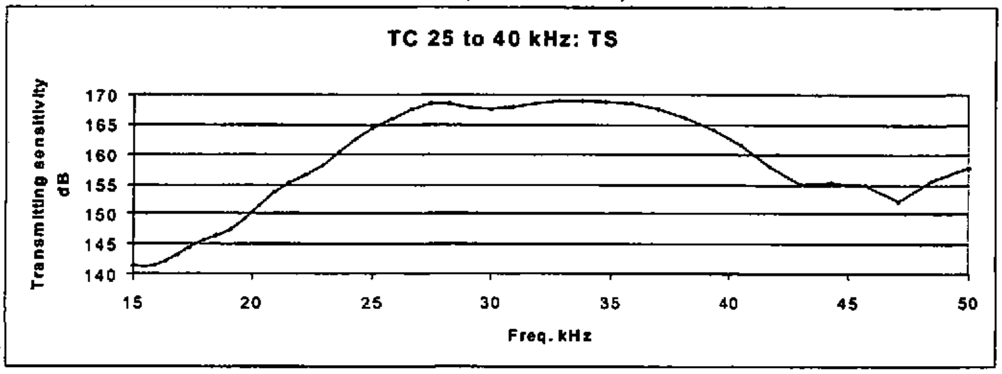
3.2 Pressure testing

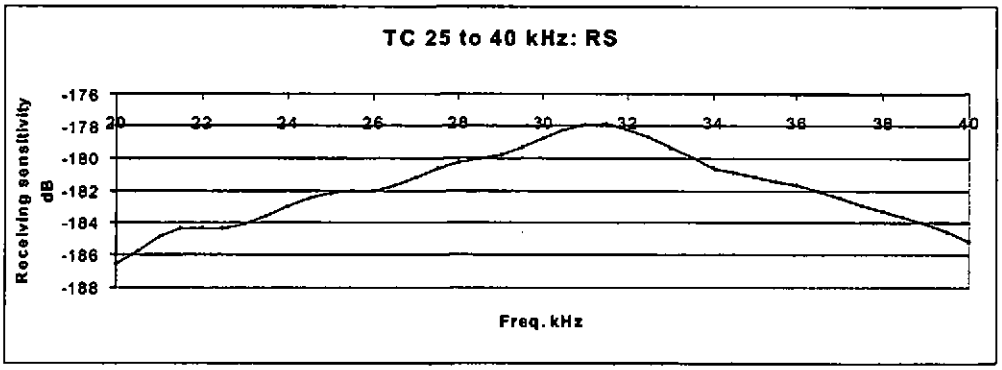
Before the final acoustical calibration of the transducers each transducer was pressure tested to the desired operational water depth. All the transducers were tested at a pressure of 25 bar, which is approximately equal to the operational depth of 250 m. Each transducer was exposed to four pressure load cycles from 0 to 25 bar and back to 0 bar. The rise time, or pressure ramp, was 50 bar per minute. At each pressure level the pressure was fixed for 30 minutes. The total duration of the pressure test was thereby 3 hours and 34 minutes.

The pressure test was conducted at the 700 bar pressure-tank located at Reson A/S. The pressure tank is provided with a 0 to 1000 bar manometer. The manometer of the pressure tank is calibrated at the Force Institute Denmark and is traceable to international references.

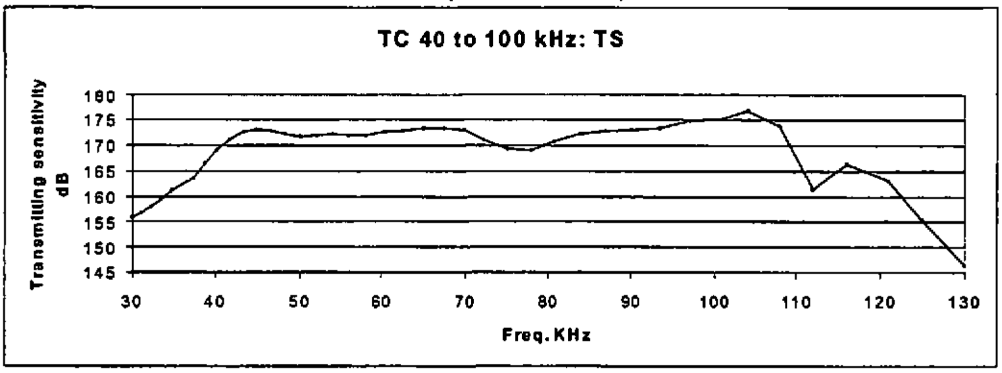
4. TRANSDUCER PERFORMANCE CHARACTERISTICS

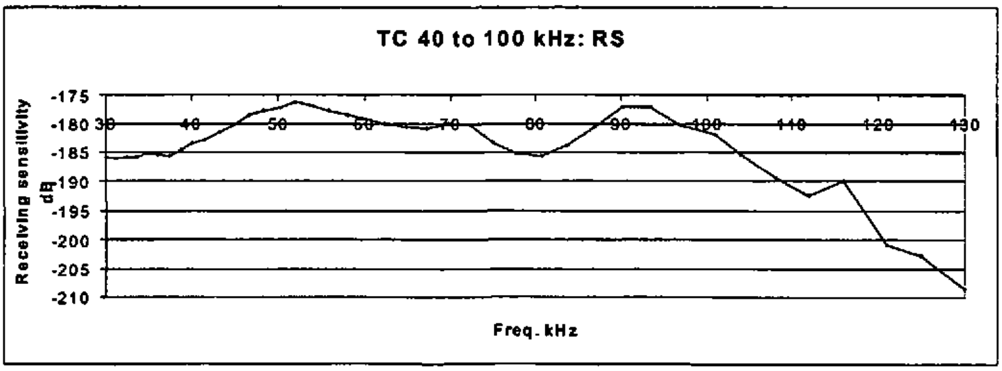
Transducer: Band 1 (25 to 40 kHz) S/N 632001:





Transducer: Band 2 (40 to 100 kHz) S/N 0397022:





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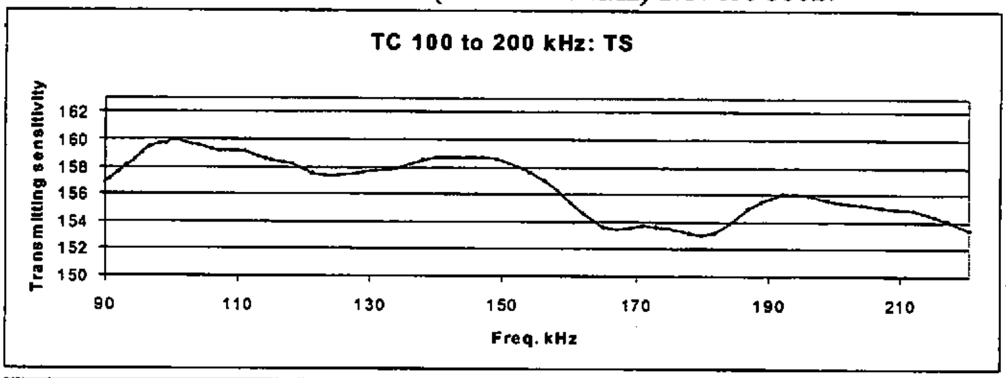
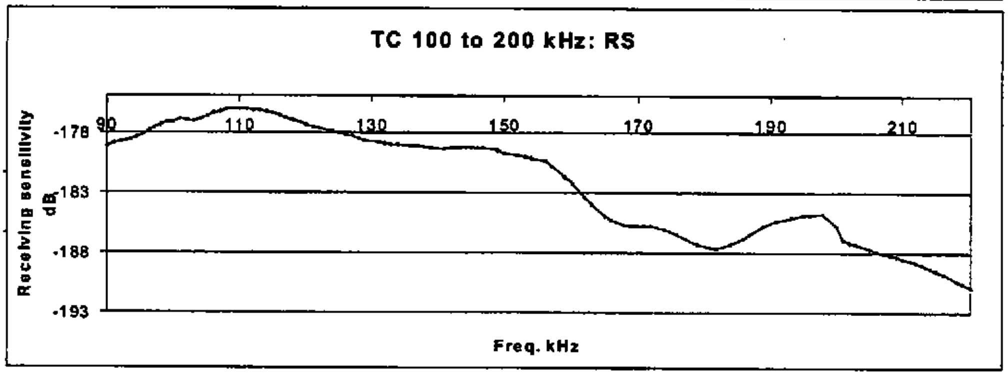
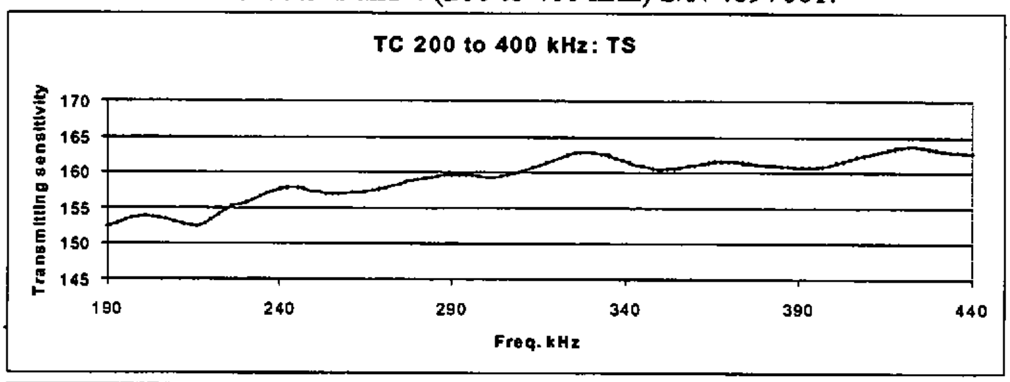
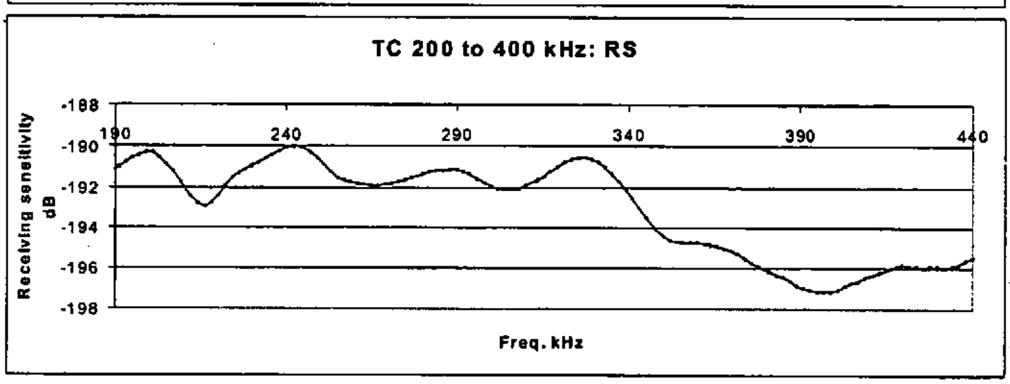
Transducer: Band 3 (100 to 200 kHz) S/N 0998002:





Transducer: Band 4 (200 to 400 kHz) S/N 4697001:





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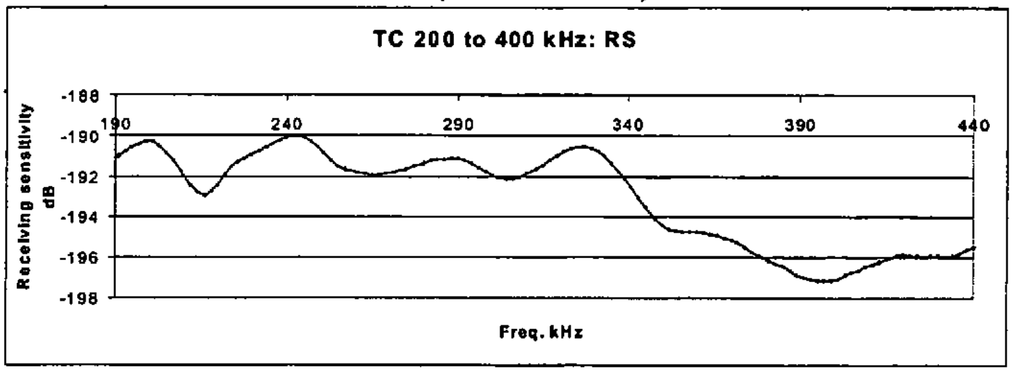
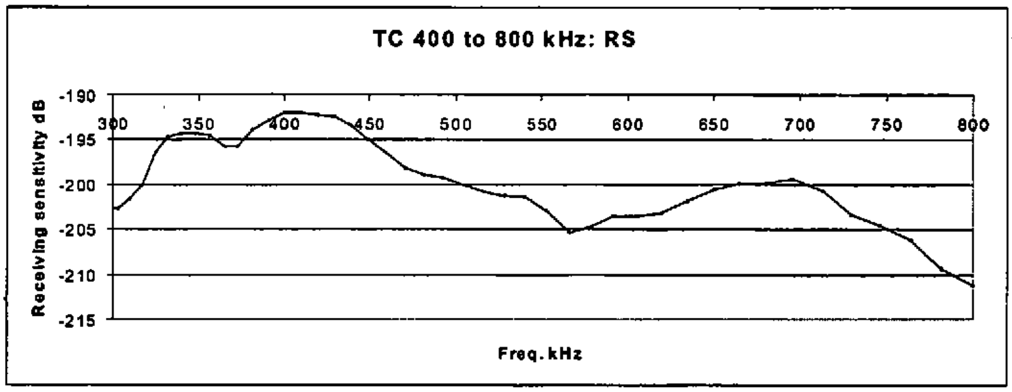
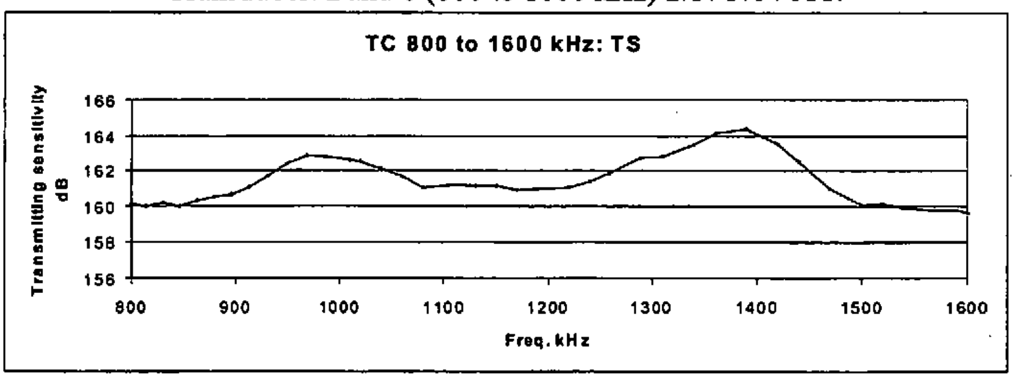
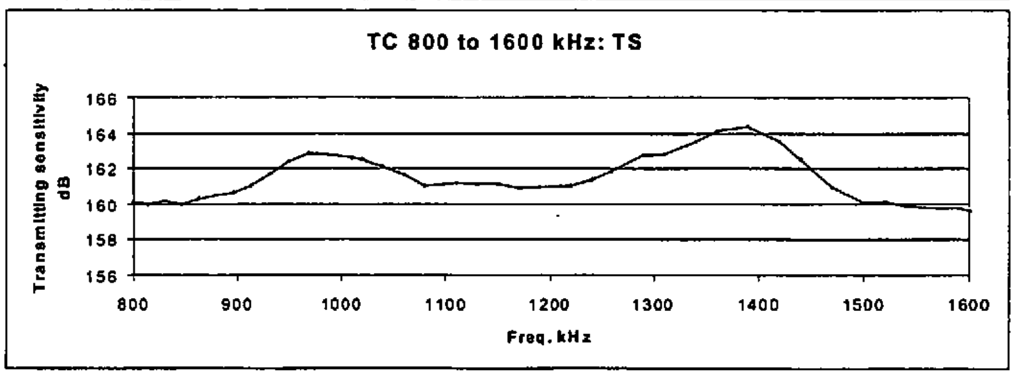
Transducer: Band 5 (400 to 800 kHz) S/N 2397003:





Transducer: Band 6 (800 to 1600 kHz) S/N 1797011:





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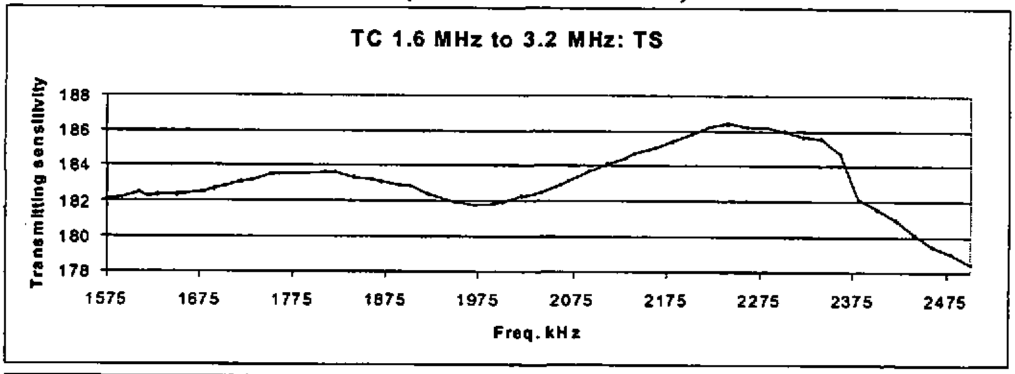
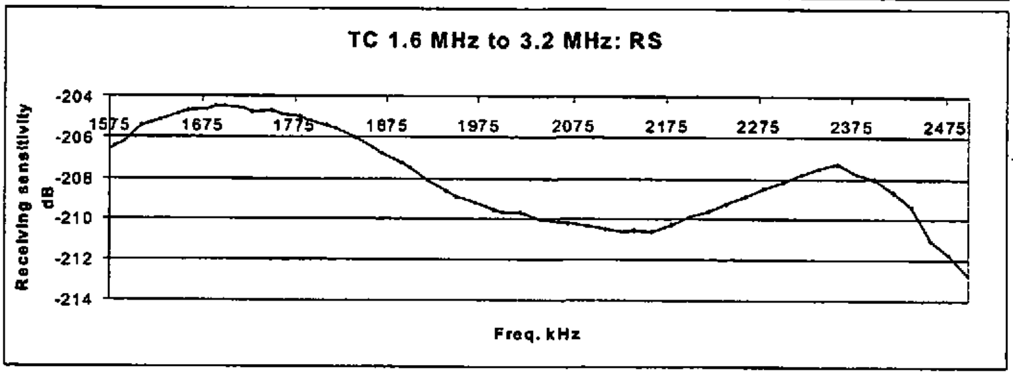
Transducer: Band 7 (1.6 MHz to 3.2 MHz) S/N 0497002:





5. EXPLOITAION

The three lower frequency band transducers developed during the BASS project have become part of the product portfolio of Reson A/S. The transducers are identified by the following product numbers:

TC2115 (25 to 40 kHz, shallow water), 2116 (40 to 100 kHz, shallow water), 2130 (100 to 200 kHz shallow water) and 2138 (40 to 100 kHz, 250 m version). All the transducers marked shallow water are produced on request in 250 m versions.

The most common use of these transducers is for depth sensors, but due to their broad band characteristic, they are frequently used for a variety of scientific research applications where a large bandwidth is required.

6. SUMMARY

The work on developing the transducers for the BASS system has been successful, not only in terms of the transducers available for the BASS system but also due to the fact that the transducers are now used in other broadband measurement applications.

This project provided the authors with invaluable experience in the fields of designing broad band transducers, sonar systems and the deployment of large underwater acoustic instruments from fishery research vessels especially during rough weather conditions and at low temperatures. An overview of the problems encountered by scientists active in the field of fisheries research was also gained.

7. ACKNOWLEDGMENTS

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the partial funding of the project by the European community MAST III programme, contract number MAS3-CT95-0031, that makes such a joint venture project possible.

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