NEW DESIGN FOR SWATH BATHYMETRY TRANSDUCER WITH MULTI-ELEMENT PVDF DISCRETE RECEIVING SYSTEM

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1. INTRODUCTION

Swath bathymetry has become a very effective tool in mapping the coastal littoral as well as deeper water offshore. Specialized systems have been developed for seabed mapping, route, site or pipeline survey and trench profiling in depths up to 200 meters using frequencies from 120 kHz to 455kHz. Mill's Cross [1] transducer configurations are used in most swath bathymetry systems. The included beam angle (at -3dB) ensonified by transmitting and receiving beams is typically on the order of 3° x 3°. This narrow angle yields good bottom definition. A second benefit is that generally in the volume ensonified by both beams, there are few artifacts provided and therefore spurious echoes are reduced. Most, if not all existing high frequency swath bathymetry systems electronics utilize beamforming and both arc and planar transducer arrays have been used. By using beamforming, a small transducer size is achieved but cost and complexity of the electronics are increased. Since the market for these systems is limited, there is no economy of scale to drive down the electronics cost. Artifacts produced by electronic beam forming reduce system performance.

Most swath bathymetry systems lose 100% bottom coverage at moderate survey speeds. Since four to eight performed receive beams are typically used and the beamwidth along the fore-aft axis is typically 3 degrees, 100% coverage can be compromised at vessel speeds of 5 to 7 knots. Inherent in the speed limitation for 100% coverage is that there may be only one echo for a surveyed segment. The corollary is that existing swath systems using electronic beamforming often do not produce many echoes per unit area making data correlation and smoothing problematic.

In this paper we have taken a completely different design approach. Our objectives are to significantly increase the echo data per unit area surveyed while reducing artifacts and to markedly reduce system cost and complexity. The tradeoff is that the transducer size will increase over designs using beamforming. Our swath bathymetry transducer is a Mills Cross configuration with an operating frequency of 200kHz. The projector is an arc array comprised of PZT ceramic elements creating a 2.5° x 100° fam beam.

The receiving array in our design consists of discrete PVDF elements. Since PVDF elements can be shaped easily, we have designed a receiving element which provides a 3° x 15° beamwidth and a "near-Gaussian" receiving pattern along the 3° axis. To cover a 90° swath, 30 discrete PVDF elements are used. See Figure 1 for a representation of the superimposed transmitting and receiving beams. The system is envisioned to have 30 receiving channels so their data rate per unit area will be increased by a factor of 5 or so over most present systems.

2. THEORY

A) Acoustic Diffraction of An Aperture

The sound pressure p is given by the Kichhoff's integral

$$p(\bar{x}) = \oiint_{S} \left[p(\bar{x}')\hat{n}' \cdot \nabla' G(\bar{x},\bar{x}') - G(\bar{x},\bar{x}')\hat{n}' \cdot \nabla' p(\bar{x}') \right] dS', \qquad (1)$$

here $\hat{n}'$ is directed inwardly normal to the surface S [2]. Figure 2 shows the geometry used for the integral. The Green function describing the out going wave is:

$$G(\bar{x},\bar{x}') = \frac{\exp(-j\bar{k}\cdot\bar{R})}{4\pi R}, \qquad (2)$$

where $\bar{R} = \bar{x} - \bar{x}'$. With this Green function, the Kichhoff's integral formula becomes

$$p(\bar{x}) = -\frac{1}{4\pi}\iint_{S1} \frac{\exp(-j\bar{k}\cdot\bar{R})}{R}\hat{n}' \cdot \left[\nabla' p(\bar{x}') - jk(1-\frac{j}{kR})\frac{\bar{R}}{R} p(\bar{x}') \right] dS', \qquad (3)$$

with the integration only over surface S_1 of the diffraction "screen". Furthermore, the higher order terms in 1/R may be dropped for far-field distances, giving

$$\hat{n}' \cdot \frac{\bar{R}}{R} = \cos(\hat{n}', \bar{R}),$$

and

$$\hat{n}' \cdot \nabla p(\bar{x}') = \frac{\partial p}{\partial \hat{n}'} = -jkp. \qquad (4)$$

From Eq. 3 and 4, we have [3]

$$\begin{aligned} p(\bar{x}) &= -\frac{1}{4\pi}\iint_{S1} \frac{\exp(-j\bar{k}\cdot\bar{R})}{R}\left[-jkp(\bar{x}') - jk\cos(\hat{n}',\bar{R})p(\bar{x}') \right] dS' \\ &= \frac{jk}{4\pi}\iint_{S1} \frac{\exp(-j\bar{k}\cdot\bar{R})}{R}\left[1+\cos(\hat{n}',\bar{R}) \right] p(\bar{x}')dS' \\ &= \frac{j\rho\omega}{2\pi}\iint_{S1} \frac{\left[1+\cos(\hat{n}',\bar{R}) \right]}{2} \frac{\exp(-j\bar{k}\cdot\bar{R})}{R} U(\bar{x}')dS', \end{aligned} \qquad (5)$$

with the consideration of acoustic specific impedance Z = $\rho C = p/U$ (U is the particle velocity). The far field directivity of the radiation area S_1 can thus be found

$$|D(\theta,\varphi)| = \frac{|p(\bar{x})|}{|p(\bar{x})|_{\max}}, \tag{6}$$

when $|\bar{x}|$ be kept constant at far field. The receiving directivity can be obtained by applying reciprocity principle.

B) Design of System Bathymetric Transducer

Projector

The design objective for the projector is to generate a source level of 225 dB re 1 uPa at 1 meter. This should be sufficient to enable satisfactory system operation to 200 meters depth under most conditions. Since transmitter power is relatively inexpensive, a pulse power rating for the projector was chosen to be 5 Kw RMS.

The building blocks space for the projector are rectangular PZT-4 elements which are thickness resonant, and whose length has been optimized to create a coupling coefficient of 0.56. The projector design uses five rows of PZT elements with 55 elements per row arranged to form an arc array. Row element spacing per is approximately $\lambda/2$. The active surface area of the projector is 323 cm^2. At -3 dB, the beamwidth is 2.5° x 100° and shading is used to reduce sidelobes. Refer to Figures 3, 4 and 5 for predicted 2D and 3D radiation patterns for the projector. Projector sidelobes within the -10 dB beamwidth of the receiving elements are suppressed below -22 dB.

Receiving Array

The primary goal of swath bathymetry systems is to obtain accurate depth measurements with 100% bottom coverage and be able to survey the bottom as quickly as possible. As is always the case, system cost should be as low as possible. To overcome the limitations of beamformed swath systems, a completely different approach is used. The maximum amount of data can be obtained if a receive element(s) is dedicated to receive echoes from each swath sector. Sidelobes in the receiving transducer which overlap the area ensonified by the projector has been minimized. To ensure that sufficient bottom resolution is obtained, the athwartship beamwidth of each beam is 3°. Using dedicated elements for each 3° (athwartship) receive beam means we need 30 elements to cover a 90° swath. For minimum sidelobes, the ideal would be to shape receiving surface so as to form a Gaussian beam. One of the easiest ways to approach a Gaussian beam is to use a shaped PVDF element. To achieve a satisfactory receiving response, we chose 0.5mm thick PVDF. The specified receiving response for this 0.5mm PVDF in the hydrostatic mode is -191 dB [5].

Transducer size tradeoffs dictated that each receiving element have a 15° beamwidth along the fore-aft axis. To achieve a near Gaussian beam pattern along the 3° axis, we used a cosine cubed geometry with the upper and lower electrode boundaries defined by the function $y = \pm 1.676\text{ cm} \cdot [\cos(x\pi/23.67\text{ cm})]^3$ function.

Though the analytic diffraction solution is available [4] for cosine cube apertures, our numerical simulation is obtained by using array design and synthesis software developed by Huang [3] based on the Eq.5. The software can handle any type of array (linear, plannar, arc, cylindrical spherical or any other spatial array) with elements in the array of arbitrary weighting, shapes, normal particle velocity distributions and element acoustic axis orientations etc. This array synthesis software was used to predict the projector radiation pattern. Figures 6 and 7 show the predicted receiving 2D radiation patterns; sidelobes are very low on the 3° axis.

To visualize the receiving directivity clearly, the three dimensional beam pattern is shown in both cylindrical coordinates (Figure 8) and spherical coordinates (Figure 9).

Further, the receiving array is designed such that each discrete cosine cube element is mechanically oriented 2.8 degrees apart such that total 32 discrete elements cover a 90 degree swath. Figures 10 and 11 shows the mechanical configuration for the receiving array.

The Mills Cross configuration is employed for our bathymetric transducer, the included angle ensonified by both transmitter and receiver is 2.5° by 3°. Figures 12 and 13 show the transmitting and receiving radiation patterns superimposed.

It follows that there is the potential for a high echo data ratio in this design. In our design 90° coverage is achieved by transmitting with a 100° wide fan beam and by receiving with 30 discrete elements. If the bathymetry system employs 30 dedicated receivers, the maximum allowable vessel speeds for 100% coverage would be in excess of 30 knots.

3. EXPERIMENTAL VERIFICATION

To identify construction problems and to verify if the TVR can meet design goals, a 25 element 200kHz array was built and tested. It consists of PZT-4 bars as discussed in Section 2 arranged in a 5 x 5 array. The measured peak TVR for this array is 171.5 dB re 1 uPa per volt at one meter. The impedance is 80 ohms. We scaled the directivity index (DI) of the 25 element planar array and the DI of the 275 element arc array and calculated TSL for a 5 Kw RMS pulse power. We predict the TSL will be 228.6 dB (RMS) re 1 uPa at 1 meter. This provides some margin of safety over the 225 dB goal to account for design and production tolerances.

To verify our new design concept for a bathymetric transducer, we shaped 0.5 mm thick PVDF so that the boundaries were defined by $y \cong \pm 1.27\ \text{cm} \cdot [\cos(x\pi/14.38\text{cm})]^3$ functions, where $|x| < 6.35$ cm. A piece of PVDF material with electrodes on both sides were mechanically cut to form the cosine cubed shape within the boundaries. The PVDF element was then bonded to a 19 cm long aluminum backing. Urethane was used as an acoustic window and covered the surface of the PVDF. Figures 14 and 15 show the predicted and measured radiation patterns along the narrow beam axis, respectively. Not only do the predicted and measured beam patterns agree very well, but also the sidelobe suppression achieved experimentally within the area of transmitting main beam is around -35 dB. Since there is little acoustic absorbtion in the backing layer and substrate, some energy transmission through the backing was expected.

With this success, 23.67 cm long receiving elements were prepared by electrode plating the PVDF. Both sides of the 0.5mm thick PVDF material were shaped with boundaries defined by cosine cube function discussed in Section II. Both single and double layers of PVDF receiving elements were fabricated with glass used as backing and a mechanically supporting stainless steel plate was bonded to the backing. In close proximity, a low noise preamp was designed to match the electrical impedance of the PVDF and to provide 20 dB signal gain. The predicted radiation patterns have alread been shown in Figure 5 through Figure 8. The RVR data is shown in Figures 16. As expected, "Q" is very low for both single layer and double layer PVDF prototypes. The RVR of the single layer is very close to that listed in the Raytheon material specifications [5]. The RVR of the double layer is lower than predicted and below that of the single layer. This is attributed to the fact that the thickness resonance of double layer of PVDF and backing is below 200 kHz.

4. CONCLUSIONS

A PVDF multi-element receiving array has been proposed to replace a conventional phased array receiving system for swath bathymetry. The discrete receiving PVDF elements are shaped to achieve in excess of -30 dB sidelobe suppression. With this design approach, artifacts intrinsic to electronically formed beams are eliminated. As compared to systems with electronic beamforming, our new system simplifies signal processing and improves system accuracy. Using a fan beam projector and 30 discrete receiving channels, the amount of echoes available for processing is greatly increased. Although the discussion herein is focused on bathymetric transducers, the general concept can be evaluated as an alternative to multibeam and phased array systems for other applications.

5. FUTURE WORK

A prototype of the transmitting and receiving transducer is presently undergoing field testing. The prototype consists of a 25 element planar array to simulate the projector and a single full size PVDF receiving element. Results to date are very encouraging. A full scale transducer is scheduled to be built and tested by mid 1995.

6. ACKNOWLEDGEMENTS

The authors wish to thank Dr. Roger H. Tancrell and David T. Wilson and Neil Dionestes of Raytheon Research Division for providing PVDF material and their guidance in optimizing Raytheon PVDF to this application.

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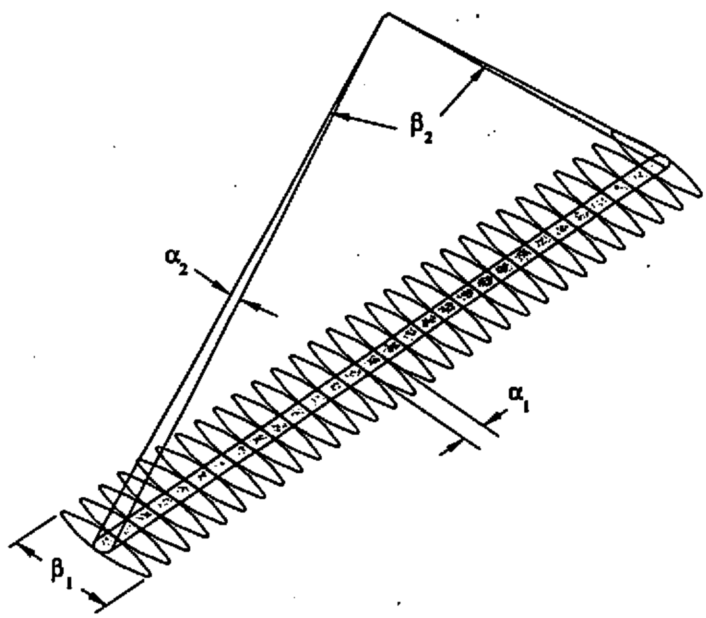

Figure 1

Representation of transmitting and receiving beams for swath bathymetry transducer.

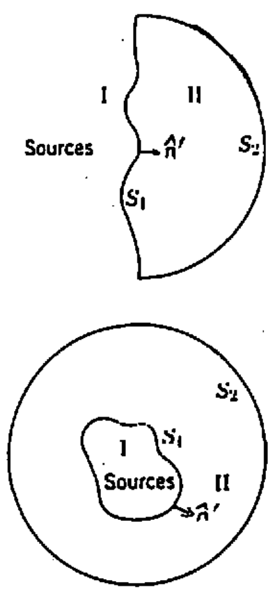

Figure 2

Possible diffraction geometry
Region I contains the sources of radiation;
Region II is the diffraction region, where the fields satisfy the radiation condition.

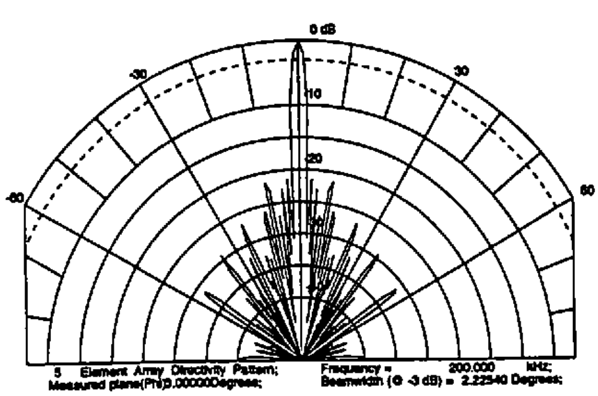

Figure 3

Simulated transmitting beam pattern on narrow beam plane (5 row arc array with rectangular PZT elements)

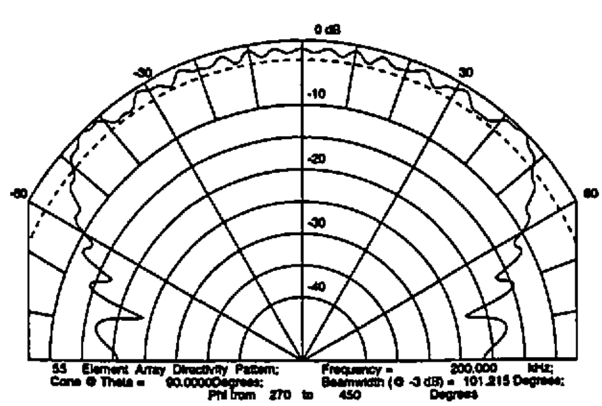

Figure 4

Simulated transmitting beam pattern on wide beam plane (55 element arc array with rectangular PZT elements).

Figure 5

Simulated arc array three-dimensional beam pattern
(5 x 55 rectangular PZT elements)

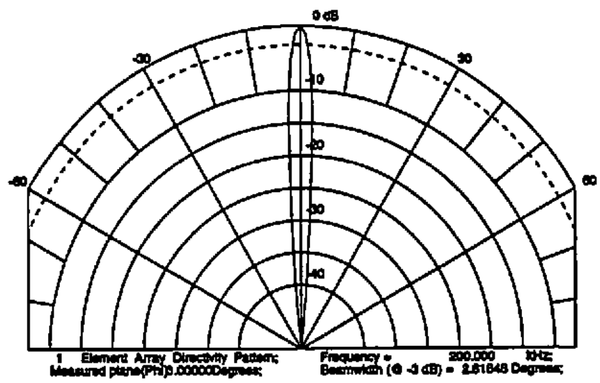

Figure 6

Simulated receiving beam pattern on 3° beam plane
for PVDF element with cosine cube boundary functions
(y= 1.676 cm * {cos(x*pi/23.67 cm)}^3: |x|<11.84 cm)

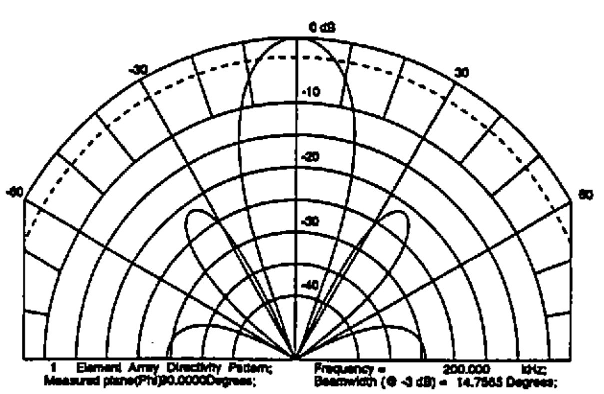

Figure 7

Simulated receiving beam pattern on 15° beam plane
for PVDF element with cosine cubed boundary functions
(y= 1.676 cm * [cos(x*pi/23.67 cm)]^3; |x|<11.84 cm)

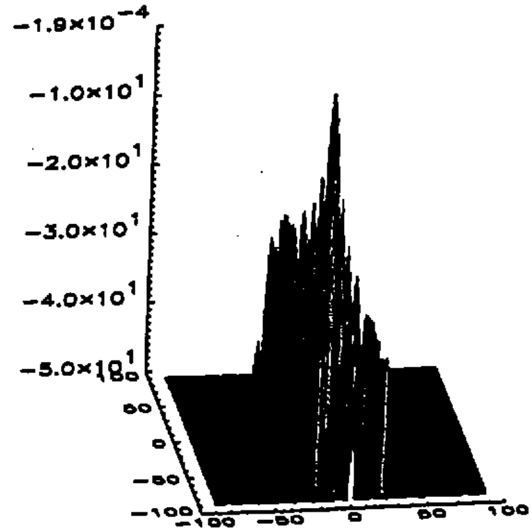

Figure 8

Simulated receiving beam pattern viewed in 3 - dimensional
cylindrical coordinates for PVDF element with cosine cube boundary
functions (y = 1.676 cm * [cos(x*pi/23.67 cm)]^3; |x|<11.84 cm;
axial angle Theta is zero at the center and is 90° on the edge)

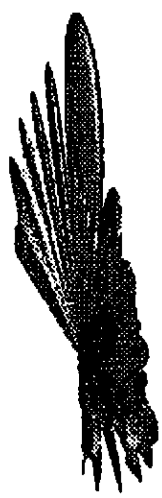

Figure 9

Simulated receiving beam pattern viewed in 3 - dimensional Spherical coordinates for PVDF element with cosine cube boundary functions (y= 1.676 cm* [cos(x*pi/23.67 cm)]^3; |x|<11.84 cm;)

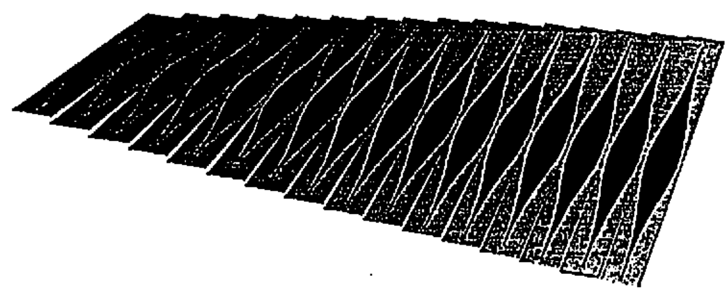

Figure 10

Receiving array configuration with discrete cosine cube element mechanically oriented 3° apart (only half of the 30 shaped PVDF is shown here for symetry).

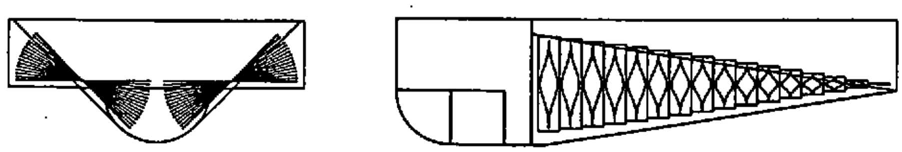

Figure 11

Mechanical configuration for the receiving array in swath bathymetry transducer.

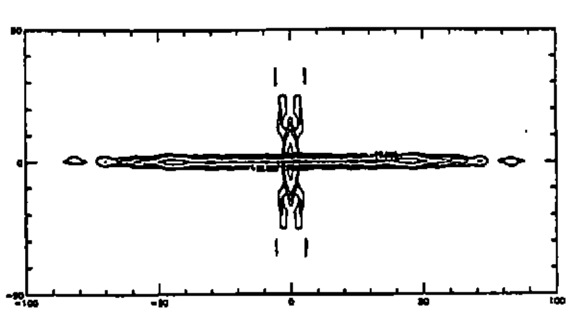

Figure 12

Contour plot for both transmitter and receiver beams (contour plot levels: -3 dB, -10 dB, -15 dB and -20 dB)

Figure 13

3-dimensional beam spherical coordinate patterns for bathymetry transceiver in 1.

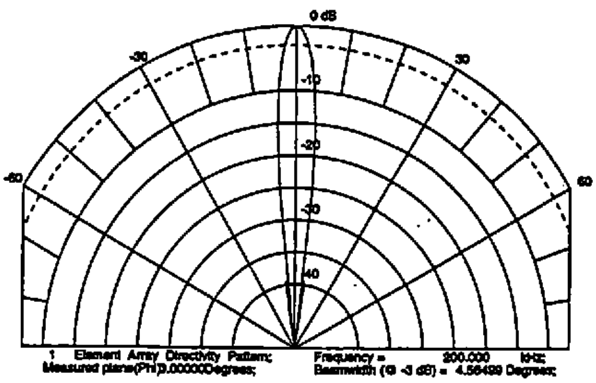

Figure 14

Simulated receiving beam pattern on narrow beam plane for PVDF element with cosine cube boundary functions (y= 1.27 cm * [cos(x*pi/14.38 cm)]^3; |x| <6.35 cm)

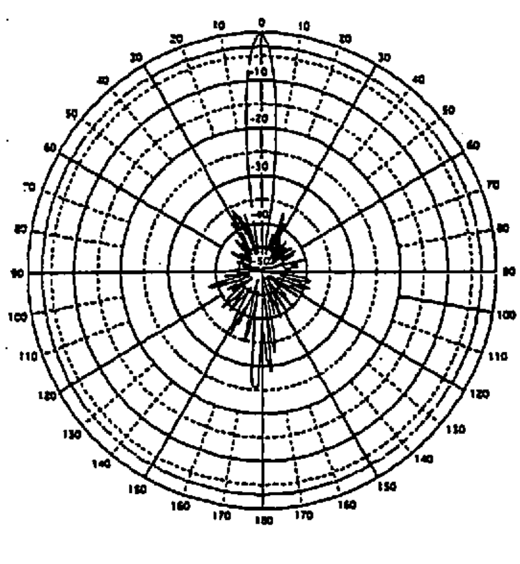

Figure 15

Measured receiving beam pattern on narrow beam plane for PVDF element with cosine cube boundary functions (y = 1.27 cm * [cos(x*pi/14.38 cm)]^3; |x| < 6.35 cm)

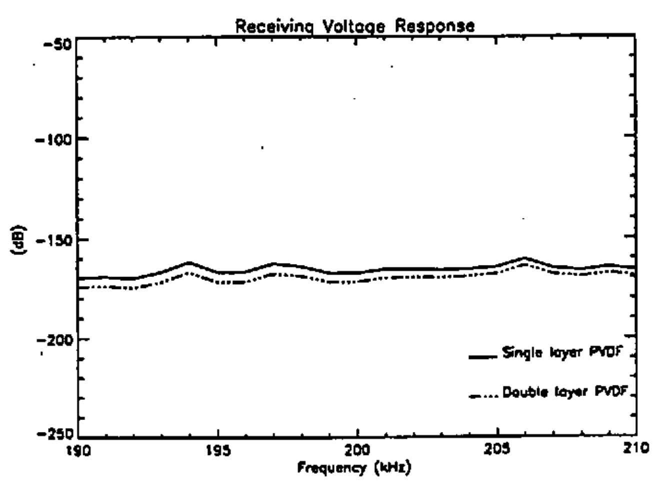

Figure 16

Measured Receiving Voltage Response (RVR) for a single layer and a double layer PVDF receiving element.