LOW FREQUENCY FLEXURAL DISC SOURCES FOR HIGH POWER, COMPACT ARRAYS

C.Minto

Marine Acoustics Ltd, Unit 3, Weller Drive, Hogwood
Lane Industrial Estate, Finchampstead, Berkshire,
RG40 4QZ

1. INTRODUCTION

The major problems that designers of low frequency underwater transducers routinely face are, in general, the conflicting aims of achieving high power, low frequency transducers and at low cost with low weight. Each individual application may have a particular weighting of these factors and indeed development of all four factors is often necessary! These factors are, in general, mutually exclusive and compromises have to be made in order to achieve a useful working device at the correct cost. Over the past 15 years, Marine Acoustics has used and explored a variety of designs, aimed at varying tasks. In general, the preferred solution which we have adopted has been to use transducers taken from a family of flexural disc devices. Although such choices can often be made from the point of view of historical preference, a great deal of effort has been expended to improve the performance of these devices and to provide solutions with various frequencies and power handling capabilities. It is our belief that although these transducers do have shortcomings, their advantages do outweigh them for certain applications. The following article explores the features of such designs and how they can be tailored for particular applications, together with an analysis of some of the problems associated with their use. This is followed by an analysis of the use of the devices in high power, compact source arrays.

2. FLEXURAL DISC TRANSDUCERS

Woolet described in some detail the Physics behind the operation of flexural discs as long ago as 1960 [1,2], later reviewed by Stansfield [3]. To this day, Woolet's work is largely the standard body of reference for workers in this area with few additions having been made over the years. For a full description of the Maths, the reader is referred to these references, especially reference [1].

In the design of flexural discs, a number of construction variations are available. The basic method involves bonding two ceramic disks back to back with identical polarisation directions, the resulting disk is supported (not rigidly fixed) by a moderately compliant housing. Application of an electric field in opposite directions to each disk simultaneously results in the generation of planar stresses. With the above polarisation scheme these stresses are in opposition, resulting in an expansion in one half of the disk and a contraction in the other, this gives rise to a flexural motion. As the motion is flexural, the amplitude at the centre is significantly greater than that which can be achieved by the ceramic alone. The generation of these large amplitudes of motion is of course an essential requirement for the production of low frequency sounds from these omnidirectional devices.

Variations on this theme involve adding a third layer of an inactive material - usually a metal which can be used as electrode. This eases the mounting arrangements and also produces a higher efficiency design.

One of the most useful alternative designs which Marine Acoustics has adopted for the 'Sonoflex' family of flexural discs utilises a ceramic plate bonded to a backing plate (of varying metallic construction), two such plates are then attached to either side of a polymer housing with a pressure release air gap between, the plates are connected in parallel with the wiring brought out either through a moulded gland or a fitting in the side of the housing. The ceramic is always placed on the outside of the device to ensure that the ceramic is kept *in compression* to as great a depth as possible. The same principles apply to the operation of this design, but of course the stresses in the backing plate are generated

generated purely by the single plate of ceramic. Figure1 illustrates the dimensions and appearance of a typical flexural disc transducer.

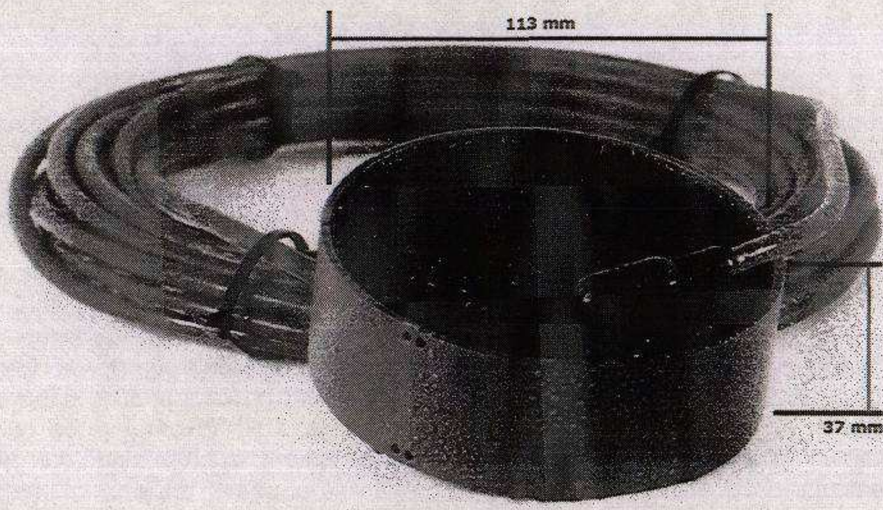

Figure 1: Typical flexural disc (1.9kHz)

Replacing one of the ceramic plates with a metal plate significantly improves the mechanical properties of the device (i.e depth rating), but of course at the expense of coupling coefficient and power output.

Turning the argument around, replacing a ceramic backing by a metallic plate of similar bulk stiffness (thus preserving a given depth capability) results in a much thinner device and as we shall see, this will give a lower resonant frequency.

The basic parameters for design of these devices are surprisingly simple:

The frequency is related to the dimensions by:

$$f_0 = \frac{A_1 \frac{t}{r^2}}{\sqrt{1 + A_2 \frac{r}{t}}} \qquad \text{Equation 1}$$

Where f_0 is the resonant frequency in water, t is the combined thickness of the plate and r is the radius of the plate. The factors A_1 and A_2 relate to the method of mounting and the materials used for both parts of the disc and are discussed in Woolet [1].

Again, simply, the bandwidth Q factor can be described as:

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$$Q = A_3\left(\sqrt{1 + A_2\frac{r}{t}}\right)^3 \qquad \text{Equation 2}$$

These two equations alone describe accurately the bandwidth and resonant frequency of any device we wish to model. Typically, these models would be used develop surfaces in the *r,t* planes as follows:

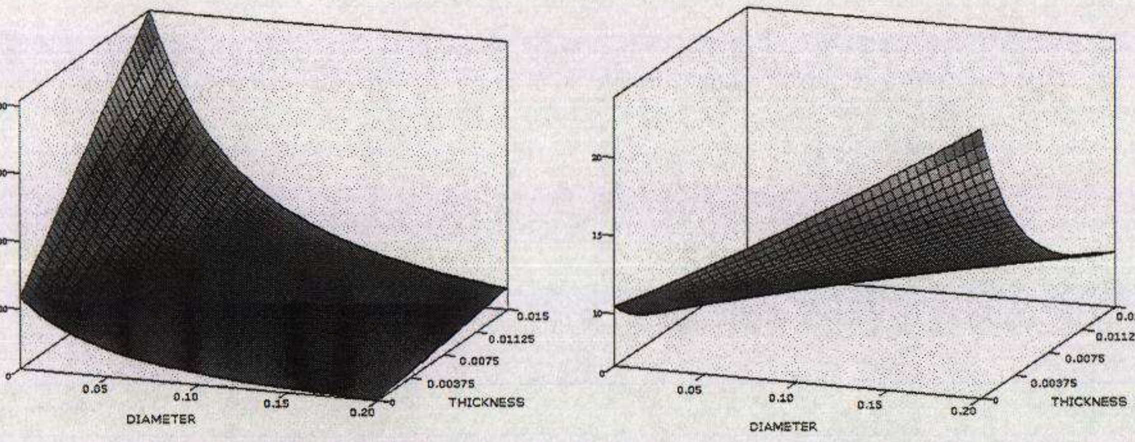

Figure 2: Left - Frequency Right - Q factor

From these two figures we see that the lowest frequencies are obtained by large, thin plates but these also give the highest Q factor, which at low frequencies becomes very undesirable as covering the most modest bandwidths can become quite a task. Hence some care needs to be taken to select values of Q and f_0 which give the most useful devices. Once all of the design parameters of the flexural disc are taken into consideration (to give the parameters $A_{1,2,3}$) the acoustic performance of the disk can be predicted with sufficient accuracy to avoid extensive prototyping, hence reducing the turnaround time between new ideas and real products.

The final necessary mathematical theory needed for assessing designs pertains to the depth capability of the device and the power output. The depth capability can be found from a straight forward consideration of the external pressure acting on the bilaminar construction. The failure mode is designed not to be that of the backing collapsing, but the backing bending to such a degree that the ceramic exceeds the intrinsic tensile strength and fractures. The bottom surface of the ceramic is in tension and the top surface in compression hence, once a certain pressure is exceeded the ceramic will fail. The role of the bond between the discs is crucial, the shear strength of the bond must be sufficient to allow the material to flex but not fail before the ceramic fractures but have as little compliance as possible with respect to this to allow good energy transfer. This is only achieved through strict control over bonding procedures and extensive trials of varying adhesives.

We have found that the most accurate prediction method for failure incorporates both the tensile features of the ceramic and the backing disc, essentially treating the disc in a similar manner to a supported "bimetallic strip" under compression.

The somewhat complicated equation used is developed from formulae from Roark [4]. The tensile stress in the ceramic is given by:

$$\sigma = \frac{-6M}{t_a^2 K}\left[\frac{E_b t_b (1-\nu_a^2)}{E_a t_a (1-\nu_b^2)} + \frac{t_a(1-\nu_a^2)(1+t_b/t_a)(1+E_a t_a/E_b t_b)}{t_b(1+E_a t_a/E_b t_b)^2 - (\nu_a + \nu_a E_a t_a/E_b t_b)^2}\right] \qquad \text{Equation 3}$$

Where the subscripts refer to the top and bottom plate materials (*a* and *b*) respectively, *E* is the Young's modules and ν is the Poisson's ratio. *K* is another extensive expression relating the two materials:

$$K = 1 + \frac{E_b t_b^3 (1-\nu_a^2)}{E_a t_a^2 (1-\nu_b^2)} + \frac{3(1-\nu_a^2)(1+t_b/t_a)^2(1+E_a t_a/E_b t_b)}{(1+E_a t_a/E_b t_b)^2 - (\nu_a + \nu_b E_a t_a/E_b t_b)^2} \qquad \text{Equation 4}$$

These two equations are used with the appropriate equation for *M*, the bending moment:

$$M = pr^2 \frac{3+\nu}{16} \qquad \text{Equation 5}$$

Where, *p*, is the ambient pressure field that the plate is exposed to. Thus, from a known value of *p* we can establish at what pressure the tensile stress in the ceramic will exceed the manufacturers rating. Hence different geometries are easily compared to weigh up different performance requirements.

We find that this formula quite accurately describes the maximum pressure that the devices will take prior to failure, to within ± 10m. Current popular designs vary in depth rating between 100m and 350m.

The remaining consideration is of course the power output of the transducer, simple estimates based on ceramic volume suggest that the power handling of these devices can be quite high - which explains why we consider these devices as useful low frequency sources. The combined conversion efficiency of the vibrational mode is however quite low - circa 40%, giving a low sensitivity. As an example, our Sonoflex 1350 transducer, has a resonant frequency of 1350 Hz and a bandwidth Q factor of 8. Both of these factors are readily predicted from Equations 1 and 2 and the depth rating of 250m is predicted by Roark. The device has a peak sensitivity of 134 dB re 1μPa/V @1m, which reflects the conversion efficiency of 40%. With a ceramic volume of 72 cm^3 and for a quick estimate using a value of 5.6 W/kHz cm^2 for PZT4 [5] suggests a maximum source level of 198 dB re 1μPa @1m at resonance, using the recommended maximum field conditions (Tan δ=0.04, E=3.9 kV/mm) [5].

The transducer was recently tested at the NAMAS approved, Marine Acoustics Wraysbury reservoir facility [6], at resonance (1350 Hz) in both continuous wave (CW) and pulsed modes, the results demonstrated the following:

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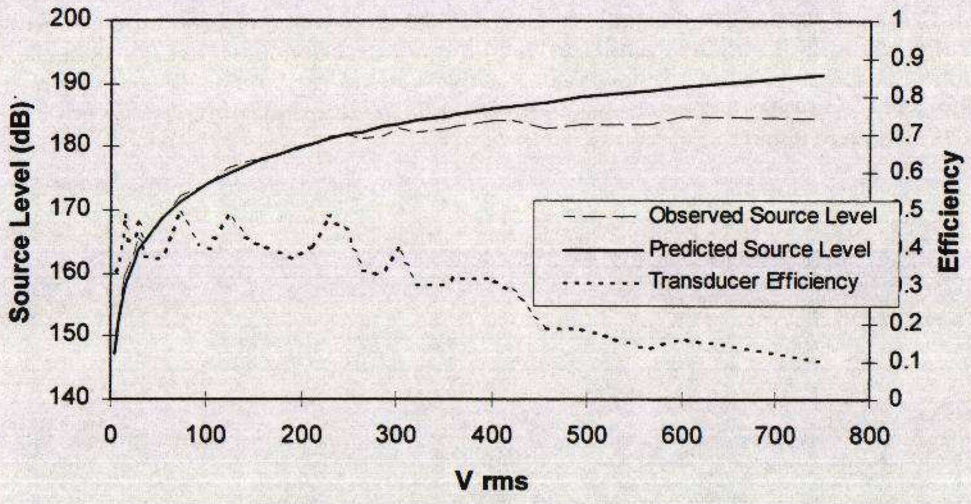

Figure 3: Source Level and electro-acoustic efficiency of 1350 Hz flexural disc transducer at 10m depth

The device was quite clearly saturating with power outputs well below the predicted maximum and a gradually dropping conversion efficiency is clearly in evidence. After a number of trials with different types of devices, all were found to be delivering power outputs well short of their predicted maximum, this particular device levelling off around 184.5 dB re 1µPa@1m. At first this was though to be due to dielectric losses or cavitation, rough calculations based on the size of the transducer suggest however that the cavitation limit would be as around 0.25 W/cm^2 or 196 dB re 1µPa @1m, again well short. Dielectric losses also should not cause a major problem at such low drive levels.

This transducer does not exhibit a simple planar, piston like motion, instead, the motion is flexural, with maximum amplitude at the centre of the disc. Hence, cavitation is not as simple a problem to define as initially thought. Finite Element analysis has also be used to predict the device performance and as can be seen from a cross section of the disk (Figure 4), the mode shape is not a simple piston like motion, but there is of course a prominent curvature of the ceramic.

Instead of considering the motion arising from the whole surface area of the device but rather consider instead that the maximum amplitude is concentrated at the geometric centre of the disc, with a decreasing amplitude around this. Cavitation would then be more localised and could begin to appear at power levels less than expected for the disc as whole. The onset of cavitation would therefore be much more gradual than initial predictions suggest. This could therefore also explain why the cavitation is not as marked as would traditionally be expected, with little evidence of a definite maximum in the power output of the transducer.

The simplest way to test the validity of this assumption is to observe how the response varies with increasing applied pressure. The same experiments were carried out at applied pressures of up to 10 Bar. In order to expose the transducer to a static 10 Bar pressure field, the pressure transducer is suspended in a glass fibre vessel which can be pressurised. Source level measurements at 10m depth showed negligible attenuation from the pressure vessel. The measurements were performed up to a maximum applied field of 750Vrms, which represented the electrical limits of the power amplifier. Quite clearly, the two graphs shown in Figure 5, expose little difference. A maximum source level of 193 dB re 1μPa@1m was produced. No dielectric heating effects were observed, with the efficiency remaining stable over the period of the measurement at each frequency. Hence, it was not possible to ascertain the maximum CW power output of the device. Observations on smaller flexural discs devices also exhibited the same saturation at low depth, but with a lower maximum output power - consistent with the idea of focused cavitation.

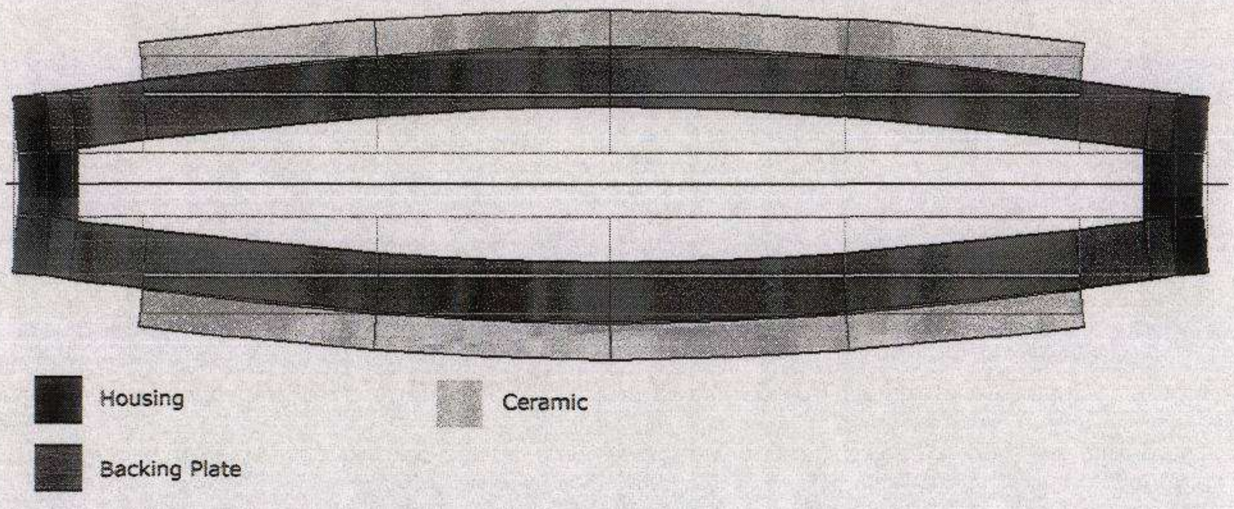

Figure 4: Axial section of FEA model of flexural disc, showing static (outlined) and deformed (filled) structure. Protective (insulating) encapsulant not shown.

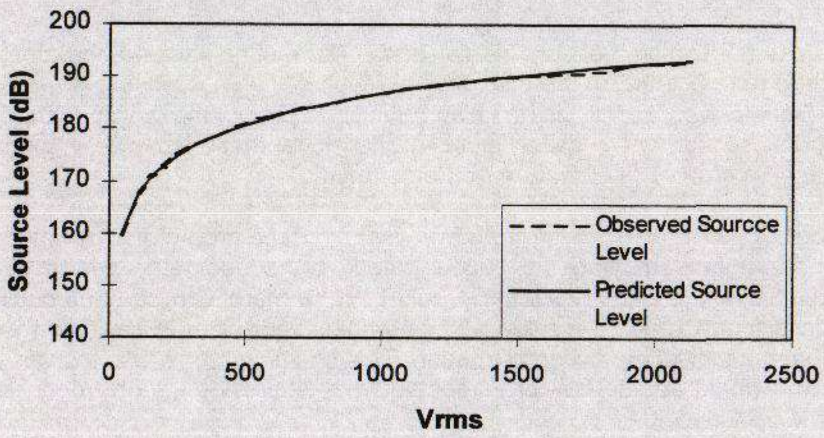

Figure 5: Source Level exhibited by 1350 Hz transducer at a simulated 100m depth.

It is not possible to assume that the device has a smaller effective surface area and establish a convincing formula. We found that on 165mm discs, the cavitation threshold corresponded to 25% of the disc surface area and smaller (113mm) disks saturated at a level corresponding to 50% of the surface area.

Hence, we see one fundamental problem with the transducers is that although they can promise to deliver impressive power outputs, this is not always realisable under all conditions of operation and indeed, the transducers may not give a fully realised potential until at appreciable depths. The other alternative is of course to manufacture larger transducers - and this can be done up to the limits of the ceramic plates and the backing materials which are available

The only other major drawback of this design of transducer is the requirement for a sufficient face pressure before the resonant mode develops. The vibrational mode that is used for the transducer is one of a flexing plate supported at the edges. It is very important that the device be supported at the edge and not rigidly fixed otherwise, the mode will be suppressed. Similarly, without adequate pressure against the face of the transducer the mode will not develop at all. This leads to rapid changes of properties over immersion in the first 5 to 10m of water (depending on design). This renders the transducers largely more suited to deeper water requirements.

As can be seen in Figure 6, in shallow water, the resonant frequency does not fully begin until at least 10m depth, the conductance develops in a similar manner. Once stable however, the transducer still does change frequency gradually, but only by minor amounts.

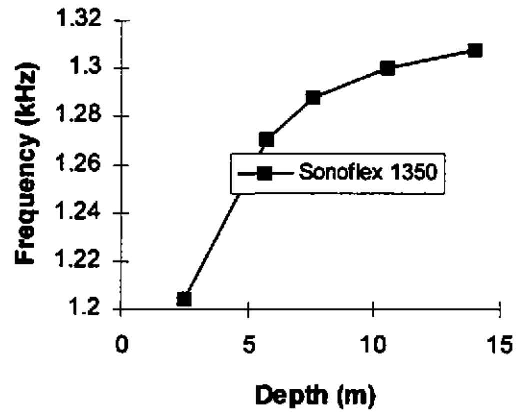

Figure 6: Shallow water performance of 1350 Hz flexural disc transducer

This technology, although not without it's downside is attractive for a number of reasons. Primarily, the resulting transducer is a very simple device, which is readily designed and manufactured. Without any complex pressure compensation systems or curved fabrications, a low frequency device is available which will satisfy the majority of users needs. The other major advantage of such designs is their

As in all such exercises, compromises are inevitable and there are strict limits which can be placed on Comparing the technology to discussions available in the literature gives a good feel for where such technology can be applied and the limits to which it can be exploited. The devices are clearly not entirely suited as single, omnidirectional, extreme power (>210 dB re 1µPa@1m) projectors, such as free flooded rings ring shell flextensionals or large piston transducers [7]. The performance does in general match or better the barrel stave type class I and class III flextensional transducers [8], which offer similar acoustic performance and depth rating. Such devices can however often offer larger bandwidths but at the expense of added complexity of the design. the size, frequency, depth rating, bandwidth equation. weight, being only 0.5kg to 3kg in water.

The problem of achieving greater output powers is addressed in the next section.

3. HIGH POWER COMPACT SOURCE ARRAYS

Over the past 15 years, variants of these transducers have been utilised by ourselves in a number of high power, compact, directional source arrays - aimed at both the academic and defence communities. A typical defence application is Active Sonobouy research for long range submarine detection. From the transducer, such devices must have the following requirements: primarily inexpensive to the point of expendability (in volume manufacture), capable of sustaining significant source levels and being compact enough to be launched from existing Sonobuoy casings.

As discussed in the previous section, there exists a number of possible technologies which can be exploited to achieve these aims, however in addressing the weight/size penalties and the expense, the only feasible alternatives are Class II flextensionals and flexural discs. Whilst Class II flextensionals often can be seen to have a slight technical edge over flexural discs, the arrangement of dimensions does not lend themselves to close packing within Sonobuoy casings in sufficient volumes to achieve the high source levels required. Flexural discs however have packaging dimensions which lend themselves particularly well to stacking within standard size Sonobuoy cases. The transducers can be arranged to be packaged in an extendible sock which drops the transducers out of the case on release. Up to 10 transducers can be readily packaged into a volume small enough to be simply managed.

The goal of the development of the transducer is therefore to supply a low frequency moderate bandwidth and maximum power output within previously defined diameters.

The format of an a typical array as shown below.

In this experimental array, a string of 10 1.9kHz flexural disc transducers is shown suspended beneath a source module which contains the battery pack, tuning & amplification and the necessary processing and communications systems. In this instance, the use of multiple transducers, gives an overall source level of 210 dB (limited by battery power and amplifier design). Roughly 10dB of this impressive source level arises due to increased directionality of the array (there is a 10° beam width) which in itself is not necessarily undesirable and gives the optional opportunity of both shading and steering of the beam. The whole array, excluding pressure vessel, batteries etc. manages to weigh less than 20 kg (in water). The only operational drawback to the use of such transducers is therefore the 5m length of the array (although the vertical deployment and flexible sock does ease this).

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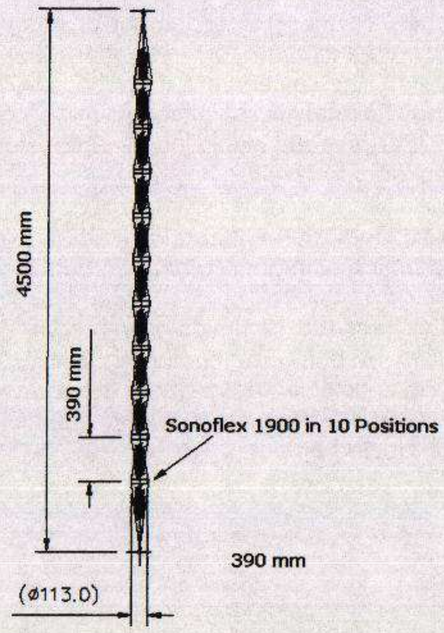

Figure 7 : Active multiple flexural disk sources, LEFT : deployment of elongated 1.9kHz test array, RIGHT : Schematic view of array geometry.

The above array is constructed with a traditional spacing of a half wavelength at resonance (0.4m). At lower frequencies the problem of radiation loading between elements in the array appears and some care must be given to a careful analysis of the acoustics before array construction, the non-rigid construction does however allow for some experimentation.

Early trials with 850 Hz arrays resulted in peak source levels considerably less than expected when assembled at 0.5λ spacings. Further investigation revealed that this was due to intense inter element acoustic loading which alters both the resonant response and power output of the device. A 5dB increase in output between 0.5λ and 0.8λ can be observed on a 4 element array. At these frequencies, the acoustic radiation loading is sufficiently great that the performance of the transducer is limited - the two main features being a downwards shift in the centre frequency and a reduction in the conversion efficiency. As the distance between two opposing transducers is reduced (or the frequency decreased), the added mass increases - this in turn affects the resonant frequency of the device.
We find that in order to restore full operational performance of the transducers a spacing of as much as 0.9 wavelengths must be applied to free each transducers from experiencing detrimental mutual loading effects.

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4. CONCLUSION

As has been discussed: a number of competing technologies are available for the production of low frequency sounds and for each individual application the properties of the transducer technology underpinning the experiment must be carefully considered. However, we have demonstrated in this paper that flexural discs, although quite often disregarded due to their low sensitivities can offer a solution that is both highly predictable, quite versatile and can be used inexpensively to generate significant source levels.

The transducers are in general limited by a localised cavitation phenomena which prevents the devices reaching their maximum power output until immersed to a significant depth.

Use of the transducers in high power, compact arrays allows the production of impressive source levels, only limited by beam angle requirements. The geometry of the transducer particularly lends itself to installation in flexible arrays where the array can be stored and launched in a compacted format. Array performance is limited by transducer spacing where deviation from ideal conditions is necessary to restore expected output.

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