Free-Flooded Ring Transducers: Design Methods and Their Interaction in Vertical Arrays

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Abstract. **Free-flooded ring underwater transducers provide major benefits such as high power handling, low mechanical quality factor (hence reasonably flat transmit response) and virtually no performance changes due to hydrostatic pressure. They can be manufactured in large dimensions and assembled as an array to achieve higher power levels and/or more directivity. In this paper a review of the free-flooded ring design methods will be presented. In addition, some examples will be given.**

I. INTRODUCTION

A free-flooded ring is best described as a hollow, cylindrical transducer. During their initial development period the free-flooded rings were also called “squirters”. The central cavity is open at both ends and filled with a “free-flooding” medium, i.e., seawater. Its major dimensions, diameter and length in particular, define its resonance frequencies, both radial and cavity. These two resonance frequencies can be optimized for specific applications. The electroacoustic conversion mechanism is usually made from piezoelectric ceramics but earlier ones were made of magnetic scrolls (Fig. 1). In piezoelectric ceramics, the ring is solid or of multiple staves (parallelepipeds) bonded together for larger dimensions. The ceramic ring is protected from the water environment either with polyurethane or an oil-filled rubber boot.

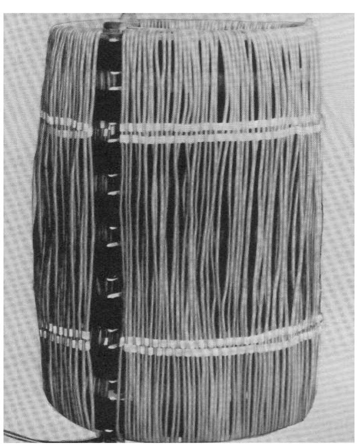

Fig. 1 A Magnetostrictive scroll transducer before final packaging [6].

The advantages of free-flooded rings are numerous: their performance is virtually unaffected by the hydrostatic pressure levels in the oceans; in cavitation-free environment they can handle high power; since they can be made as composite transducers they can be large to achieve low frequencies and the utilization of dual resonance frequencies provides a lower mechanical quality factor and hence wider bandwidth. In addition, narrower beam widths can be achieved with shorter elements and arrays made of free-flooded rings. For example, the –3 dB beamwidth of an array made of two coaxial rings, with a total length of 0.47λ, was measured as 56°. A line source with the same length would give 106° beamwidth [1].

Possible minor disadvantages can be toroidal beam pattern in one plane (and omni in the other) or mutual acoustic interaction on cavity resonance in closely packed arrays. It is known that acoustic interaction in an array changes the radiation impedance affecting the acoustical characteristics of a single element. This phenomenon is more complex in free-flooded arrays. In vertical arrays this interaction can be used to lower the cavity resonance without changing the diameter of individual transducers.

Although not assembled as individual free-flooded rings, in some designs the ceramics are used in oil-filled, booted transducers as arrays.

II. DESIGN METHODS

The earliest known analysis of free-flooded rings is by Robey [2], [3]. In these papers Robey studied the free-flooded rings radiating from their open ends and also calculated the approximate radiation loading with a simple solution that did not include the interaction between the inner and outer surfaces.

Merriweather [4] examined the free-flooded piezoelectric ceramics in his 1961 paper. The results of magnetostrictive free-flooded ring transducer developments through 1966 are described in a paper by Bulwer, Meyers and Parssinen [5]. The design and performance of free-flooded magnetostrictive transducers are examined by Camp with examples [6].

In 1964, McMahon [7] introduced a rather practical method to predict the cavity resonance of rings for different ratios of ceramic height, thickness and radius. Unfortunately, this simple method neglects all the effects of water-blocking material (the moisture barrier layer on the ceramic), i.e., polyurethane. This layer effects the cavity resonance. As it is shown in the two figures of [7], especially at lower height/radius ratios, the experimental data do not closely track the theoretical predictions. No other design parameters are examined in McMahon's paper, such as impedance, transmitting voltage response (TVR), open circuit voltage response (OCVR) or beam patterns. In [7] the free-flooded ring arrays are examined only experimentally. Therefore, McMahon's paper is helpful as a practical guide to predict the approximate cavity resonance of a free-flooded ring but it should be used with caution.

Later, various radiation loading approximations have been suggested that can lead to better theoretical predictions [8], [9], [11], [12].

Porter studied the free-flooded ring arrays with the help of equivalent circuits and the surface velocity of transducers [10]. Although the results were generally satisfactory, this approach could not accurately predict the acoustical responses or the beam patterns.

In following years, more rigorous design methods were suggested that achieved better results [13], [14]. In 1974 a finite element method (FEM) was applied modeling free-flooded transducers [15]. In this approach FEM was used to calculate the normal velocities on the boundaries of a transducer. This information is then used as input to Helmholtz integral radiation software program known as CHIEF (Combined Helmholtz Integral Equation Formulation) to calculate the acoustic radiation impedance and the pressure. The experimental results proved to be in close agreement with theory.

In 1986 Rogers developed another mathematical model for the transmitting voltage response (TVR) and electrical impedance and used SHIP (Simplied-Helmholtz-Integral Program) to calculate radiation effects [17]. Various application fields were investigated for free-flooded rings and arrays [16], [18], [19].

Many of the solutions summarized above require unique software programs such as SHIP and CHIEF. The input data to these programs still need to be calculated in advance through other programs. Some of the software is no longer available or supported. Although they do not necessarily include the water-blocking material, the analytical solutions are very rigorous and require heavy (in advance) programming to examine specific cases. Due to these difficulties, a simple McMahon model for an approximate cavity resonance frequency or a FEM approach to examine all acoustical and electrical parameters might be considered as the design tools.

Free-flooded ring transducers can be manufactured in different configurations, e.g., using inactive extender tubes on the ends of the ceramic ring and inactive segments in the case of a composite ring [21]. Ellis, Fanning and McMahon used both of these techniques in a "resonant pipe" projector [20]. With the use of a cylindrical insert made of properly selected characteristic impedance (ρc) material, a free-flooded ring can also be made to have a conical beam pattern [22]. See Fig. 2 for a planar array of free-flooded ring transducers with inserts.

Fig. 2 Directional Free-Flooded Ring Array with Inserts.

One of the most practical design methods is examining the previously manufactured and tested free-flooded transducers and the possibility of frequency scaling. Scaling is done in three dimensions with the same factor for all components of the transducer. For example, cutting the resonance frequency by two the scaling factor has to be ½ and this means doubling all the dimensions. With this, all acoustical parameters are kept inherently the same as the reference transducer.

A wide range of database is essential to review the options in frequency scaling. In the case of scaled units, additional short and simple software can be utilized to predict acoustical and electrical performance and minor modifications are easily applied and checked. Although the theoretical design models are very helpful for new units, the frequency scaling approach, based on previously manufactured and tested transducers and arrays, works the best.

III. CASE STUDIES

A. Modeling of a Free Flooded Ring with McMahon Approach

Three tangentially polarized C5400 type ceramic rings with dimensions of OD=5.2 inch, t=0.35 inch and h=2 inch were encapsulated in 0.25 inch thick PRC-1570 polyurethane on the inner and outer diameters and near 0.1 inch at the ends. These free-flooded rings were first tested as single units and then as continuous, longer rings by stacking two and three of them on top of each other, wired electrically in parallel (see Fig. 3).

Fig. 3 Three encapsulated free-flooded ceramic rings as a stack with 0.1 inch spacing.

The results of the model and the measured cavity resonance values are shown in Fig. 4. The results show that for low Height/Outer Diameter (h/OD) ratios the model fails to predict the cavity resonance; at a ratio of near 0.4, the error is almost 35%. When the separation between the rings is increased (i.e., to near 1 inch, with water in between) the rings start behaving closer to their individual performance with small effects of acoustical interaction. The other data are summarized in Table 1.

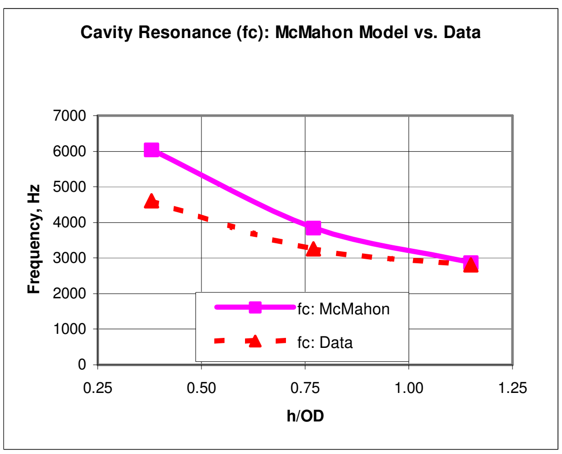

Fig. 4 Cavity Resonance Comparison: McMahon Model vs. Data.

Table 1
ELECTRICAL AND ACOUSTICAL DATA

# of Rings	Cav. Res., kHz	G, uS	Q_m	DI, dB	Efficiency, %	TVR, dB
1	4.4	93	6.3	2.1	35	128
2	2.9	107	7.1	2.6	14	125
3	2.3	105	7.6	2.9	11	124.5

The dimensions of the ceramic ring (including its wall thickness) and the encapsulation material and its thickness control the cavity resonance. The encapsulation material is a strong contributor to the cavity resonance. In addition, the speed of sound of the water within the cavity shifts the cavity resonance frequency [7].

B. FEM of a Free-Flooded Ring with End Tubes

Another free-flooded ring with different dimensions was built (OD=6 inch, t=0.11 inch, h=2.99 inch; tangentially polarized). It was again encapsulated in 0.25 inch thick PRC-1570 polyurethane. The ends of this ring were later extended with two stainless steel tubes with the same diameter and thickness of the ceramic. The inner surfaces of the steel tubes were potted with polyurethane. Both ends then were cut one inch at a time after collecting the data. See Fig.5.

Fig.5 Free-flooded ring with extended stainless steel end tubes (shown with 1 inch long end tubes).

The ceramic ring alone and with the extended end tubes were modeled with ATILA FEM (ATILA was developed by ISEN in Lille, France). The measured cavity resonance of this unit and the results of ATILA are shown in Fig. 6. As can be seen, when h=3 inch (ceramic ring alone) the ATILA model predicts approximately 2300 Hz cavity resonance for the encapsulated ring and the data shows approximately 2120 Hz, an error of near 8.5%. The source of this error is believed to be from the inaccurate material properties of the ceramic and the polyurethane available at the time of the modeling. The acoustical estimates by ATILA were in close agreement with the data. The McMahon model for the same height of ceramic predicts a 3062 Hz cavity resonance. Additional data are summarized in Table 2. The data show that the acoustical performance of a ring can be improved with the addition of end-tubes, in addition to lowering its cavity resonance frequency.

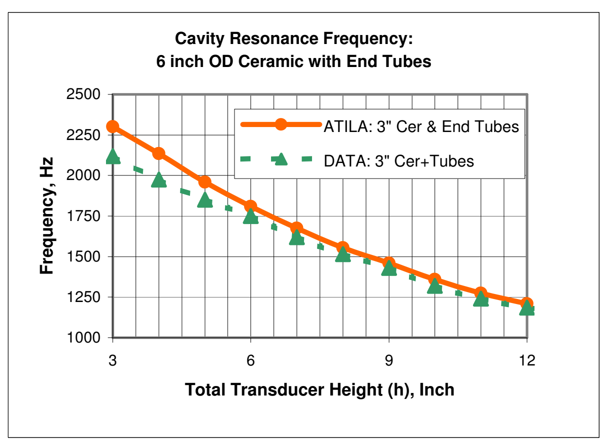

Fig. 6 Cavity Resonance Frequency: Ring with End Tubes.

Table 2
ELECTRICAL AND ACOUSTICAL DATA

Configur-ation	Cav. Res., kHz	G, uS	Qm	DI, dB	Efficiency, %	TVR, dB
Ring Alone	2	114	7	1.6	8	122
Ring+1 in. End Tubes	1.8	128	10	1.9	18	126.3
Ring+2 in. End Tubes	1.6	113	9	2.3	14	125

C. *Frequency Scaling of a Free-Flooded Ring and a Vertical Array.*

A free-flooded ring transducer, based on a previous unit was frequency scaled and manufactured for a specific application in ITC. It is encapsulated in polyurethane and has cavity and radial resonance frequencies at 4 and 8.5 kHz, respectively. The finished diameter and height of the ITC-2040X are 6.5 inch and 3.75 inch, respectively. The admittance and TVR data of this unit are provided in Fig. 7 and 8. These values, along with the beam patterns, turned out to be exactly as estimated from frequency scaling. This approach is based on the ceramic dimensions, its type and configuration (i.e., radially or tangentially polarized) and on the effects of the encapsulation material and its thickness.

Later five of these rings were assembled as a vertical array with center-to-center spacing, which is half wavelength at 10 kHz. This spacing was due to beam pattern and other requirements. Fig. 7 clearly shows the effects of the acoustic interaction effects around cavity resonance with varying conductance (G) from the theoretical prediction of five elements wired in parallel. The TVR of a single ITC-2040X and 5-element array are shown in Fig. 8.

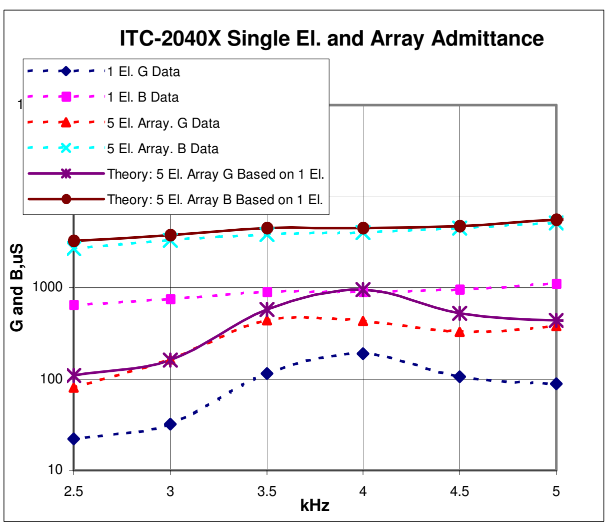

Fig. 7 Admittance of ITC-2040X.

The TVR of a single transducer, in terms of dB re μPa/V.m, can be found from:

$$TVR_1=10\log(G_1)+DI_1+10\log(\eta_1)+170.8, \quad (1)$$

where G_1 is the conductance, DI_1 is the directivity index and η_1 is the electroacoustic efficiency of a single transducer. For an array made of 5 identical transducers, the ideal TVR, using the same analogy in (1), can be found as:

$$TVR_5=TVR_1+10\log n+(DI_5-DI_1)+[10\log(\eta_5)-10\log(\eta_1)]. \quad (2)$$

In (2), n is ratio of the G of 5-element array and a single element. The DI_1 and DI_5 were calculated at a few frequencies from beam pattern data of a single ring and array, and the rest are curve fitted. These are shown in Fig. 9. Using (2) and the values shown in Figures 7, 8 and 9 it is possible to see that the efficiency of a single element and the array are not equal. For example at 4 kHz, with TVR_1=131 dB, n=2.2, DI_5=5.8 dB and DI_1=1.6 dB and TVR_5 is found as 142.2 dB. However, it was measured only 137 dB. The difference of 1.6 dB is the drop in efficiency.

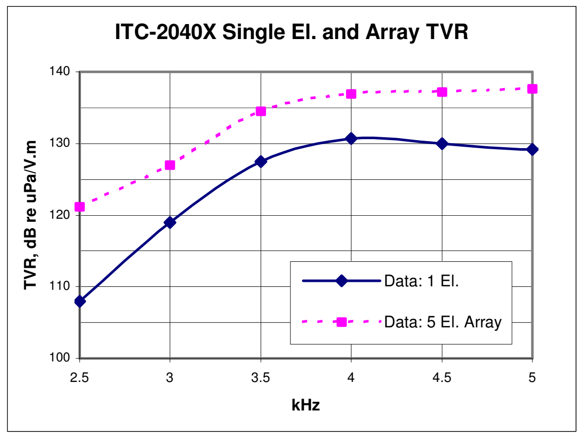

Fig. 8 TVR data of ITC-2040X.

Larger free-flooded rings are successfully built and assembled as arrays. Fig. 10 shows a 5-Element array made of ITC-2082 rings that have 280 Hz cavity resonance.

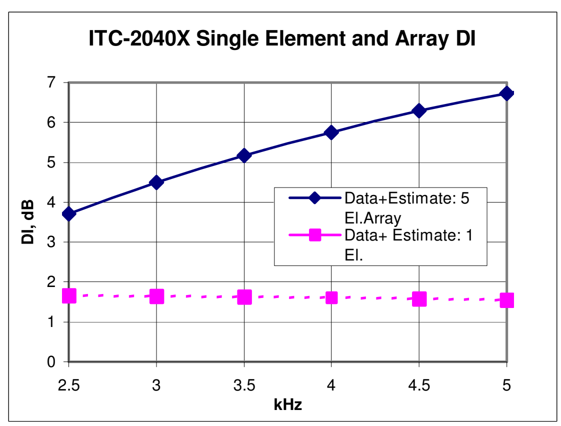

Fig. 9 DI of ITC-2040X Element and Array.

Fig.10 A 5-Element array of ITC-2082.

IV. CONCLUSIONS

Free-flooded rings are widely used in underwater applications. They provide many advantages, especially in deep-water applications. There are various methods to design free-flooded rings. Although some are practical and provide only approximate results the others require detailed preparations with more time. Especially in vertical arrays, acoustic interaction plays a big role in the final outcome and advance review of similar data and/or use of software models might be necessary. In the manufacturing environment, where budgets do not allow extensive research and development time or money, past experience and a wide selection of previously tested designs help to mitigate the needs.

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