Sub-Marine Sonics

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A speaker with a 2-in. diaphragm, underwater, can produce sound equal in quality to a good 12-in. speaker in free air. The reason for this is the much higher acoustic resistance of water as compared with air.

IN THIS AGE of background music, hi-fi, stereo, audio-visual teaching, and aural work instructions, we are literally surrounded by sound. And we think of this sound almost exclusively as vibrations of *air*. Let anyone mention underwater sound, and most people's thoughts turn to sonar, to sonic depth finders, and the like. It may come as a surprise that a field of application has been steadily developing for underwater reproduction of voice and music.

Formation swimming and underwater ballets are performed to music. The music the audience hears cannot penetrate the water at all, and is unheard by the performers. Special means must be provided to enable them to hear the music to which they must keep time. As an example of the extent to which one application has been standarized, the Synchronized Swimming Rules of the American Athletic Union of the U. S. specifically state: "The organization holding the competition is responsible for—providing an underwater speaker."

Similarly, skin divers are cut off from communication with the rest of the world, except through visual signals and such crude sonic means as tapping metallic objects together. This makes instruction particularly difficult and impedes efforts at group action. Here, again, underwater sound restores the vital missing link of aural transmission of intelligence.

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With the current increase in outdoor living and the accompanying popularity of swimming pools, there is also widespread use of "patio" speakers—weatherproof speakers to bring outdoors hi-fi music and other program material. Among these who like to take music with them are swimmers. Normally, a coolplunge into the depths of a pool brings virtual silence except for the swirl and bubbling of the water. But today one's reaction need no longer be "Who turned off the music?" Music in the water is becoming almost as common as music in the air.

Now let us take a look at the underlying theory of sound reproduction in water.

Sound in Water

To transmit sound, a medium must have the following attributes:

1. Mass
2. Elasticity
3. Low internal friction or viscosity

A comparison of water with air in respect to these properties is interesting. Water has a density 780 times that of air. Water decreases in volume one part in 20,000 per atmosphere of external pressure. Air decreases in volume by one-half when the normal pressure is increased by one atmosphere. The velocity of sound is determined by these two factors. In air it is 344 meters per second. In water, it is 1440 meters per second, or 4.2 times as great.

Considering the wide differences in these properties between the two media, it is not surprising to find that they also differ in their specific acoustic resistance, in the ratio of 3300 to 1. This is derived from the data already given, since, for plane waves, specific acoustic resistance:

$$R_A = \rho c \qquad Eq.\ (1)$$

where ρ = density
and c = speed of sound

Hence:

$$\frac{R_A\ water}{R_A\ air} = 780 \times 4.2 = 3300 \qquad Eq.\ (2)$$

It will be recalled that specific acoustic resistance, multiplied by the area of a vibrating surface is the mechanical resistance, R_{MA}, which is a measure of the power transferred to the medium for a given velocity v.

$$P_A = R_{MA} \cdot v^2 \qquad Eq.\ (3)$$

Radiating surfaces whose dimensions are large compared to a wavelength produce plane waves, and the power radiated is easily calculated from *Eq. (3)*.
ated is easily calculated from *Eq. (3)*.
As the source decreases in size, the wave tends to become spherical; as a result of its divergence, the value of R_{MA} decreases as the square of the frequency (inversely as the square of the wavelength), for radiation from a piston in an infinite baffle. The variation of R_A with frequency is shown in *Fig.* 1 for both air and water.

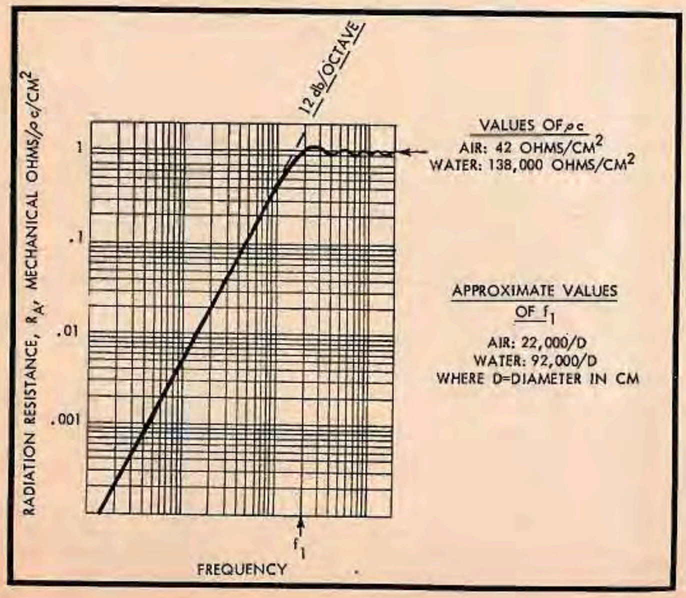

Fig. 1. Variation of acoustic resistance with frequency for both air and water.

Calculations on Underwater Speakers

Since the value of R_A is so large, compared to air, it should be possible to use a fairly small radiating area in an underwater speaker. For a 2-inch (5-cm) diaphragm, the transition point, f_1, or the "bend" in the radiation resistance curve, occurs at 18,600 cps. This means that, over the useful range, operation will take place on the sloping portion of the curve. This means that the speaker must be mass-controlled, that is, resonance

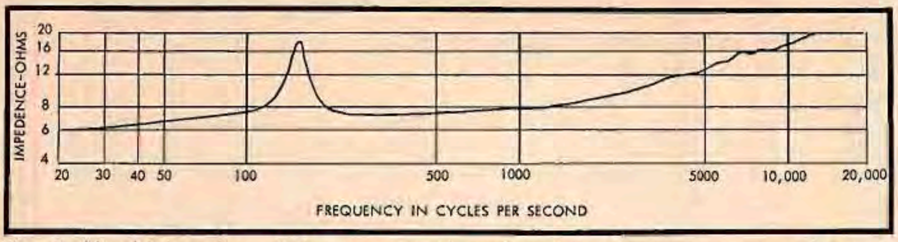

Fig. 2. The high value of the mass load pushes the primary resonance down to 155 cps.

must occur at the lower end of the frequency range.

Practical considerations dictate that the speaker be enclosed in a compact housing. Consequently, it will radiate into a full sphere—4π steradians. For full spherical radiation:

$$R_{MA} = \frac{\pi \omega_2 \rho D^4}{4c} \qquad Eq. (4)$$

where $\omega = 2\pi f$

ρ = density of water
D = diameter of piston
c = speed of sound in water

This equation of the straight, sloping portion of the curve in *Fig.* 1.

In simplified form:

$$R_{MA} = 2.15\ f^2\ D^4 \times 10^{-4} \qquad Eq. (5)$$

For a 2-in. (5-cm) diameter diaphragm at 1000 cps

$$R_{MA} = 13{,}450 \text{ mechanical ohms}$$

In air, the same piston would have a radiation resistance of only 88 ohms at 1000 cps. The comparison would lead one to think that a great deal more efficiency could be obtained in water than in air. There is, of course, a difficulty.

In either medium, a certain mass of the medium itself moves as if it were attached to the diaphragm. This "mass load" creates a mismatch of impedances between the piston and the medium. In water, as can readily be believed, the mass load is very great. Quantitatively:

$$M_A = \frac{D^3}{3} \qquad Eq. (6)$$

where D = diameter of the diaphragm, in cm
M_A = mass in grams

For the 5-cm diaphragm we have been considering, $M_A = 63$ *grams*. This is many times the mass of the voice coil and diaphragm taken together. At 1000 cps the reactance of the mass load

$$2\ \pi\ f\ M_A = 26{,}900 \text{ ohms}$$

which is double the radiation resistance.

For an efficient magnetic structure with a flux density in the gap of about 13,000 gauss, the efficiency comes out something under 2 per cent. This is quite comparable to the efficiency of a high-quality 12-inch speaker used in air.

The high value of mass load is helpful in one respect: it pushes the primary resonance of the 2-in. diaphragm down to 155 cps (*Fig.* 2) providing good bass reproduction. As for the high end, a 2-in. rigid piston in water should radiate well up to f_1 (*Fig.* 1) which we already calculated as 18,600 cps. We are quite justified in calling this a hi-fi speaker.

Directivity and sound distribution are determined, first, by the fact that the diaphragm diameter is small compared to a wavelength even at the highest frequencies of interest, and by the "closed-box" effect of a swimming pool. The second point requires some explanation.

When a sound wave travels from one medium to the other, the amount of reflection is determined by the ratio of the "characteristic impedances" of the two media. The values of interest are as follows:

Substance	Specific Acoustic Resistance (mechanical ohms/cm²)
Air	42
Water	140,000
Brick, Rock, Concrete, Tile, Marble	700,000–1,000,000

These figures tell us that a sound wave in water will be reflected at least 80 per cent when encountering a wall, and, surphisingly, that the reflection at the water-air interface is over 99.9 per cent. The result is that the pool acts like an exceedingly live room in which reverberation is high. This distributes the sound quite uniformly throughout the water and greatly increases the average sound-pressure level.

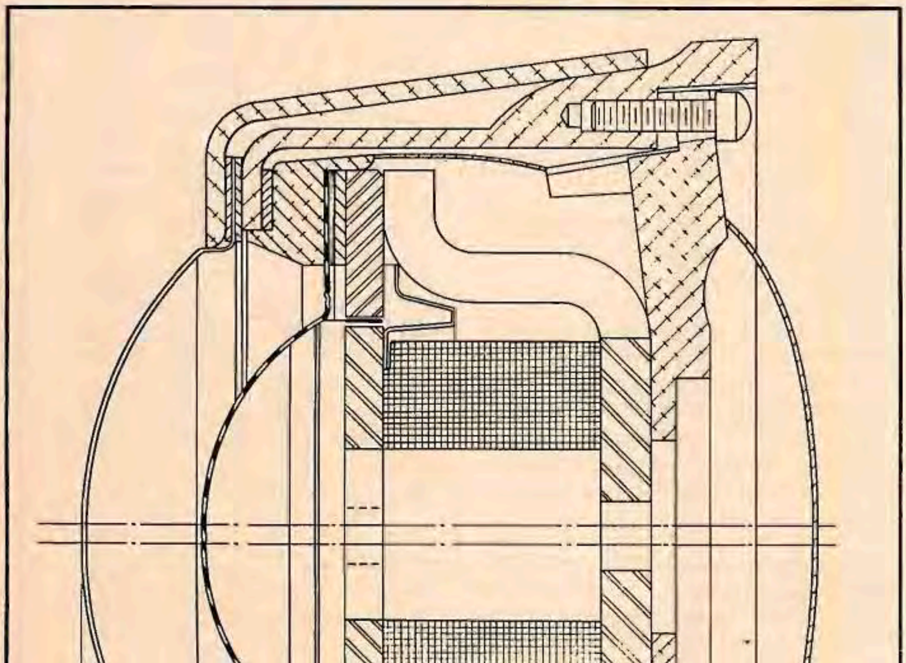

Fig. 3. Cross section of University MM-2FUW underwater speaker.

Construction of the Speaker

For a direct radiator of 2-in. diameter, a domed diaphragm offers advantages in rigidity and ease of fabrication. Such a diaphragm is integral with its supporting surround, that is, the entire assembly is molded in one piece, which facilitates design of a watertight assembly. Diaphragms of this type are used in public

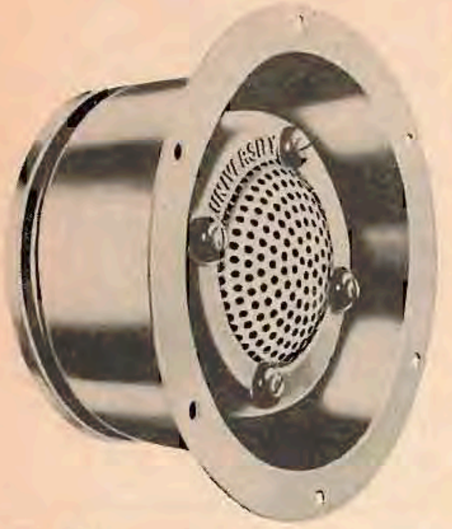

Fig. 4. University model MM-2FUW underwater speaker.

address as well as hi-fi compression driver units for use with horns, and are most often made of phenolic-impregnated cloth, or of aluminum alloy. The latter is much too delicate and subject to corrosion to be used in continuous contact with water. One would expect the phenolic type to be ideal for this application, since it is used in weather-resistant, outdoor speakers. Unfortunately, it was discovered that impregnated cloth practically dissolves after prolonged immersion!

After a long period of experiment, a suitable material named "Unilar" was developed for the application. It is tough, completely impervious to water, and capable of being molded to shape. To the last property should be added the words "if you know how." It was only after a period of intensive development at University Loudspeakers that a satisfactory method was worked out for molding the "Unilar" diaphragm. Underwater speakers using these molded diaphragms have been in production for diaphragms have been in production for some time and a great deal of field experience has indicated completely satisfactory preformance. A cross section of the center assembly of model MM-2FUW is shown in *Fig.* 3 and a photograph of the entire speaker is shown in *Fig.* 4.

The University underwater speaker is constructed essentially like a compression driver unit as far as mechanical assembly is concerned. The diaphragm is in direct contact with the water on its convex front face and is mechanically protected by a perforated stainless steel grille. The back of the diaphragm has access to an air chamber which is hermetically sealed by the watertight housing. The enclosure is of the so-called "infinite baffle" type. The connections to the voice coil are brought through the housing by means of watertight terminals which have waterproof cables soldered on the outside. A third lead is provided for grounding the case of the speaker. The entire section containing the terminals is coated with waterproofing compound.

An interesting feature of the design is its simplicity. Sufficient rigidity is incorporated into the diaphragm assembly to enable it to withstand the pressure of several feet of water without any complicated pressure-compensating means, and a simple and reliable device is used to insure that the coil is properly centered axially in the magnetic field, with the modest variations in water pressure encountered in various applications.

Use of the Underwater Speaker

The frequency range of the MM-2UW is 100–10,000 cps, its impedance is 16 ohms, and it will handle 30 watts of integrated program material under water. It distributes sound almost uniformly throughout the pool in which it is used, although for larger pools, or for cases such as swimming instruction classes in which there is a high level of turbulence in the water, several units should be used. Not only will the noise level in the water be more effectively overcome, but each speaker can be operated at a lower level, avoiding excessive sound intensities in the immediate vicinity of the units. For example, two speakers would be recommended for a pool 30 × 60 feet; 4 units would be recommended for the same pool if it is expected that there will be a good deal of turbulence or noise in the water.

Underwater speakers come in two types: those primarily designed for installation in a "wet niche" light box, in pools which are being planned or which are now under construction, or which already have wet niches of the size required, as well as associated conduits and watertight flush junction boxes in the deck surfaces near the pool area; and for existing pools which do not have these facilities. The Model MM-2UW is recommended for the latter type of installation and MM-2FUW for the former. Preferred operating depth is 2 feet.

It will be necessary for the user to make a mounting ring for the "built-in" type of speaker, since there is no standardization in the size of wet niches in swimming pools. This adapter may be made of marine plywood or cut from sheet aluminum 1/32-in. to 1/16-in. thick, 2S or 3S alloy, ½ H to H hardness. The inner diameter of the mounting ring is 6-in., and the wet niches must be sufficiently large so that screws to mount the ring do not interfere with those which mount the speaker. Stainless steel, aluminum, or zinc-coated steel bolts may be used, but not brass. It is also desirable that there be enough space in the niche to accommodate a sufficient length of cable, coiled neatly in the niche behind the speaker, to permit removal of the unit from the water in the event that servicing should be required, without the necessity of drawing the cable down through the conduit, re-installing it after repairs are completed, and so on.

The speaker for already constructed pools may be mounted to the side of the pool by means of the integral adjustable bracket. The exact hardware required to do this is selected by the user, but will usually take the form of wood screws, which are driven into rawl plugs inserted into holes in the concrete made with a masonry drill. It should not be mounted in a location where it might be used as a step.

An easy alternative to the above method of mounting involves the use of a special adapter such as the University SPA Adapter. The adapter is substituted for the triangular base that comes with the speaker, and screwed to the end of a ½-in. threaded IPS pipe. This pipe may be cut to the desired length, bent, and hung over the edge of the pool or drainage gutter.

The case of the speaker should be grounded to a grounding lug in a junction box, if one is involved in the installation, or some other earth ground. Æ

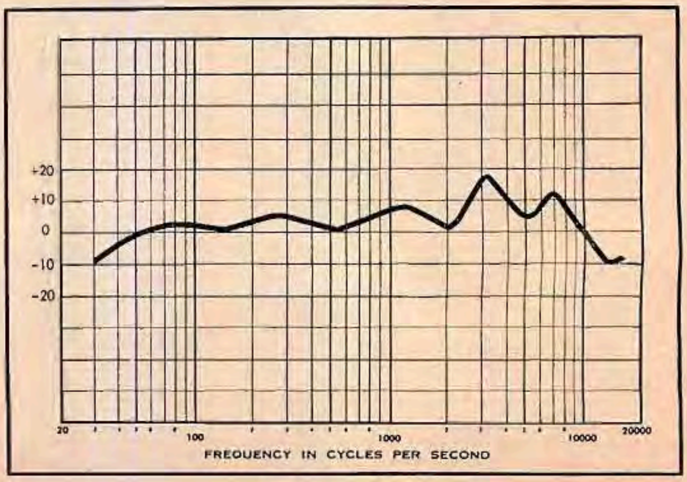

Fig. 5. Response of MM-2FUW speaker in tank.