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PRESSURE-COMPENSATING SYSTEMS FOR UNDERWATER GAS-FILLED ELECTRO-ACOUSTIC TRANSDUCERS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two types of systems have been developed to equalize the pressure on opposite sides of the diaphragm in low-frequency moving-coil electroacoustic transducers at depths of several hundred meters. The configuration, operation, and design theory of these systems are described.

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Introduction

The trend in naval underwater sound detection systems today is toward operation in the low audio range of frequencies (down to 10 Hz), where sound attenuation in sea water is the least. Calibration of these systems and their associated hydrophones dictates the need for low-frequency sound sources that operate at ocean depths of several hundred meters.

Most of the low-frequency electroacoustic transducers that the Underwater Sound Reference Division (USRD) has designed for use at sea are of the moving-coil type, similar to the air loudspeaker [1]. Inherent in the design of this type of transducer is a vibrating diaphragm supported by a low-stiffness suspension in contact with the water at its front face and with an air volume at its rear face.

To balance the force due to the hydrostatic pressure acting on the front face of the submerged diaphragm, the air pressure acting on the rear of the diaphragm must be of the same magnitude. Two types of pressure-compensating systems have been developed to provide this equalizing pressure.

System Design and Configuration

To be used effectively at sea, a gas pressure-compensating system must (1) maintain zero pressure differential between the front and back of the diaphragm; (2) be self-contained and self-regulating; (3) provide high reliability; (4) have sufficient transient response to sudden changes in depth (hydrostatic pressure); (5) consume no compensating air or at least a minimal amount; (6) have minimum bulk; and (7) have little effect on the transmitted sound pressure.

The two types of pressure-compensating systems that have been developed and tested are: a closed-circuit system and an open-circuit SCUBA-type system. The closed-circuit system will be considered first.

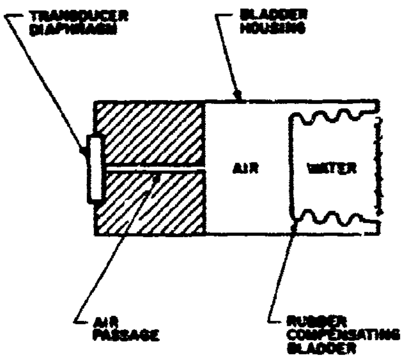

Fig. 1. Schematic of closed-circuit pressure-compensating system.

Figure 1 shows the physical operation of this system schematically. As the operating depth of the transducer increases, water flows into the limp open-ended rubber compensating bladder, decreasing the volume of air in the bladder housing, thus increasing the pressure of the air behind the transducer diaphragm. This system will operate until the bladder is completely pressed against the retaining housing by the water, decreasing the air volume of the bladder housing to its limit. The compensating bladder must be at the same level as the transducer diaphragm so that they are exposed to the same hydrostatic pressure, otherwise a pressure balance on the diaphragm will not be achieved. The bladder can be positioned to operate above or below the diaphragm, if a positive or negative bias on the diaphragm is desired.

The closed-circuit system has the following advantages over the open-circuit system: (1) simplicity and therefore higher reliability, and (2) zero consumption of compensating gas, allowing continuous operation at depth. Its main disadvantage is the large volume required for the compensating bladder, especially for operation to great depths.

Figure 2 is a schematic showing the open-circuit system in which a gas pressure-regulating system has been added to the closed-circuit system. The rubber compensating bladder provides the gas pressure

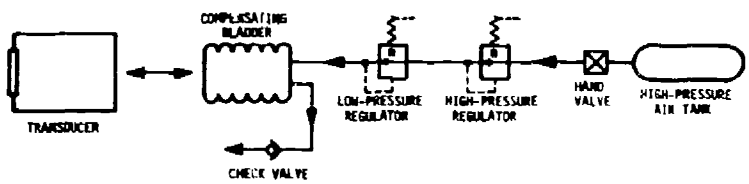

Fig. 2. Schematic of open-circuit pressure-compensating system.

equalization to the transducer diaphragm for small changes in depth, but for large increases in depth, air is delivered to the transducer from the high-pressure air tank by the high- and low-pressure regulators at a pressure close to the ambient hydrostatic pressure. Large decreases in depth cause the discharge check valve to bleed excess air to prevent pressure build-up in the transducer.

The open-circuit system has the advantages of (1) small system size with the ability to provide pressure-compensating gas to greater depths than the closed-circuit system, and (2) conservation of system air supply within the limits of the ability of the rubber bladder to provide pressure equalization for small depth changes. Its major disadvantages are complexity and the need to recharge the air tank after recovery from its operating depth.

Design Theory

The pressure-density relationship of the air in the closed-circuit compensating system, assuming a perfect gas, is $p = \rho RT$, where p is the absolute pressure, $\rho = m_t/V$ is the density at any water depth, m_t is the total mass of gas in the transducer and compensating bladder, V is the total internal air volume, including the transducer and compensating bladder at any pressure, R is the gas constant for air, and T is the absolute air temperature. Then, at any water depth, $pV = m_t RT$ = constant for small changes in absolute temperature. From this equation,

$$p_m V_r = p_s (V_r + V_b), \quad (1)$$

where p_m is the absolute pressure at maximum operating depth of the compensating system, V_r is the residual volume of the system with the compensating bladder deflated, p_s is the absolute pressure at the water surface, and V_b is the maximum internal volume of the compensating bladder. Where

$$p_m = (0.01)d_m + 0.10,$$

with p_m in megapascals, the maximum operating depth d_m in meters, volumes in cubic meters, and p_s = 0.1 MPa, Eq. (1) gives

$$d_m = (10.0)V_b/V_r.$$

Thus, d_m is directly proportional to the size of the compensating bladder, and, for a given maximum operating depth, the compensating bladder volume needed is directly proportional to the internal volume V_r of the transducer.

The maximum operating depth also can be calculated for the open-circuit pressure-compensating system. By using the same closed system approach, we assume that the depth limit is set by the maximum amount of gas that can be delivered from the tank by the pressure regulators to the transducer. Therefore,

$$m_g = \Delta p_g V_g / RT = \Delta p_r V_r / RT, \tag{2}$$

where m_g is the total mass of gas delivered from the high-pressure tank to the transducer, Δp_g is the pressure drop in the tank, V_g is the internal volume of the tank, Δp_r is the change in compensating pressure in the transducer, and V_r is the residual volume of the transducer as before.

$$\Delta p_g = p_{gm} - (p_m + \Delta p_{gr})$$

where p_{gm} is the fully charged tank gage pressure, p_m is the hydrostatic pressure at the maximum operating depth, and Δp_{gr} is the pressure drop due to the pressure regulators. Also,

$$\Delta p_r = p_m = (0.01) d_m,$$

where d_m is the maximum operating depth of the system in meters, pressures are in megapascals, and volumes are in cubic meters. Substitution of p_{gm}, p_{gr}, and p_m in Eq. (2), gives

$$d_m = (100) V_g (p_{gm} - \Delta p_{gr}) / (V_g + V_r).$$

This equation shows that for an air tank whose internal volume V_g is much larger that V_r, no increase in operating maximum depth can be achieved by increasing V_g. Also, because p_{gm} usually is much larger than p_{gr}, d_m is proportional to the maximum air tank pressure.

The closed-circuit compensating system must have sufficient response to sudden changes in depth. To determine the maximum flow rates of compensating air required, one must estimate the maximum hydrostatic pressure change rate to which the system will be exposed. The pressure change rate is a function of the rate of depth change $\dot{d}_m$:

$$\dot{d}_m = \dot{d}_h + \dot{d}_w,$$

where $\dot{d}_h$ is the vertical velocity component of the system due to ship heave and $\dot{d}_w$ is the vertical velocity component due to winch payout or retrieval, all in meters per second. Because

$$\dot{d}_h = h\omega,$$

where h is the amplitude of the ship heave in meters and ω is the angular frequency of the heaving motion, this is equivalent to the rate of pressure change

$$\dot{p}_m = (0.01)\dot{d}_m = (0.01)(h\omega + \dot{d}_w) \text{ MPa/s}. \quad (3)$$

The required mass flow rate $\dot{m}_m$ of compensating air to achieve an equivalent rate of pressure change is given, for a constant absolute temperature T, by

$$\dot{p}_m V = \dot{m}_m RT,$$

where V is the total internal air volume of the transducer and the other symbols are as before. Then

$$\dot{m}_m = \dot{p}_m V/RT. \quad (4)$$

At any depth, the absolute hydrostatic pressure is

$$p_h = (0.01)(d + 1), \quad (5)$$

where d is the depth in meters. This mass flow rate corresponds to a volume flow rate of constant-temperature compensating air of

$$\dot{V}_m = \dot{m}_m RT/p_h \text{ m}^3/\text{s}. \quad (6)$$

Substituting for $\dot{m}_m$ and p_h from Eqs. (4) and (5) in Eq. (6) produces

$$\dot{V}_m = \dot{p}_m V/[0.01(d + 1)].$$

Substituting for $\dot{p}_m$ from Eq. (3) produces

$$\dot{V}_m = V(h\omega + \dot{d}_w)/(d + 1).$$

From this equation, the maximum volume flow rate of compensating air for the closed-circuit system occurs at the surface (d = 0) and is

$$\dot{V}_m = V(h\omega + \dot{d}_w).$$

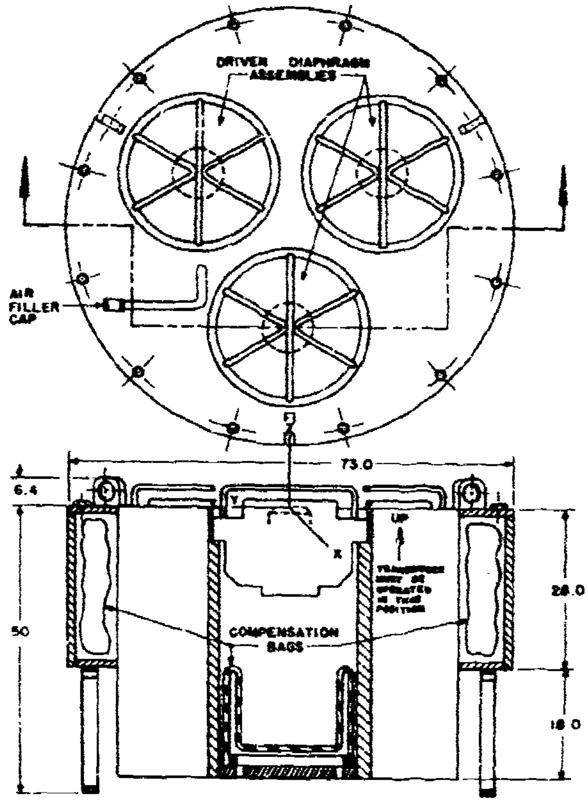

Fig. 3. Closed-circuit pressure-compensating system as applied to USRD type J15-3 transducer. All dimensions are in centimeters.

Systems in Operation

Figure 3 shows a closed-circuit compensating system as applied to a USRD type J15-3 projector. This projector consists of a cluster of three moving-coil diaphragm assemblies. To achieve the maximum compensating bladder volume with the minimum total external volume, we have used four compensating bladders. Three open-ended bladders occupy the internal volume of the diaphragm assembly housings. Additional volume is provided by a large toroidal butyl compensating bladder surrounding the projector cluster. This system allows the projector to be used to a depth of 300 m.

Figure 4 shows an open-circuit compensating system used with a USRD type J11 projector [2]. An external 3-liter tank supplies air through a SCUBA-type first-stage regulator to a sensitive diaphragm-actuated second-stage regulator within the transducer housing on descent to the

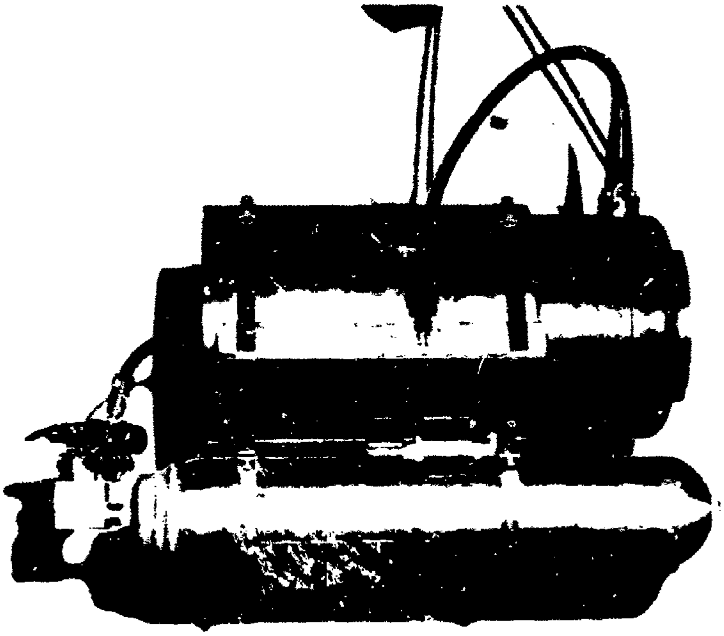

Fig. 4. Open-circuit pressure-compensating system as applied to USRD type J11 transducer.

working depth. A high-flow-capacity check valve in series with a rubber-covered flapper valve bleed excess pressure from the transducer during ascent to the surface. The rubber compensating bladder provides exact pressure equalization to the transducer at the operating depth for a depth range that increases with operating depth. Figure 5 shows this effect [3]. This system permits the J11 transducer to be used to a maximum depth of 600 m.

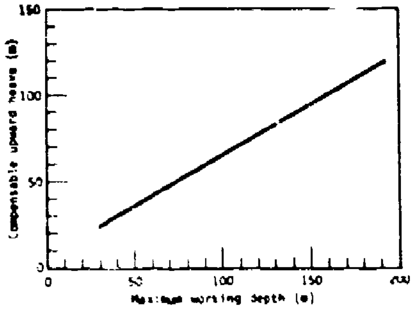

Fig. 5. Relation of bladder-compensable upward heave to maximum working depth.

Conclusion

Two types of systems have been developed for compensating pressure in moving-coil projectors at depths of several hundred meters. These systems are self-contained, self-regulating, highly reliable, compact, and consume a minimal amount of compensating gas.

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