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ELECTROACOUSTIC CHARACTERISTICS OF MARINE SEISMIC STREAMERS†

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To specify intelligently an unambiguous tow-noise level in marine seismic exploration, the electroacoustic characteristics of the streamer must be understood. In this paper, these characteristics are examined as a basis for an industry-wide standard for specifying streamer tow-noise level.

Sources of tow noise—including electrical, ambient, flow, radiated, and mechanically induced—are examined and the important parameters that control their amplitude spectrum are presented. The theoretical bases for various means of reducing the components of tow noise are analyzed and compared with experimental results.

With this background of tow-noise sources and noise-reduction schemes, the noise signal is traced from the hydrophone/seawater interface to the recording system. The hydrophone array's amplitude response and phase response are determined from the transfer characteristics of the coupling circuit and the recording system.

Finally, a method for specifying tow-noise level is proposed. The specified tow-noise level is *referenced* to the hydrophone input terminals and is *monitored* at the output of the recording system. Therefore, the standard requires that the important electroacoustic characteristics outlined in this paper be specified.

INTRODUCTION

In offshore exploration for petroleum, a ship pulls 24 or more groups of hydrophones through the water at constant velocity. Each group may be up to several hundred feet long and, spaced throughout its length, there may be five or more hydrophones, usually connected in electrical parallel. These groups are joined together end-to-end to form what is called a streamer. The streamer is typically 2.5 inches in diameter and 8000 ft long. Hydrophones are mounted inside a thin-walled, flexible, plastic jacket, which is filled with a fluid having a low specific gravity, so that the streamer is approximately neutrally buoyant in seawater. The streamer is normally maintained at constant depth by dynamic controllers.

Each hydrophone group (or data channel) is coupled to the recording system aboard ship by an electrical network. In addition to the reflected signal from the earth's subsurface, the hydrophones are subjected to a number of acoustic and mechanical disturbances. The response of the hydrophones to these disturbances is commonly called tow noise. Currently, there are a variety of methods of specifying this tow noise; this variety makes it difficult to compare crew performance and data quality on a common basis.

A common understanding should exist between those specifying a maximum permissible tow-noise level for recording marine seismic data and those attempting to meet or exceed this specification. No uniform standard of specifying tow noise now exists in the exploration industry to bridge this concept gap. It is hoped that the background of electroacoustic characteristics given in this paper will lead to an understanding and acceptance of a proposed industry-wide standard for specifying tow noise.

First, background information is presented on noise sources; this is followed by the means of reducing noise generated by various sources. Next, the array of hydrophones and the coupling

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circuit between the sensors and recording equipment are examined. Finally, a standard for specifying tow noise is outlined and an example of its use is given.

NOISE SOURCES

Noise contributed by a multitude of sources limits the quality of data recorded in marine seismic exploration. Each survey contract usually includes a clause to the effect that "data will not be recorded if the tow-noise level is equal to or greater" than some specified value The following noise sources encountered in offshore exploration will be examined separately in their approximate ascending order of importance:

1. Electrical noise,
2. Ambient sea noise,
3. Radiated noise,
4. Flow noise,
5. Mechanically induced noise.

Each source is examined from the standpoint of where it originates, how the noise energy is propagated from its origin to the streamer hydrophone arrays, and what parameters determine its spectral characteristics and limiting values. Typical values for the noise level are presented and discussed.

Electrical noise

The electrical noise component of tow noise may be represented by

1. input equivalent noise of the amplifier,
2. thermal noise represented by the equivalent resistance of the streamer,
3. miscellaneous noises due to crossfeed between channels, fluctuations of wires within the earth's magnetic field, changes in line capacitance due to wire fluctuation, etc.,
4. 60 hz pickup from the power distribution of the boat.

Input equivalent noise of the amplifiers is typically 0.1 to 0.2 μv rms over an 8 hz to 300 hz bandwidth.

The source resistance of the streamer, as measured from the amplifier input, is typically about 2000 ohms. This is equivalent to a thermal noise voltage, over a 300 hz frequency band at 28°C, of only 0.1 μv rms.

Thus, as will be shown later, the summation of electrical noises due to amplifier input and source resistance is negligible compared to other noise sources. These other sources are one order of magnitude or more above source and input-amplifier electrical noises.

Crossfeed and fluctuation of wires in stray magnetic fields are easily controlled with proper design and construction techniques. It is possible to achieve all-other-to-one-channel crossfeed values 100 db below signal level for one channel.

Of the four electrical noise sources listed, 60 hz pickup from the ship's power distribution is dominant. This noise source must be carefully controlled by providing high electrical impedance to ground and high impedance on the order of 100 megohms between channels.

In summary, proper design and precautions can easily eliminate electrical sources as a significant component of streamer tow noise.

Ambient sea noise

Variability is the only thing about ambient sea noise that is constant. This variability is due to the presence or absence of dominant noise sources such as high waves, shipping traffic, and marine life. The purpose here is not to dwell on and explain any of these possible noise sources but to identify the dominant source in the seismic frequency passband.

Figure 1 puts the ambient noise-level range of the seismic band in perspective by showing the upper and lower limits between one hz and 10 khz (Wenz, 1963). Although for each limiting condition a single curve is drawn for the spectrum level, it should be emphasized that the nominal variability around each curve is ± 10 db. Except for an unusual event such as an earthquake, the ambient environment is bounded by the two curves in the figure. The lower curve represents thermal noise due to molecular agitation; the upper curve represents simultaneous conditions of high seas, heavy traffic, and other sources—all of which would not normally occur at the same time. These ambient noise levels are those which would be measured with a single omnidirectional hydrophone.

The most important source of ambient noise in the seismic passband is the condition of the sea surface. Knudsen et al (1948) showed ambient-noise results which did not extend below 100 hz, but Marsh (1963) presented a theory on the origin of the Knudsen spectrum, ascribing it to the generation of sound by surface waves and

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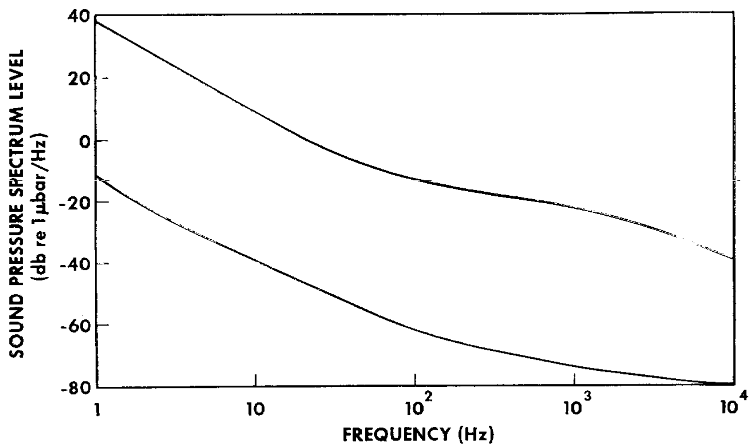

FIG. 1. Sound-pressure spectrum level of minimum and maximum prevailing ambient sea noise.

extending, on a theoretical basis, the Knudsen spectrum down to one hz. Figure 2 shows Marsh's results; these curves were calculated from the following equations:

$$P^2 = 2.90H^{1.2}/f^{1.67} \quad \text{for } f < 13.5 \text{ hz},$$

$$P^2 = 94.0H^{1.2}/f^3 \quad \text{for } f > 13.5 \text{ hz},$$

where

P = mean pressure, μbar in a one-hz band,
H = crest-to-trough wave height, ft,
f = frequency, hz.

The wave-height range associated with each sea state of Figure 2 is given by Urick (1967). It is doubtful whether operations would continue in sea state 5 or above (8 to 12 ft waves) because of crew safety—regardless of tow-noise considera-ations.

Bandlimited noise pressure levels may be found by integrating the previous equations between desired frequency limits. For a given sea state, for example, the noise level in the one hz to 500 hz band is 16 db above that in the 8 hz to 500 hz band. This result shows the importance of increasing the low-frequency limit to reduce the ambient noise.

The point to be made from this discussion is that ambient noise due to rough sea conditions over which there is no control causes excessive tow noise and, at times, requires work stoppage.

Radiated noise

Radiated noise is that noise which is transmitted through the water from an identifiable source to the streamer groups. In marine exploration, there are several sources: lead-in cable, depth controllers, tail buoy and line, and the ship. The last is dominant by far. Comprehensive measurements of ship's noise have been made for larger military ships but only sketchy information is available for noise radiated by geophysical vessels.

Ship's noise has three major sources—machinery, hydrodynamic, and propeller—and the overall spectrum depends primarily on the ship's size, speed, and construction. At a given survey speed, the radiated noise should be similar for ships used in geophysical exploration.

Machinery noise arises from mechanical vibrations transmitted through the hull into the water and actuated by the ship's engines, air compressors, etc. Narrowband peaks in the spectrum, having frequencies dependent on the machinery's speeds of rotation or multiples of rotation speeds, are expected to dominate. This is one source of 60 hz energy observed on most seismic records. Amplitudes depend on machinery characteristics, mounting, degree of unbalance, etc.

Hydrodynamic noise results from the ship's motion through the water; it is not propagated to

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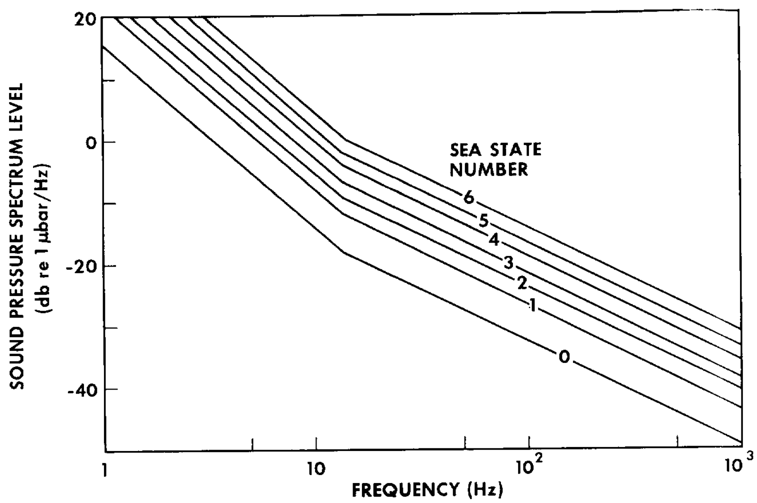

FIG. 2. Effect of sea state on sound-pressure spectrum level of ambient sea noise.

great distances (as discussed under flow noise) but is strong in the near field, i.e., in the turbulent boundary layer of the ship, and may excite hull resonances that are subsequently radiated to the streamer groups. Noise radiated due to these resonances is expected to be peaked, narrowband noise.

Propeller noise is important because the propellers act directly on the water; the level of this noise can be expected to be high. The peak in the spectrum is associated with the blade frequency given by $f = nV/60$, where n is the number of blades and V is the propeller's rotational speed in rpm. At 800 rpm, the frequency of radiated propeller noise is 40 hz for a 3-bladed propeller.

Although the ship's noise may be a large portion of the tow noise, especially for the near groups, there is still much to learn about this noise source. The effect of ship's noise is currently reduced by increasing the offset or distance to the hydrophone groups and by arraying the hydrophones. Experimental results for the latter are given in a following section.

Flow noise

Flow noise is caused by pressure fluctuations in the turbulent boundary layer and by vortex shedding from individual surface-roughness particles; it does not include noise due to flow-induced vibrations such as cable strumming (considered to be mechanically induced and discussed in a following section). At present towing speeds, flow noise is not the largest component of tow noise but, as speeds increase, it can become dominant due to its dependence on higher powers of velocity. Thus, an understanding of flow noise is necessary. Much of the development of this section is based on the flow-noise study of Skudrzyk and Haddle (1960).

Flow noise is a near-field effect and is commonly called "pseudo sound" (Lighthill, 1952) because it lacks the property of propagation at or near the characteristic speed of sound. This is so because turbulent eddies are carried along with the flow, but the pressure fluctuations causing the pseudo-sound are largely balanced by fluctuations in acceleration of volumes of fluid in the boundary layer. Nevertheless, a hydrophone suitably placed in or near a turbulent boundary layer will respond to pressure fluctuations, resulting in flow noise.

Flow noise generated by pressure fluctuations in the turbulent boundary layer.—In a turbulent boundary layer, the fluctuating velocity component V' normal to the boundary can be approximated by

$$V' = 0.04V,$$

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