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ANALYSIS OF THE UNDERWATER NOISE OF CCGS JOHN A. MACDONALD

L.J. Leggat

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ABSTRACT

A sound range trial with the Canadian icebreaker CCGS JOHN A. MACDONALD was carried out on the Halifax Sound Range to provide data for the "Marine Arctic Transportation Sound Physics and Responses of Marine Mammals" Project. The ship underwater noise was measured for a number of ship speeds and propeller operating conditions.

Underwater radiated noise results are reported for the conditions tested in octave-bands in terms of the equivalent source mean spectrum level over the frequency band of 8 Hz to 32 kHz. A comparison is drawn between the measured levels and levels predicted using an empirical technique. Results show that, in general, measured noise levels exceed predicted levels by between 6 and 8 dB.

Résumé

On a effectué, à l'aide du brise-glaces canadien NCGC John A. Macdonald, des essais dans le polygone acoustique de Halifax afin d'obtenir des données dans le cadre du projet "Acoustique du transport maritime dans l'Arctique et réactions des mammifères marins". On a mesuré le bruit produit sous l'eau pour un certain nombre de vitesses du navire et de conditions d'exploitation des hélices.

Les résultats quant au bruit émis sous l'eau sont signalés pour les conditions d'essai en bandes-octaves en termes du niveau moyen du spectre d'une source équivalente couvrant la bande de fréquences de 8 Hz à 32 kHz. On compare les niveaux mesurés aux niveaux prévus au moyen d'une méthode empirique. Les résultats indiquent qu'en général les niveaux mesurés de bruit dépassent les niveaux prévus par 6 à 8 dB.

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1. INTRODUCTION

The Defence Research Establishment Atlantic (DREA) and the Directorate of Maritime Engineering Support (DMES) have been co-operating over the years toward the development of a data base for ship radiated noise levels. The primary effort has been directed to acquiring data and developing predictive techniques for naval vessels such as frigates and destroyer escorts. The data base has been extended to include noise levels of other ship types. These include trawlers, container ships, cargo vessels and icebreakers. Some theoretical methods have been derived to predict the noise levels from merchant ships, icebreakers, and trawlers[1]; however, full-scale measurements of the noise are required to support the development of the mathematical models.

Recently various opportunities have arisen which have resulted in Canadian Coast Guard ships being made available for sound range trials. The resource development in the Arctic has spurred concern over the effects on the environment of increased levels of underwater sound produced by shipping and offshore activity. While performing their role in the North, icebreakers contribute to the levels of underwater sound, and so there is interest in industry and government about the magnitude of noise levels produced by icebreakers and the effect of the noise on the environment.

In June 1981 CCGS LOUIS S. St. Laurent was sound ranged in support of Arctic Pilot Project research into icebreaker noise and its effects on sea mammals[2]. More recently, the Department of Indian and Northern Affairs, the Arctic Pilot Project, the Canadian Coast Guard, and the Danish Government have carried out a project entitled "Marine Arctic Transportation Sound Physics and Responses of Marine Mammals". The purpose of this study was to assess the potential effects of shipping on arctic marine mammals. The scope of the study included measurement of the ship radiated noise on a sound range and while breaking ice in the North, so that underwater sounds generated by icebreaking could be distinguished from propeller cavitation and other ship noises. Thus the Department of National Defence undertook the measurement of the radiated noise of CCGS JOHN A. MACDONALD, the trials ship, on the Halifax Sound Range to provide baseline data for the sound physics project.

This memorandum describes the sound range trials on the Halifax Sound Range and compares measured sound levels with those predicted using empirical methods[1,3].

2. SHIP CHARACTERISTICS

CCGS JOHN A. MACDONALD is a 96 metre long icebreaker which displaces 9,300 tonnes. Launched in 1960, she is powered by an 11.2 MW diesel electric propulsion system, giving her a top speed in open water of 15.5 kt. She is fitted with three identical four-bladed, fixed-pitch propellers (centre, and port and starboard wings) designed to meet the Lloyds Ice Class I Specification. The propeller diameter is 4115 mm. Its expanded area ratio is 0.490. The pitch to diameter ratio is a constant 0.772 from the 50 per cent radius to the tip. It decreases to a value of 0.685 at the hub (30 per cent radius). The blade sections are flat-faced hydrodynamically shaped forms with a 12.7 mm wide flat ground on the leading edge of sections from the 30 per cent radius to the 90 per cent radius.

3. EXPERIMENTAL PROCEDURE

The sound range trial was designed to provide as much information as possible about the character of the ship's propeller and machinery generated noise under conditions similar to those that might be encountered during ice breaking operations. Thus in addition to normal runs at various speeds with ship's power distributed equally to the three propellers, tests were also carried out with propellers trailing, propellers operating in opposite directions, and with the ship accelerating and decelerating.

By trailing one or two propellers, it is possible to increase the load on the driving propeller or propellers, thus simulating to some extent the additional load on the propellers that would be experienced during transit in ice. The condition of propellers operating with equal power in opposite directions approximately simulates the bollard-pull condition. Ahead accelerations and decelerations simulate ramming and emergency manoeuvres.

The sound ranging was accomplished by steering the ship over the Halifax Sound Range on reciprocal northerly and southerly runs, with identical ship machinery settings. The conditions initially planned for the trial are summarized in Table 1. The full extent of the trial was completed with the exception of runs 3N,S and 5N,S which could not be carried out owing to problems with one of the generators in the ship.

The ship noise was measured with a single omnidirectional hydrophone mounted on the sea bottom at a depth of 27 m. On northerly runs, the hydrophone was to port of the ship; and on southerly runs, to starboard. The closest point of approach between the ship and the hydrophone for all runs except 8N,S was 100 m. On run 8N,S the ship was stationed directly over the hydrophone. The distance between the ship propellers and the hydrophone was measured using a continuously trained theodolite pair connected through a digital encoder to an analysis computer.

The noise was analyzed over a frequency band of 8 Hz to 32 kHz, and presented in terms of the equivalent source pressure mean spectrum level in octave-bands. This level is arrived at by measuring the noise in the far field of the ship, determining the acoustic pressure spectrum of the signal through Fourier analysis, and correcting the levels for distance so that they reflect the level as if the measurement were performed one metre from the propeller. In other words, the levels are increased by 20 log R where R is the range between the propellers and the hydrophone.

4. RESULTS

A summary of the actual propulsive conditions measured during the trial is given in Table 2. The revolution rate and engine power were read from the ship's instruments. Speed was determined with the aid of the sound range tracking instrumentation. Propulsive conditions are close to those given in Table 1. However, there were some problems encountered in ensuring that equal revolution rates were achieved on all shafts when all three propellers were driving (see runs 2N,S and 10S). This unbalance in propeller rpm leads to more load being shifted to the higher rpm propellers and could result in higher than expected overall ship noise levels.

The ship noise spectra for the eight conditions tested are shown in Figures 1 to 3. Figure 1 shows the 12.4 kt and 14.5 kt conditions for normal operation in open water; that is all three shafts operating. Figure 2 shows levels for variations on propeller advance ratios: wing propellers driving, centre propeller trailing (13.2 kt); and centre propeller driving and wing propellers trailing (9.0 kt and 10.5 kt). The heavily loaded extreme conditions are shown in Figure 3: bollard pull simulation and ship acceleration and deceleration.

The spectra of Figure 1 are characteristic of propeller cavitation noise. A broad-band hump in the spectrum is evident between octave-band centre frequencies of 63 Hz and 500 Hz. Above the hump, noise levels drop at a rate of about 6 dB per octave. As the ship speed increases from 12.4 kt to 14.5 kt, the sound levels likewise increase. With the higher rpm and propeller loading, cavitation extents and intensity increase, producing the observed higher sound levels.

The curves for centre shaft driving, wings trailing in Figure 2 show a similar increase in sound levels as the shaft revolution rate increases from 125 rpm to 145 rpm. The increase is particularly significant at 63 Hz where the revolution rate increase results in a 14 dB increase in the sound level. Experience has shown that these large increases in radiated noise level at low frequency are often caused by the onset of a particularly noisy form of cavitation. In this case, bubble or cloud cavitation may start between ship speeds of 9.0 kt and 10.5 kt when the centre shaft is driving.

The condition of wing propellers driving and centre trailing in Figure 2 produces lower noise levels than that of the 10.5 kt centre driving and wings trailing condition below 100 Hz and higher levels between 100 Hz and 4 kHz. This is a somewhat interesting result. To reduce complexity in discussing possible explanations, it is convenient to refer to runs 4N,S as condition A (wings driving) and to runs 7N,S as condition B (centre driving).

The revolution rates are about the same for the two conditions; the loading is higher in condition B than it is in condition A. Thus one would expect condition B to be noisier than condition A. However, as the two propellers are operating in condition A, the sound power from each propeller will add. In addition, icebreaker propellers are usually designed for low advance coefficients, and so the operating point of condition B would be closer to the design condition. Thus it would appear that the higher noise levels below 100 Hz experienced in condition B are produced by the higher loading and perhaps the emergence of a cavitation type which produces high low frequency noise levels. Because the differences at higher frequencies are relatively small, they can be attributed to the number of propellers operating and the proximity of the propeller operating condition to the propeller design point.

Because of the measurement situations, the extreme operating condition underwater sound levels shown in Figure 3 are somewhat approximate. During the acceleration and deceleration trials the levels varied over the duration of the measurement as the ship either increased or reduced speed. In the case of the bollard pull simulation (run 8) the precision of the measurement could be expected to be better owing to the steady condition of ship rpm and speed. Regardless, the results shown in Figure 3 demonstrate that the decelerating ship produces the highest sound levels, reaching a maximum of 182 dB at 125 Hz. Surprisingly, the acceleration and bollard pull levels are not significantly greater than those of normal operation at 14.5 knots (compare Figures 1 and 3). For run 2, the maximum level at 63 Hz of 174 dB is equal to that of the bollard pull condition (run 8) and greater than the acceleration condition (run 9). It is probable that the cavitation is fairly heavy in all of these conditions, and so large differences among the levels would be somewhat improbable.

5. COMPARISON OF MEASURED AND PREDICTED LEVELS

The predicted levels are based on a modified version of the empirical relationship proposed by Ross[3] :

$$L_{100} = 155 + 60 \log \frac{U_t}{25} + 10 \log \frac{B}{4}$$

where L_{100} is the spectrum level at 100 Hz;
U_t is the propeller tip speed, m/s; and
B is the number of blades.

The predicted spectrum is made to decrease with increasing frequency at 6 dB per octave from its level at 100 Hz out to 32 kHz. In cases where more than one propeller is operating, the level is calculated for each propeller and the powers are summed to arrive at the total level. Below 100 Hz the spectrum is assumed flat down to 8Hz. This predictive method estimates ship propeller noise levels exclusive of the contributions of blade-rate pure tones. The octave-band measurements, on the other hand, include the contribution from these pure tones, usually in the 8, 16 and 32 Hz octave bands.

A comparison between measured and predicted levels for runs 1, 2, 4, 6 and 7 are given in Figures 4 through 8. Predicted levels at 100 Hz for these conditions are given in Table 2.

In general the statistical prediction underestimates the measured noise levels consistently above 63 Hz. Differences are as high as 19 dB at the highest frequencies (32 kHz, Figure 8), but are more usually in the order of 6 to 8 dB. Thus in comparison to the data base from which the empirical method was derived, CCGS JOHN A. MACDONALD can be considered relatively noisy.

There are a number of reasons why the ship would experience high noise levels.

a. The propellers are of constant pitch and have not been adapted to the ship wake in which they operate. Thus cavitation can be expected to start at relatively low revolution rates.

b. The propellers are not operating near their design point, and so can be expected to experience noisy forms of cavitation at moderate to low revolution rates.

c. The leading edges of the propeller blade sections have been ground flat, producing a condition which favours the early onset of noisy types of cavitation.

CONCLUDING REMARKS

A sound range trial was carried out with CCGS JOHN A. MACDONALD to determine its levels of underwater radiated noise under a variety of ship operating conditions. The maximum noise levels in the open water propulsive condition were observed in the 63 Hz octave-band, and were 165 dB at 12.4 kt and 174 dB at 14.5 kt. The noisiest conditions tested were the crash-astern manoeuvre (~ 180 dB re $1\mu Pa/Hz^{1/2}$ at 1 m at 125 Hz) and single screw propulsion at 10.5 kt (177 dB re $1\mu\ Pa/Hz^{1/2}$ at 1 m at 63 Hz). The presence of particularly noisy forms of cavitation such as bubble and cloud cavitation at these conditions is thought to be responsible for the high noise levels.

Agreement between results from a statistical model for ship noise prediction and those from the trial is generally poor. In the 32 kHz octave band, the predictive method produced values some 19 dB below those measured in one case. However, in general, predicted levels were 6 to 8 dB below measured values. The absence of wake adaption in the propellers, the flats on the propeller blade leading edges, and the operation of the propellers at conditions other than the design point are thought to be factors responsible for the lack of agreement between experiment and the statistical model.

It can be concluded that compared to ships used to develop the statistical model the CCGS JOHN A. MACDONALD is a relatively noisy ship. The statistical model was derived principally from warship data. In warship design, special care is taken to shape the hull and propellers, and to isolate machinery so that ship noise levels are kept as low as possible. Thus it is not surprising that the icebreaker, designed for operating in ice, produces higher noise levels than a statistical mean of destroyer data.

TABLE 1. SHIP CONDITIONS PROPOSED FOR TESTING

Run Number	Propeller Status	Propeller rpm (nominal)	Ship Speed kt (nominal)	Advance Coefficient
1N,S	All 3 driving	110	12.5	0.85
2N,S	all 3 driving	125	14.5	0.87
3N,S	all 3 driving	135	15.5	0.85
4N,S	wings only	140	13.0	0.70
5N,S	wings only	155	14.5	0.70
6N,S	centre only	125	9.0	0.54
7N,S	centre only	145	10.5	0.54
8N,S	centre ahead, wings astern	145(C),125(W)	0	0
9N,S	acceleration: all 3 driving	145	0-15 kt	
10N,S	deceleration: all 3 driving	120	10-0 kt	

TABLE 2. PROPULSIVE CONDITIONS FOR SOUND RANGE TRIAL

RUN	SPEED KT	RPM			POWER (KW)				ADVANCE COEFFICIENT			L_{100}*			
		PORT	CENTRE	STARBOARD	PORT	CENTRE	STARBOARD	TOTAL	PORT	CENTRE	STARBOARD	PORT	CENTRE	STARBOARD	TOTAL
1N	12.4	108	110	115	600	1110	814	2524	0.86	0.85	0.81	153	154	155	159
1S	12.4	108	104	115	600	1008	814	2422	0.86	0.90	0.81	153	152	155	158
2N	14.3	123	128	144	871	1896	1530	4297	0.87	0.84	0.75	157	158	161	164
2S	14.6	124	125	140	1104	1896	1424	4424	0.88	0.88	0.78	157	157	160	163
4N	13.2	141		139	2030	0	1691	3721	0.70		0.71	160		160	163
4S	13.2	139		135	1904	0	1548	3452	0.71		0.73	160		159	163
6N	9.0		125			2394		2394		0.54			157		157
6S	8.8		122			2394		2394		0.54			156		156
7N	10.5		145			3915		3915		0.54			161		161
7S	10.3		145			3915		3915		0.53			161		161
8N	0	124	145	130	1680	3850	2625	8155				157	161	158	164
8S	0	125	128	130	1680	3690	2550	7920				157	158	158	163
9N	0-15kt	145	150	152	1890	3780	1980	7650							
9S	0-15kt	145	145	148	1836	3800	2047	7683							
10N	0-10 kt	115	115	120	1430	1800	2700	5930							
10S	0-10 kt	115	100	125	1608	1500	2250	5358							

*dB re 1μPa/$Hz^{1/2}$ at 1m

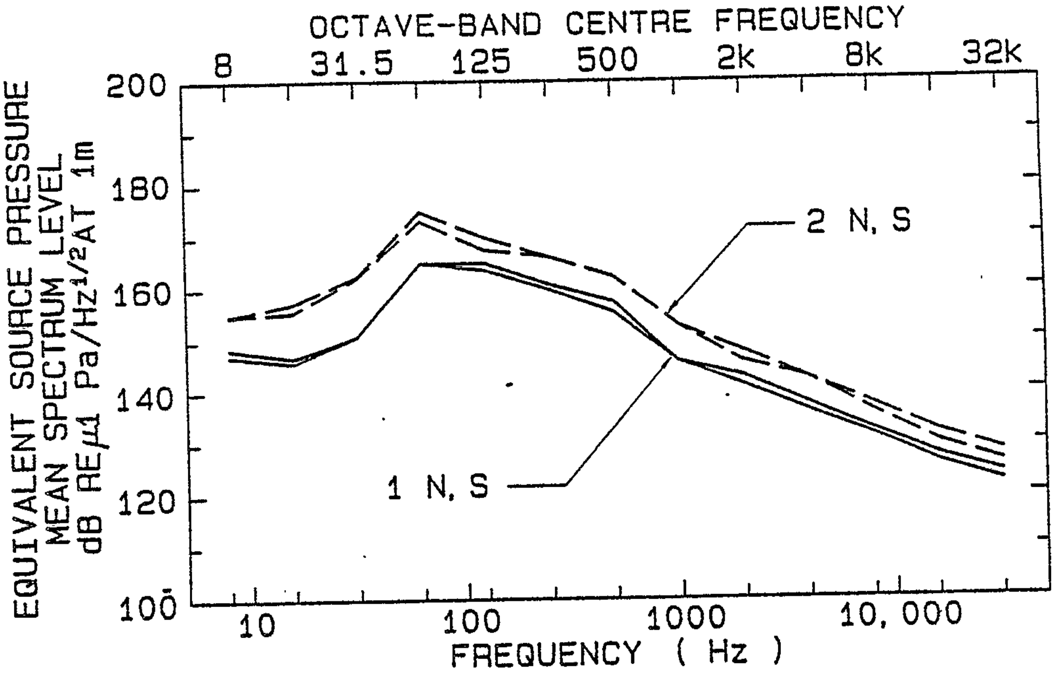

FIGURE 1. RADIATED NOISE AT OPEN WATER OPERATING CONDITIONS
(SEE TABLE 2)

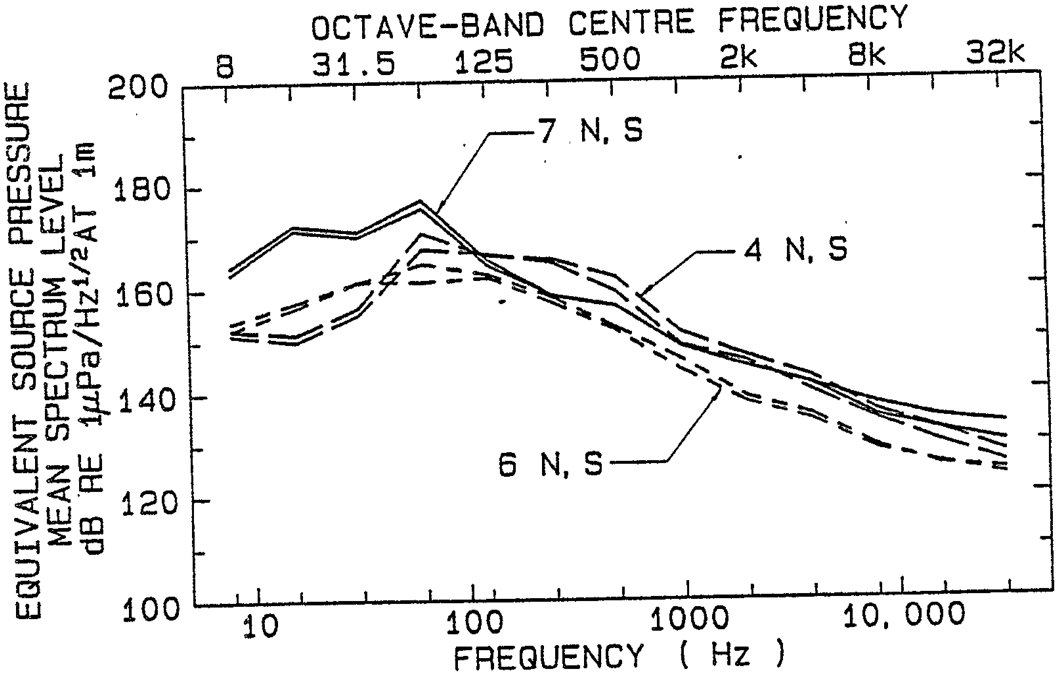

FIGURE 2. RADIATED NOISE AT THREE PROPELLER CONDITIONS
(SEE TABLE 2)

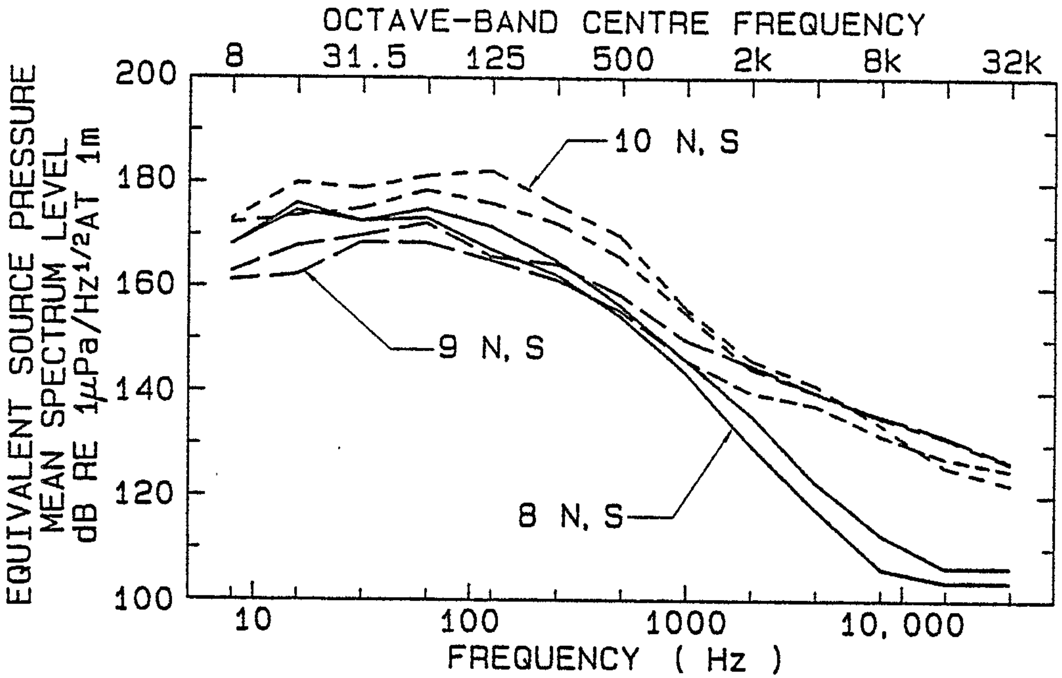

FIGURE 3. RADIATED NOISE AT EXTREME OPERATING CONDITIONS (SEE TABLE 2)

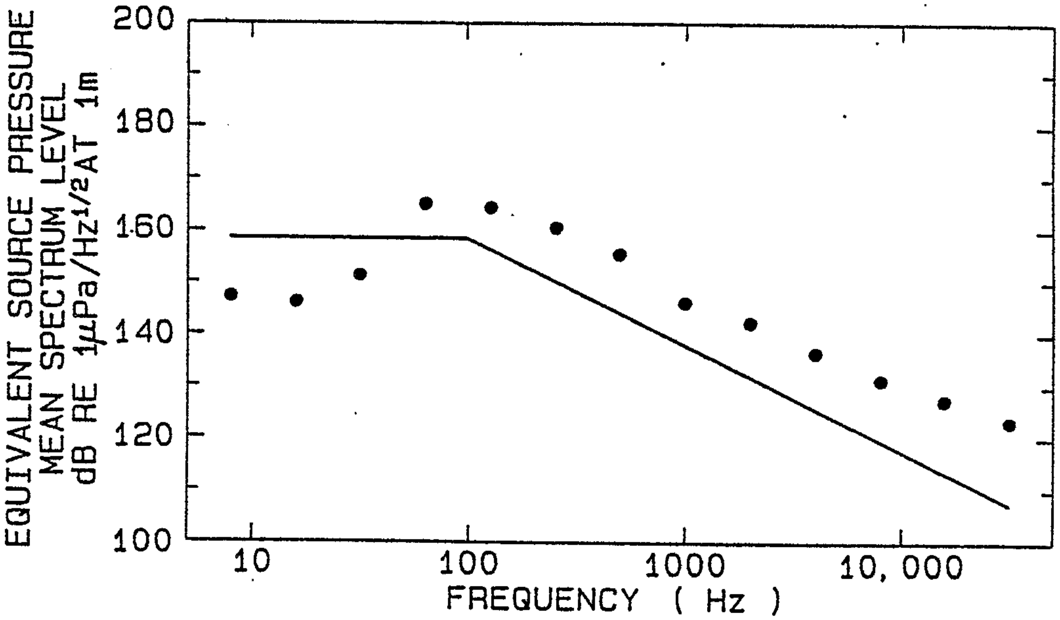

FIGURE 4. COMPARISON OF MEASUREMENT AND PREDICTION, 12.4KT, RUN 1N, S

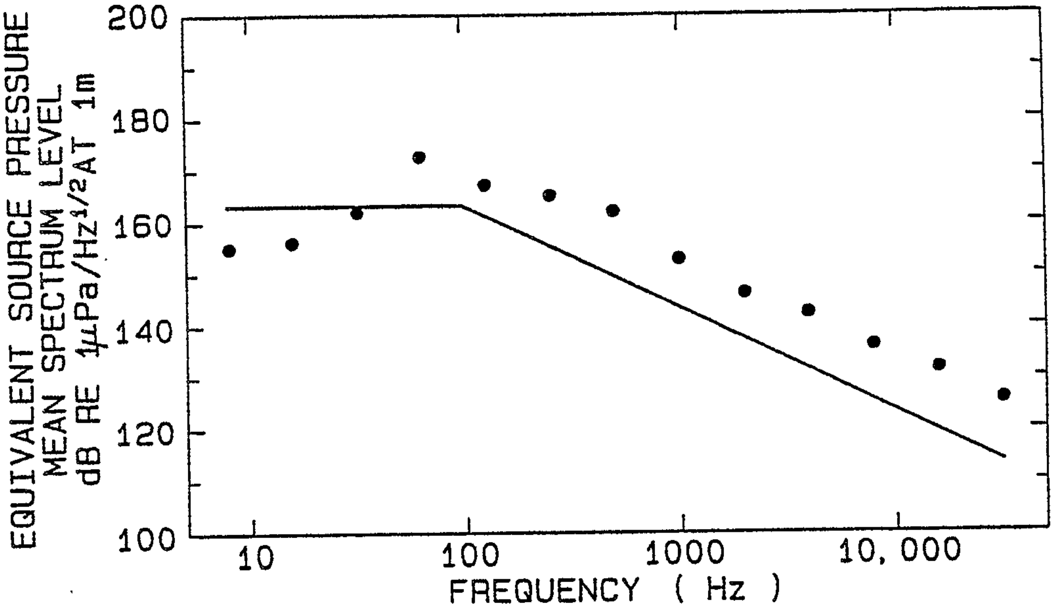

FIGURE 5. COMPARISON OF MEASUREMENT AND PREDICTION. 14.5KT, RUN 2N, S

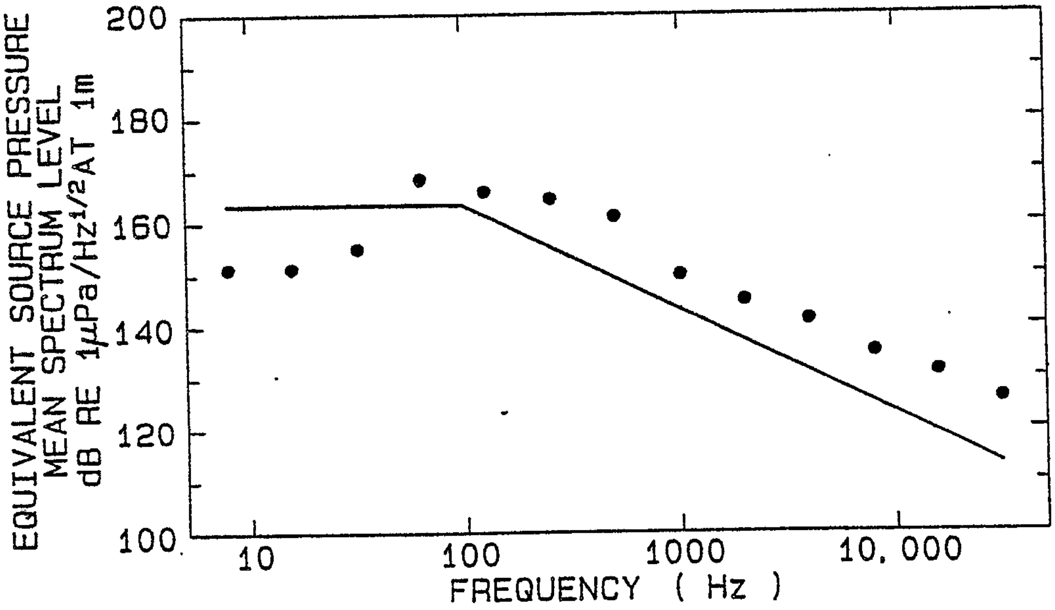

FIGURE 6. COMPARISON OF MEASUREMENT AND PREDICTION. 13.2KT, RUN 4N, S

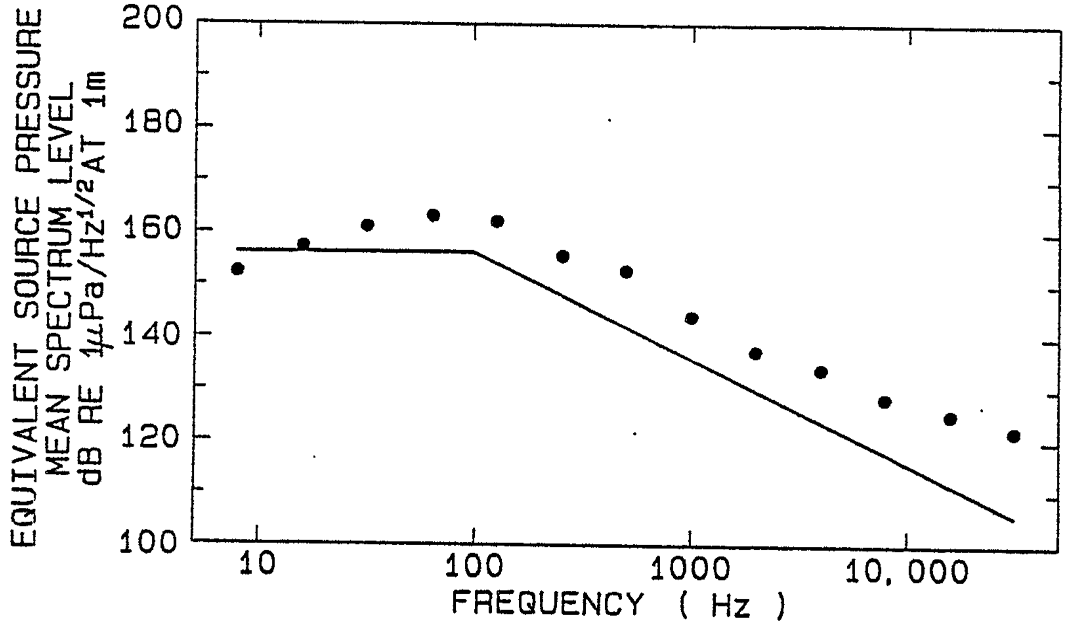

FIGURE 7. COMPARISON OF MEASUREMENT AND PREDICTION, 9.0KT, RUN 6N, S

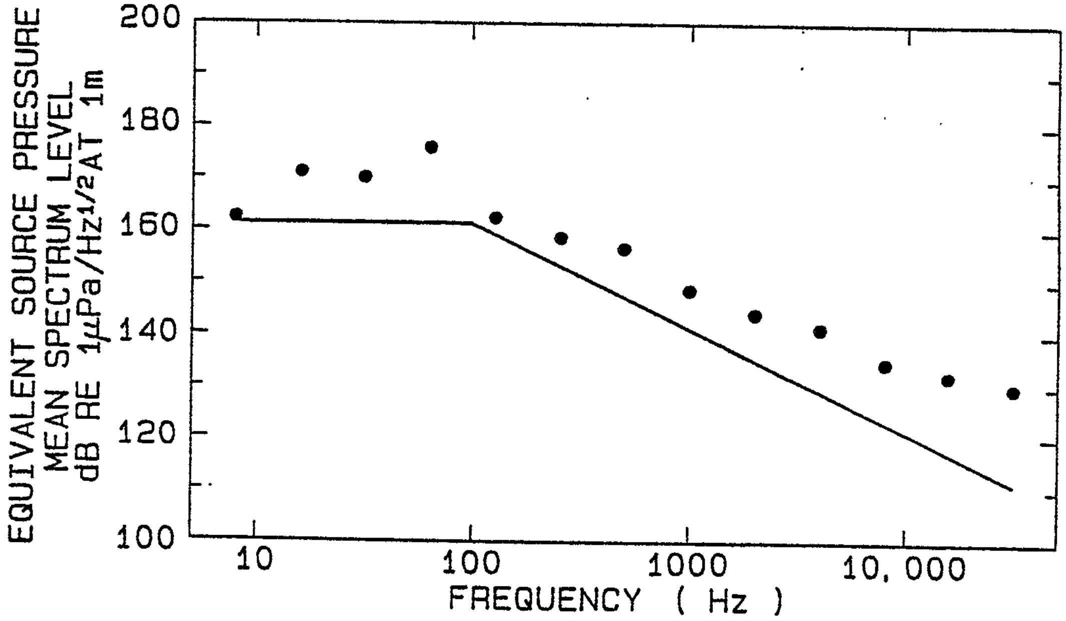

FIGURE 8. COMPARISON OF MEASUREMENT AND PREDICTION, 10.5KT, RUN 7N, S

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