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Report on

Sound Analysis of the U.S.S. S-20

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AUTHORIZATION

1. This work was authorized by Bureau of Engineering letter, reference (a). Additional correspondence pertinent to this problem is listed as references (b) and (c).

Reference: (a) BuEng let.SS125/S68(10-7-Do) of 21 Feb.1936.
(b) NRL let.C-S68/61:C-S68/L5 of 9 March 1936.
(c) NRL Report No. S-1199 of 25 September 1935.

STATEMENT OF PROBLEM

2. An immediate problem was to determine whether the sound insulation of certain auxiliaries on the S-20 had any material effect on the range at which she could be heard by another ship listening to the sound through the water. The general problem was to measure the intensity of the sound in water produced by the S-20 under different operating conditions at different speeds, ranges, and depths; to compare the relative intensity of the sounds produced by each of the driving units; and, if possible, to determine the mechanism of the production of sound in water by a ship underway.

DESCRIPTION OF MATERIAL

3. The submarine S-20 was used as a target ship throughout these experiments. The converted destroyer SEMMES was used as a listening ship. The S-20 has a direct drive low speed diesel engine and a direct drive motor working through a conventional clutch to the propeller shaft on the port side. On the starboard side the S-20 has a high speed, opposed cylinder diesel engine driving an electric generator. The generator is connected through a Ward Leonard control system to a high speed motor and reduction gear directly connected to the propeller shaft. A flexible rubber, sound insulating coupling had been installed between the reduction gear and the thrust bearing of the propeller shaft and felt sound insulation had been installed under the motor and reduction gear unit and under the line shaft bearing supports. Means were also provided for bridging the insulation on these units during particular tests to determine their effects. In general, the port side is of the conventional type, but on the starboard side numerous attempts have been made to isolate the driving source so that it cannot transmit its vibrations to the hull or to the propellers.

METHOD OF TEST

(a) To determine the effect of insulating the auxiliaries.

4. The S-20 hauled down on her anchor in 50 feet of water and operated the minimum auxiliaries necessary when submerged for a short time. The SEMMES anchored at 1,000 yards range and measured the noise level over the frequency range from 8 to 50 kilocycles. The range was reduced to 600 yards and the S-20 increased the number of auxiliaries

until all were in operation. The SEMMES was unable to identify any noise from the S-20 above the general background of noise in the bay. All the sound insulated auxiliaries were then bridged with C clamps and operated full blast. In addition, the diving planes and steering gear were operated continuously and both motors were idled at 255 turns. As the results were still negative, the S-20 got underway on the surface on one motor at 205 turns and circled the SEMMES at 600 yards range. This is about the minimum turns at which the S-20 can operate submerged and gave a basis for comparison with the auxiliary noise.

(b) General Problems.

5. In order to determine the relative importance of the different sound sources in producing sound in the water and the effects of speed, range, depth of submergence, and shadowing by the hull, the schedule of runs given in Table 1 was worked out and partially completed in the available time. In preparing the table, it was assumed that, under the favorable conditions of weather and temperature gradient found in the Guantanamo area on previous expeditions, it would be possible to compare the absolute value of the readings on one day with those of a later day. This proved not to be so, except where a large quantity of data permitted statistical treatment. The order of the tests was later modified so that comparative instead of absolute results could be obtained. For example, the port motor would be used as a reference level with which to compare the starboard side under different operating conditions.

6. The speed corresponding to 205 turns was chosen as about the minimum speed at which the diesel engines could be operated on the surface and the ship controlled when submerged. The speed corresponding to 255 was about the maximum the S-20 could make submerged for a full day's operation and also requires twice the shaft horse power used at 205 turns.

7. The SEMMES was equipped for listening with a sound analyzer and a special flat analyzing transceiver fully described in reference (c) and with separate horizontal echo ranging equipment to measure the range. The background of noise on the SEMMES at speeds below 10 knots is low and did not interfere with the listening to the S-20 on a beam bearing. A run consisted of 20 readings of the intensity of the noise from the S-20 above minimum audibility on phones in the main sound room of the SEMMES at 20 frequencies of 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 18, 20, 22, 24, 26, 28, 30, 32, 36, and 40 kilocycles. These frequencies were chosen to permit plotting an accurate curve, being closer together where the slope is changing rapidly. After the first series of readings, every third or fourth reading was repeated and if the check readings agreed within 2 decibels, the run was considered satisfactory. If there were too much variation, the whole series would be checked, but in an irregular order.

8. To get a single numerical value for a run to permit simple comparison with another run, the averages of the readings at each frequency were added and divided by 20, the number of frequencies at which

readings were made. From the energy standpoint, since db = 10 log P/P_0, to add decibels is to multiply the ratio of the energies above an arbitrary level and to divide this sum by the number of readings is to extract the root. The number thus obtained is the geometrical mean of the series of readings of energies. Since the response of the human ear is approximately logarithmic; i.e., directly proportional to decibels, the arithmetical mean of the decibels, or the geometrical mean of the energies, gives a number proportional to the response of the ear over the selected frequency range. A comparison of these average values therefore represents their relative intensities as heard by a listener, which is the practical purpose of this study.

DATA OBTAINED

9. Approximately 100 runs of 30 readings each, or 3,000 separate intensity measurements, were made during this study. These have been grouped for comparison in a series of tables. The numbers given in the tables are the averages for a run under the conditions stated. The abbreviations are: P, port; S, starboard; E, engines; M, motors.

(a) Effect of sound insulating auxiliaries.

10. When all the auxiliaries were operated full blast either when insulated or uninsulated, they could not be heard on the SEMMES at a range of 500 yards so as to be recognized above the general background of noise in the Bay, averaging 21.4 decibels.

11. The data at 500 yards for comparison between auxiliaries, charging batteries, and running at 205 turns are shown in Table 2. This table shows the apparent sound from the auxiliaries to be approximately the same as the general background of noise in the Bay. It is probable that the auxiliaries were really below this level and were not heard at all. When operating at minimum practical speed, the sound averaged 14.5 decibels above the ambient noise level. When charging batteries on the port engine, delivering the same power as when running at 205 turns, the sound averaged only 4.5 decibels above the ambient level; that is, the noise in the water from the engine and generator was only 10% of that from the propellers when underway.

(b) Sound Output vs. Turns

12. The effect of the number of turns on the sound output is shown in Table 3 for different conditions. The average gain in noise for the increase in speed is 5.3 decibels.

(c) Kilowatts vs. Turns

13. From the records kept by the S-20 on the volt-ampere readings required for each speed under different conditions, the average values given in Table 4 were obtained. To increase the speed from 205 turns to 255 turns required that the power be increased by a factor of 1.92.

(g) Intensity vs. Range.

18. A limited number of runs were made at both 1,000 and 2,000 yards. The data are summarized in Table 8. There is considerable variation as the runs at different ranges were made on different days and under different sea conditions, but they are sufficient to warrant averaging. The average loss in intensity is 6.4 decibels for an increase in range from 1,000 yards to 2,000 yards. This gives a low absorption coefficient of α = .0004. The practical meaning of it is that if the noise of a submarine can be reduced by 6.4 decibels, the range at which it can be heard would be reduced 1,000 yards for the same absorption coefficient. For example, driving from the side opposite the listening ship would reduce the range at which the S-20 could be heard by over 1,000 yards (see Table 7).

(h) Effect of Speed on the Frequency Distribution of the Noise.

19. In order to determine the effect of speed on the frequency distribution of the noise, the intensity at 30 kilocycles was compared with that at 15 kilocycles for 205 and 255 turns. Because of the different effects in deep and in shallow water, the data have been averaged in two groups in Table 9. In deep water and long range, the 15 kilocycle noise is about 10 decibels louder than that at 30 kilocycles. In shallow water and at short range, the difference is much less and the higher speed seems to accentuate the higher frequency.

(i) Background of Noise on the SEMMES as a Function of Speed.

20. The background of noise on the SEMMES was measured at different speeds and bearings using the QC-2 and QC-5 magnetostriction gear with an attenuation box and an output meter as an indicator with an arbitrary zero level. This level was some 10 to 15 decibels above the level used in sound analysis. The selectivities of the transceivers and amplifiers differed from the analyzer. The distance from transceiver to propellers was about 160 feet, although some of the sound must have traveled farther due to reflections from surface waves. Therefore, the decibel readings are not directly comparable with those obtained in the sound analysis of the S-20.

21. The QC amplifiers overloaded at about 28 decibels output so that it was necessary to reduce the gain by 25 decibels to go above 15 knots. The values above this speed as shown in Table 10 are adjusted to compensate for the change in gain but are not considered so reliable.

(j) Temperature Data.

22. The surface temperature in the open sea gradually increased from 24.5 to 27.0° C during the five weeks at Guantanamo. Whenever the S-20 submerged, she measured the temperature on two thermometers outside eyeports in the conning tower. The difference between the surface and 60 feet was always less than 0.5° C. A typical series is shown in Table 11.

ACCURACY

23. The discrimination and constancy of the sound equipment is good to 1 decibel. Readings were made to the nearest 2 decibels. The two listeners consistently checked to better than 2 decibels on the average. Ranges were maintained within 5%, except on some of the 500 yard runs, which should make less than 1 decibel error in sound intensity. The temperature difference between 1 and 55 feet was always less than 0.5° C and frequently was less than 0.1° C. The absorption coefficient was very low. The only other known variables are the surface sea conditions - swells and ripples - and the sound output of the S-20 for a given condition. While all the work was done under what would normally be considered good sea conditions, yet there was always a ground swell and the ripples varied from calm to light white caps. A course was always chosen into or with the swells and the ripples were usually about 30° off the course. Considered as an accidental irregularity, the effect of the sea should average out in a sufficient number of readings. This condition was only partially met for some problems and is believed to be a major cause of the inconsistencies in the data. The analysis always gives a differential effect between two or more operating conditions. Since the difference is usually a small percent of the total, a small error in the total may make a relatively large percentage error in the difference.

CONCLUSIONS

24. The following conclusions are drawn from the foregoing data:

(a) Sound generated in the water by all the auxiliaries of the S-20 forms less than 10% of her total sound output when submerged and underway at 205 turns. Under such conditions the range of detection will not be appreciably affected by supplying the auxiliaries with flexible mounts.

(b) The major portion of the sound generated in the water by both the S-20 and the SEMMES originates in the driven propellors. This statement probably holds true for all types of ships.

(c) Within the speed limits investigated the intensity of the sound generated by and through the driven propellers increases rapidly with increase in r.p.m. In case of the S-20 increasing the r.p.m. from 205 to 255, which means about doubling the shaft horse power, the intensity of the sound is increased by a factor of 3. In the case of the SEMMES, this increase of sound output with r.p.m. becomes very marked for speeds beyond about 11 knots. At 15 knots the sound output is increasing by a factor of 4 per knot.

(d) The felt insulation under the starboard motor and reduction gear reduced the sound output at 205 and 255 turns. In the 1935 tests it reduced the noise at 260 turns, but increased it at 220. Installation of insulated line shaft bearings and a flexible coupling have changed conditions since 1935.

(e) No significant difference was found between the sound from the port and starboard engines. Since no effort was made to isolate the port engine and considerable effort was made to isolate the starboard engine by electric drive and sound insulation, the rather inadequate data tend to confirm the conclusion in paragraph (b) above.

(f) The average intensity of the sound at 1,000 yards was 6.4 decibels greater than at 2,000 yards. This is a factor of 4.4 in energy.

(g) In deep water and long range, the average intensity at 15 kilocycles is about 10 decibels greater than at 30 kilocycles. In shallow water and short range, the average difference is only about 2.0 decibels.

RECOMMENDATIONS

25. Since the differences due to the various operating conditions as shown in this study are of the order of 10 decibels or less while the average total noise is of the order of 20 to 40 decibels and has been demonstrated to come from the propelling system, it is obvious that the major effort toward the reduction of noise produced in the water by Naval vessels should be concentrated on the propellers and their associated structures. A program along those lines is being prepared.

26. Provided the SEMMES is made available for this work, it is planned to make a more complete study of the background of her noise using the analyzer equipment and covering wider ranges of speed, frequency and sea conditions.

Table 1

Program of Test Runs

Run No.	Depth of Water	Submergence	Range	Drive	Turns	Listening Side	Remarks
1	1000	Surf.	1000	PE	205	Port	
2	"	"	"	PE	255	"	
3	"	"	"	PM	205	"	
4	"	"	"	PM	255	"	
5	"	"	"	SE	205	"	
6	"	"	"	SE	255	"	
7	"	"	"	SM	205	"	
8	"	"	"	SM	255	"	
9	"	"	"	SM	205	Starboard	
10	"	"	"	SM	255	"	
11	"	"	"	SE	205	"	
12	"	"	"	SE	255	"	
13	"	"	"	PE	205	"	
14	"	"	"	PE	255	"	
15	"	"	"	PM	205	"	
16	"	"	"	PM	255	"	
17	"	Subm.	"	PM	205	Port	Periscope Depth
18	"	"	"	PM	255	"	
19	"	"	"	SM	205	"	
20	"	"	"	SM	255	"	
21	"	"	"	SM	205	Starboard	
22	"	"	"	SM	255	"	
23	"	"	"	PM	205	"	
24	"	"	"	PM	255	"	

Runs 25 to 48:

Repeat Runs 1 to 24 at 2,000 yards range.

Runs 49 to 60:

Repeat Runs 5 to 12 and 19 to 22 with insulation bridged to eliminate its effect.

Run No.	Depth of Water	Submergence	Range	Drive	Turns	Listening Side	Remarks
61	"	"	"	PM	255	Port	40 ft.
62	"	"	"	PM	255	"	65 ft.
63	"	"	"	PM	255	"	90 ft.
64	"	Surf.	"	Both E	205	"	
65	"	"	"	"	255	"	
66	"	"	2000	"	205	"	
67	"	"	"	"	255	"	
68	"	"	"	Both M	205	"	
69	"	"	"	"	255	"	
70	"	"	1000	"	205	"	
71	"	"	"	"	255	"	

Repeat inconsistent runs as time permits.

Table 2

Noise from Auxiliaries at 500 Yards.

Submergence	Sound Insulation	Operation	Average Db
50 ft.	In	All auxiliaries	21.3
50 ft.	Out	" "	19.3
Surface	In	SM on air pump	20.8
		Average -	20.5
Surface	None	PE charging batteries	25.0
Surface	None	PE at 205 turns	35.4
"	"	PM at 205 turns	34.3
		Average noise underway -	34.8
Surface		Lying to. General noise level in Bay not from S-20.	21.4

Table 3

Sound Output vs. Turns

Depth of Water	Submergence	Drive	Range	Average Intensity 205 T	Average Intensity 255 T	Db. Diff.	Remarks
(a) Deep Water, long range							
1000	Surf.	PE	1000	30.7	34.7	4.0	
1000	Surf.	PE	2000	28.6	34.0	5.4	
1000	Surf.	SE	2000	25.4	28.8	3.4	
1000	Subm.	PM	1000	35.5	37.4	1.9	
1000	Subm.	SM	2000	20.1	25.6	5.5	
					Average -	4.1	
(b) Shallow Water, short range							
50ft.	Surf.	PM	500	30.8	34.8	4.0	
50 "	Surf.	SM	500	25.7	34.6	8.9	Insulated
50 "	Surf.	SM	500	32.6	39.5	6.9	Not insulated.
					Average -	6.6	
(c) Deep Water, long range SEMMES on opposite side of S-20 from driving propeller.							
1000	Surf.	SE	1000	27.8	29.0	1.2	
1000	Surf.	SE	2000	20.6	26.8	6.2	
1000	Subm.	SM	1000	25.4	32.2	6.8	
1000	Subm.	PM	1000	23.5	29.8	6.3	
					Average -	5.2	

Table 4

Power vs. Turns

Submergence	Drive	KVA at Turns 205	KVA at Turns 255	Calculated Power Increase in Db	Calculated Power Increase in %	Submerged Power / Surface Power
Surface	PM	106.6	205.9	2.86	93.3	
Surface	SM	102.4	202.4	2.96	97.8	
		104.5	204.2	2.91	95.5	
Submerged	PM		221.2			
	SM		220.0			
			220.6			1.08

Table 5

Effect of Sound Insulation
under Starboard Motor and Reduction Gear

Drive	Avg. Intensity at Turns 205	255	Diff.	Insulation	Out minus In 205	255	Remarks
SM	22.6	35.3	12.7	In			Range 500 yds.
	26.8	33.5	6.7	"			Water 50 ft.
	27.8	35.1	7.3	"			Surface
	25.7	34.6	8.9	"			
SM	31.3	37.3	6.0	Out			
	33.9	41.7	7.8	"			
	32.6	39.5	6.9	"	6.9	4.9	
PM	26.3	34.1	7.8	None			
	34.0	36.6	2.6				
	32.1	33.8	1.7				
	30.8	34.8	4.0				
P-S	5.1	0.2		In			
P-S	-1.8	-4.8		Out	6.9	5.0	

Table 6

Port vs. Starboard Engines

Submergence	Drive	Range	Avg. Intensity 205	255	P-S 205	255	Remarks
Surface	PE	1000	30.7	34.7			Port side conventional.
			29.2	24.3			Stbd side electric
			25.4	24.4			drive and sound insu-
		2000	28.6	34.0			lated.
			28.5	29.3			
Surface	SE	1000	28.7				
		2000	25.4	28.8			
			27.1	28.8	+ 1.4	+0.5	

Table 10

Background of Noise on SEMMES

Speed	Turns	Noise Level of QC-2 Bearing 0°	90°	180°	Noise Level of QC-5 Bearing 0°	90°	180°
0	0	0	0	0	0	-6	0
5	58	-	0	-	-	-6	-
8	90	-	0	-	-	-3	-
10	112	3	1	-	5	0	-
11	123	4.5	2.5	12	3	0	16
12	136	7	7	13	7	5	17
13	148	9	9	18	9	7	15
14	159	11	13	--	15	17	17
15	171	16	17	25	18	22	23
16	184	23	25	31	25	30	30
17	197	31	33	38	32	40	42
18	205	34	37	40	38	47	47
20	235	42	45	44	46	52	50

Table 11

Temperature Gradient
13 April 1936 - Deep Water
Guantanamo Bay Area

Time	Keel Depth	Therm. Depth	Temperature °C. Port	Starboard
0820	28	1	25.7	26.2
0830	30	3	25.7	26.2
0840	30	3	25.7	26.2
0850	30	3	25.8	26.3
0900	34	7	25.5	26.0
0910	39	12	25.5	26.0
0920	40	13	25.5	26.0
0930	40	13	25.5	26.0
0940	41	14	25.5	26.0
0950	40	13	25.5	26.0
1105	26	0	25.9	26.4
1110	41	14	25.8	26.3
1120	40	13	25.8	26.3
1130	60	33	25.5	26.0
1140	60	33	25.4	25.9
1150	60	33	25.4	25.9
1200	60	33	25.4	25.9
1210	80	53	25.3	25.8
1220	80	53	25.5	26.0
1230	80	53	25.5	26.0
1240	80	53	25.6	26.1