UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 82

A Study of the Influence of Microbubbles on Hydrodynamic Flow Noise

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Prepared for
DAVID TAYLOR MODEL BASIN
Department of the Navy
Washington, D.C.
under
Bureau of Ships General Hydromechanics Research Program
S-R009-01-01
Office of Naval Research Contract Nonr 710(65)

April 1966
Minneapolis, Minnesota

PREFACE

The effect of free air bubbles on cavitation and the propagation of sound in water is a subject of continuing study at the St. Anthony Falls Hydraulic Laboratory. The work reported here is a preliminary effort to investigate the effect of microbubbles on the noise-producing mechanism of flowing water. The equipment and technique developed under this program have use in other related investigations; they have been applied to studies on non-Newtonian additives in the areas of radiated noise, boundary pressure fluctuation, and boundary cavitation.

The studies reported here were carried out in the period from October 1964 until March 1966 and were sponsored by the David Taylor Model Basin, Department of the Navy, Washington, D. C. under Contract Nonr 710(65). The report was critically reviewed by J. M. Wetzel. Appreciation is also expressed to Paul Edstrom for reduction of data and preparation of drawings. Preparation of the manuscript for printing was carried out by Marjorie Olson.

ABSTRACT

A test facility has been constructed for the measurement of flow noise generated by a rotating cylinder in water. Measurements were made of radiated flow noise in water for a frequency range of 5 to 80 kiloHertz. The surface velocities of the cylinder were varied from 44 to 100 fps. The total air content of the water was varied from 7 to 27 ppm. The radiated flow noise was observed to increase as the sixth power of the surface velocity for low frequencies. For high frequencies, the flow noise increased as the tenth power of the velocity. Release of air bubbles by shear had no effect on radiated flow noise other than to reduce the measured level of the noise.

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I. INTRODUCTION

The operation of ships and submarines in a quiet environment is highly desirable for effective application of sonar. Unfortunately, the motion of a ship or submarine gives rise to much undesirable noise. The principal causes of this extraneous noise are the structural vibration of the vessel, cavitation, and noise arising from the motion of the fluid about the vessel. In any practical situation all of these factors interact with each other in a very complex manner.

This report is concerned with flow noise which is defined as the noise arising from the motion of the fluid and its interaction with the mean motion of the boundary only.

Investigations of flow noise have been made in two principal areas: the pressure fluctuation on the boundary and the noise radiated away from the boundary. Pressure fluctuations on the boundary can have a profound influence on the sound radiated if the fluctuations result in boundary vibration. The boundary vibrations can in turn have effects on the supporting structure, fluid turbulence, and radiated sound. Pressure fluctuations in the absence of boundary interaction radiate little sound.

The work in the present investigation has been restricted to radiated noise, either the radiated component of flow noise or the radiated component of noise arising from the interaction of the near field of flow noise with inhomogeneities in the flow such as air bubbles. The previous experimental work on flow noise has been mostly concerned with the noise of jets in air. That research was greatly stimulated by the noise generated by jet aircraft. Ribner [1]* has given an extensive bibliography of this aspect. In his original mathematical formulation Lighthill [2] was concerned with the production of flow noise, neglecting the influence of solid boundaries. His work described the radiated noise intensity in terms of a volume distribution of quadrupole sources. In this situation the intensity of radiated sound, I_o, per unit volume, is proportional to the flow velocity to the eighth power (U^8). The efficiency of sound production η is proportional to the Mach number to the fifth power (M^5).

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*Numbers in brackets refer to the List of References on page 11.

$$I_o \approx \rho_o \; U^8 \, a_o^{-5} \, \frac{x^{-2}}{L}; \qquad \eta \approx (U/a_o)^5 \qquad \text{(Ref. [5])} \qquad (1)$$

where ρ_o is the density, a_o is the velocity of sound, x is the radial distance to the point of observation, and L is the scale of a large turbulent eddy.

Curle [3] extended Lighthill's work to include the effect of solid boundaries on radiated noise. He was able to show that the effect of a fluctuating stress on the boundary could be represented by a distribution of dipoles over the surface. The sound intensity in this case is proportional to the sixth power of the velocity (U^6) and the efficiency is proportional to the Mach number to the third power.

$$I_o \approx \rho_o \, U^6 \, a_o^{-3} \, x^{-2}; \qquad \eta \approx (U/a_o)^3 \qquad (2)$$

Phillips [4] also made estimates of the dipole radiation from solid boundaries. He concluded that the dipole radiation was very small for an infinite flat plate with the turbulence homogeneous in a layer parallel to the plate. In further investigation of sound emitted by boundary layers, Meecham [5] estimated the dipole sound to be reduced by a factor $(L/R)^2$ where L is the thickness of the boundary layer and R is the surface radius of curvature. He proposed the following equation for the sound intensity:

$$I_o \approx \rho_o \, U^6 \, a_o^{-3} \, (L/R)^2 \, x^{-2} \quad \text{per unit area for dipole radiation}$$

and

$$I_o \approx \rho_o \, U^8 \, a_o^{5} \, x^{-2} \quad \text{per unit area for quadrupole radiation}$$

From this it can be seen that a large flat boundary layer will radiate little dipole sound, while small bumps if extending through the laminar sublayer could radiate considerable dipole-like sound. Meecham further states that the volume quadrupole sound will be considerably increased in the boundary layer due to shear-flow enhancement.

Few experimental measurements have been made of radiated flow noise at low Mach numbers. The best known experiments are those of Wilson [6] and

Skudrzyk and Haddle [7]. Both of these experiments were conducted with a rotating cylinder. Wilson's tests were performed with air and Skudrzyk's tests were with water. It would be expected that flow noise properties of both air and water would be similar, neglecting compressibility, were it not for the ability of water to form two-phase mixtures. Different measurement procedures by each investigator make quantitative comparisons of their respective data difficult. Skudrzyk also did additional work on buoyancy-propelled bodies in water [14].

It was postulated in the original proposal for this study and more recently in Ref. [8] that the presence of air bubbles in a turbulent liquid would behave as simple sources which would contribute to the total radiated noise. The air bubbles arise generally from the release of dissolved air from the water by turbulence. It is currently believed that tiny gas nuclei are stabilized below the visible limit in natural waters. These tiny nuclei can grow by diffusion to much larger sizes in the fluctuating pressure field of a turbulent flow, particularly in the high shear region of a boundary layer. The presence of air bubbles in water is known to reduce the transmission of sound [9, 10] and in this way would reduce flow noise radiation.

An appreciation for the ability of suspensions of air bubbles to attenuate sound can be gained from the estimate of $2.5 \times 10^5 \tau$ decibels/meter where τ is the volume concentration of air [9]. This estimate is for a single size of bubbles at atmospheric pressure. The high attenuation produced by air bubbles and the susceptibility to release of air from the dissolved state by turbulent shear layers create an obvious difficulty in the experimental measurement of radiated flow noise in water. This difficulty is easily circumvented by the use of deaerated water unless the simultaneous effect of air bubbles on noise production is to be observed.

II. EXPERIMENTAL APPARATUS

It was anticipated that the relatively high mechanical noise generated by a water tunnel or towing facility would mask the low levels of flow noise. Therefore, a rotating cylinder test facility was chosen as having the potentiality of providing the lowest level of mechanical noise, as it would have a minimum of moving parts.

The rotating-cylinder test facility consisted of a hollow, rotating cylinder positioned on the axis of a steel tank 6 ft in diameter. The tank was supported on three I beams. A cork pad was installed between the I beams and the concrete floor of the Laboratory for sound isolation. Sandbags were placed against the exterior walls of the tank to provide additional damping as well as to provide some isolation from sound transmitted through the air.

The tank capacity was 1260 gallons. It was filled to a 6-ft depth from either the municipal water supply or the contents of the St. Anthony Falls Hydraulic Laboratory 6-in. water tunnel. The water tunnel is equipped with an air separator and pressure control, and thus provides a simple and rapid means of removing air from water to the concentration level required. Diversion of water from the water tunnel to the tank enabled tests to be conducted with various dissolved air contents. A steam-heat exchanger was also installed in the tank to permit adjustment or control of the water temperature.

The rotating cylinder was supported on a hollow stainless steel shaft mounted in water-lubricated rubber bearings. The cylinder itself was 1 ft long with an external diameter of 1 ft. Its top was submerged 2 ft below the water surface in the tank. The cylinder was hollow to provide space for instruments. It was constructed of a laminated, synthetic wood material (Renwood). A thickness of 3 in. was selected to reduce vibrations of the cylinder wall. This type of construction has proved to result in a system free of any measurable resonances. The cylinder was finished with a heavy coating of epoxy paint. The surface was then machined to a 0.0005 in. "run-out" and polished to a high gloss. The surface was waxed frequently during the test program.

The cylinder shaft was supported by a wood framework completely isolated from the steel tank. A water-lubricated bearing and thrust washer connected the cylinder, drive shaft, and pulleys to the support frame. A second rubber guide bearing mounted on a cross frame inside the tank held the cylinder in an axial position.

The cylinder was driven by a 20 hp, 3500 rpm, induction motor through a "Vee" belt drive. Speed changes were effected by using various sizes of pulleys on the motor and drive shaft. Fig. 1 shows a drawing of the tank and cylinder.

Considerable difficulty was experienced in developing a drive system sufficiently quiet for the purpose. Many types of bearing surfaces were tried, including ball bearings and sleeve bearings of both plastic and metal. All of these bearing materials were found to give troublesome "spikes" in the measured flow noise spectrum, particularly for the higher frequencies. The rubber bearings were found to contribute relatively few of these spikes. However, an unsatisfactory noise level still was observed for the lower frequencies. This was attributed to vibration and irregularities in the drive belts.

A set of strain gages was mounted on the drive shaft of the rotating cylinder. They were calibrated to measure torque at various speeds. Slip rings mounted on the shaft conducted the signal from the strain gages to the measuring instruments. The measurement of torque in this program was of minor importance; however, the equipment also was designed for use in another project involving non-Newtonian additives where drag measurements are most useful in detecting presence of the additive.

The drag coefficient of the rotating cylinder in "pure" water was measured as 0.00233 for the speeds ranging from 44 to 100 fps. The drag coefficient C_d is defined according to the following equation from Ref.[13]:

$$C_d = \frac{M}{qsa} = \frac{M}{\pi \rho a^4 \omega^2 \ell}$$

where M = the measured torque corrected for the torque contribution from ends of the cylinder,

ω = the rotational speed in radians per sec,

a = the radius of the cylinder,

ℓ = the cylinder length,

ρ = the water density,

R = Reynolds number = $\frac{\omega a^2}{\nu}$,

ν = kinematic viscosity,

s = area of cylinder, and

$q = 1/2\rho\omega^2 a^2$.

The drag coefficient checks very well with the value obtained from the extrapolation of the data of Theodorsen and Regier [13] to a corresponding Reynolds number R. However, it should be noted that Wilson [6] reported a drag coefficient approximately 3.5 times as high as Theodorsen.

The cylinder rotating in a large tank gives rise to two dominant motions: (1) a free vortex motion where the product of velocity and radius equals a constant $Vr = C$, and (2) an approximately logarithmic velocity distribution near the cylinder. The motion of the fluid around the cylinder was investigated by both Skudrzyk and Haddle [7] and Wilson [6]. Their data show a boundary layer-like velocity distribution on a rotating cylinder. Flow no doubt occurred along the axis of the cylinder although it was hoped that the brief operating period reduced this tendency.

The acoustic pressure in the tank was sensed by a USRL H17 hydrophone. The hydrophone was supported on a strut mounted midway between the rotating cylinder and the tank wall. Its active surface was located on a horizontal plane passing through the lower end of the rotating cylinder.

The signal from the hydrophone was amplified by a Sensonic preamplifier. A Panoramic frequency analyzer was used at high frequencies and a Hewlett Packard frequency analyzer was used at low frequencies to measure sound intensity in discrete frequency bands. Both frequency analyzers were modified by incorporating a true rms voltmeter as a second detector; the output of the true rms voltmeter was connected to an xy plotter. The frequency analyzers were used to examine a single frequency at a time. The scanning mode of the Panoramic analyzer was used for a "quick look" only. A block diagram of the electrical equipment is shown in Fig. 2.

III. EXPERIMENTAL PROCEDURE

The test tank was surveyed with a hydrophone to determine the presence of standing waves. These measurements indicated a nearly uniform pressure field throughout the liquid when the tank was excited with a random noise source or flow noise. This fact made possible the measurement of sound power output from an arbitrary point without providing a means for averaging the standing wave pattern by either shifting the entire pattern with moving reflectors or moving the hydrophone.

To relate the power input to the tank to the pressure measured by the hydrophone, a procedure similar to that of Ref. [11] was followed. A known source of acoustic energy was installed in the tank, and the proportionality constant relating the acoustic energy introduced into the tank and the resulting pressure in discrete frequency bands was determined. The acoustic source referred to above was constructed from a 1/4 in. copper pipe partially flattened near one end. The pipe was connected to a constant pressure water supply. As water flowed through the pipe, cavitation in the constriction created essentially a point source of intense noise.

The energy output was easily determined by measuring the pressure at a known distance from the cavitating source with a standard hydrophone. The intensity ($p^2/\rho a_o$) was then integrated over a spherical surface surrounding the source.

It was known from previous work [12] that air would be released from the water as tiny bubbles in the regions of high shear near the rotating cylinder surface. It was further expected that the rate of air release would be dependent on the relative saturation of the liquid. It was also reasoned that the air would be released in the boundary layer region where it would have the greatest effect on flow noise. As the air bubbles diffused away from the rotating cylinder into the water of low air content, the bubbles would return to solution and not produce attenuation of sound.

The water was deaerated in the St. Anthony Falls Hydraulic Laboratory 6-in. water tunnel and then transferred to the test tank. Air contents as low as approximately 7 ppm were obtained in this manner. It was found that the total air content as measured by a Van Slyke apparatus remained constant for a period of several days. The air content was easily increased by adding tap water which was found to be in a supersaturated condition.

The following procedure was used to measure flow noise. The entire electronic assembly was calibrated at a single frequency by the introduction of a known voltage across the calibrating resistor in the hydrophone H17, Fig. 2. An arbitrary electrical input of -120 decibel referred to 1 volt was used throughout the program. The xy plotter was set to a time sweep mode of approximately 1 minute. The xy plotter and the drive motor on the rotating cylinder were started simultaneously and a time record of the hydrophone output was taken. This procedure was repeated at each frequency for a range of surface speeds of 44 to 100 fps and air concentrations of 7 to 30 w ppm. A typical record of flow noise indicated that the noise level rose sharply during the acceleration period, dropped to a constant value briefly, and then decreased as the vortex built up in the tank and as air was released.

IV. RESULTS

Figs. 3 through 5 show the results of the measurements plotted on semi-logarithmic paper. The surface velocity of the drum is plotted on the abscissa with each cycle of the logarithmic scale including data for a single frequency as indicated. The energy output in watts per square meter of cylinder surface is plotted as the ordinate in decibels referenced to 10^{-13} watts. For low speeds it will be noticed that the data tend to approach a limiting energy output, especially at the high frequencies. This value of energy output represents the background noise of the system.

Superimposed on the experimental data are lines with slopes proportional to U^6, U^8, and U^{10}. For the frequency ranges of 5-20 kHz, 20-60 kHz, and 60-80 kHz, it appears that the sound output varies approximately as the sixth, eighth, and tenth powers of the velocity respectively. It is interesting to note that Wilson's experiments [6] on a rotating cylinder in air indicate that the total noise energy output varies approximately as the sixth power of the velocity. Measurements by Skudrzyk and Haddle [7] on a cylinder with a smooth surface in water similarly give a sixth power of the velocity variation of noise power output in a 2 kHz band centered at 24 kHz. Such a variation can arise from dipole-like sources of sound.

Similar measurements of radiated flow noise in a water tunnel boundary layer [7] show a 24 decibel per speed octave or U^8 variation of flow noise power with speed, which is indicative of quadrupole-like sound radiators. The observation [5] that dipole radiators should not occur for an infinite homogeneous boundary layer on a flat plate would seem to indicate that the curvature of the cylinder gives rise to the dipole-like character of the radiated noise observed in this investigation. Roughness elements, if they protrude through the laminar sub-layer, should also give rise to dipole-like sound [5]. An examination of the data of Skudrzyk and Haddle [7] for a rotating cylinder with roughness added to its surface shows, however, that the slope of noise power versus velocity varies as U^8 or U^{10}. A variation such as this indicates quadrupole or octupole-like sound radiators. This apparent conflict could be resolved if another mechanism such as microcavitation on the roughness element were considered.

In the data of this report variation of noise with surface velocity for frequencies near 80 kHz is approximately proportional to U^{10}. The great inefficiency of noise production of octupole radiators (efficiency $\approx M^7$) would point to a phenomenon other than flow noise as being predominant in this case also.

It has been pointed out by Ffowcs Williams [15], however, that for boundary layers thicker than an acoustic wave length, octupoles will cease to exhibit their characteristic inefficiency. Rotating cylinders have an unusually thick boundary layer and at 80 kHz acoustic wave length will very nearly equal the boundary layer thickness. Therefore the possibility exists that octupole-like radiators were observed.

The initial purpose of the investigation was to determine the influence of microbubbles on the flow noise-producing mechanism. The experimental results bearing on this factor are either negative or inconclusive. Essentially the same level of noise was obtained for all air concentrations utilized in the tests. However, this fact in itself is not significant when a negative result is obtained as the dissolved air content is not expected to be a factor influencing noise production directly but is only one step in a multistep process leading to the release of air into the boundary layer.

It should be further emphasized that the data shown in Figs. 3 to 5 were taken from the first region of constant intensity of a record of flow noise versus time, after the starting transient had died out. It was expected that this region represented a typical value of the flow noise before the effects of air became significant. After this initial reproducible period, the noise decreased, remained constant, and sometimes increased in a completely random manner for a low value of dissolved air content (less than 20 ppm). Superimposed on these effects were the attenuating properties of free air which eventually appeared in almost all tests and suppressed the measured level of flow noise.

To examine the effect of air bubbles arising from a source other than the flow shear, air was deliberately introduced on one occasion into the boundary layer from a jet of supersaturated water which would be expected to release fine bubbles. This jet did not seem to have any effect other than to produce noise attenuation. However, it is quite possible that under these conditions the air bubbles were swept away from the cylinder by the radial flows.

Cavitation is a ubiquitous phenomenon in any work involving water moving at high velocity. It is, as well, a very efficient producer of noise. For purposes of comparison, an experiment was undertaken in which cavitation was produced by a small rod (1/16 in. diameter) protruding 1/16 in. from the cylinder surface. The cavitation noise produced is shown as an isolated data point near the tops of Figs. 3 through 5. It can be seen that this tiny cavitating device produces much more noise than the flow in all frequency bands. This procedure is very similar to that described in Ref. [7] where an elliptical projection was placed on the surface of a rotating cylinder to produce cavitation. In this case up to 60 decibel increase in noise was noted in a narrow range of velocity.

It is known that cavitation produces a sharp increase of noise at a critical velocity, dimension, or pressure. Also cavitation noise, viewed in an oscilloscope, is characterized at its inception by sharp random spikes. Throughout all measurements of flow noise an effort was maintained to recognize cavitation noise by these inherent properties.

Despite the failure of the investigation to show a definite effect of free air bubbles on flow noise other than as a secondary attenuation factor (which must be carefully accounted for in any measurement of flow noise in water), basic measurements of flow noise spectrum levels in water have been made. This type of measurement is essential to further studies of flow noise reduction. These studies have served as a basis for a concurrent study of the effect of non-Newtonian additive on radiated flow noise.

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FIGURES

(1 through 5)

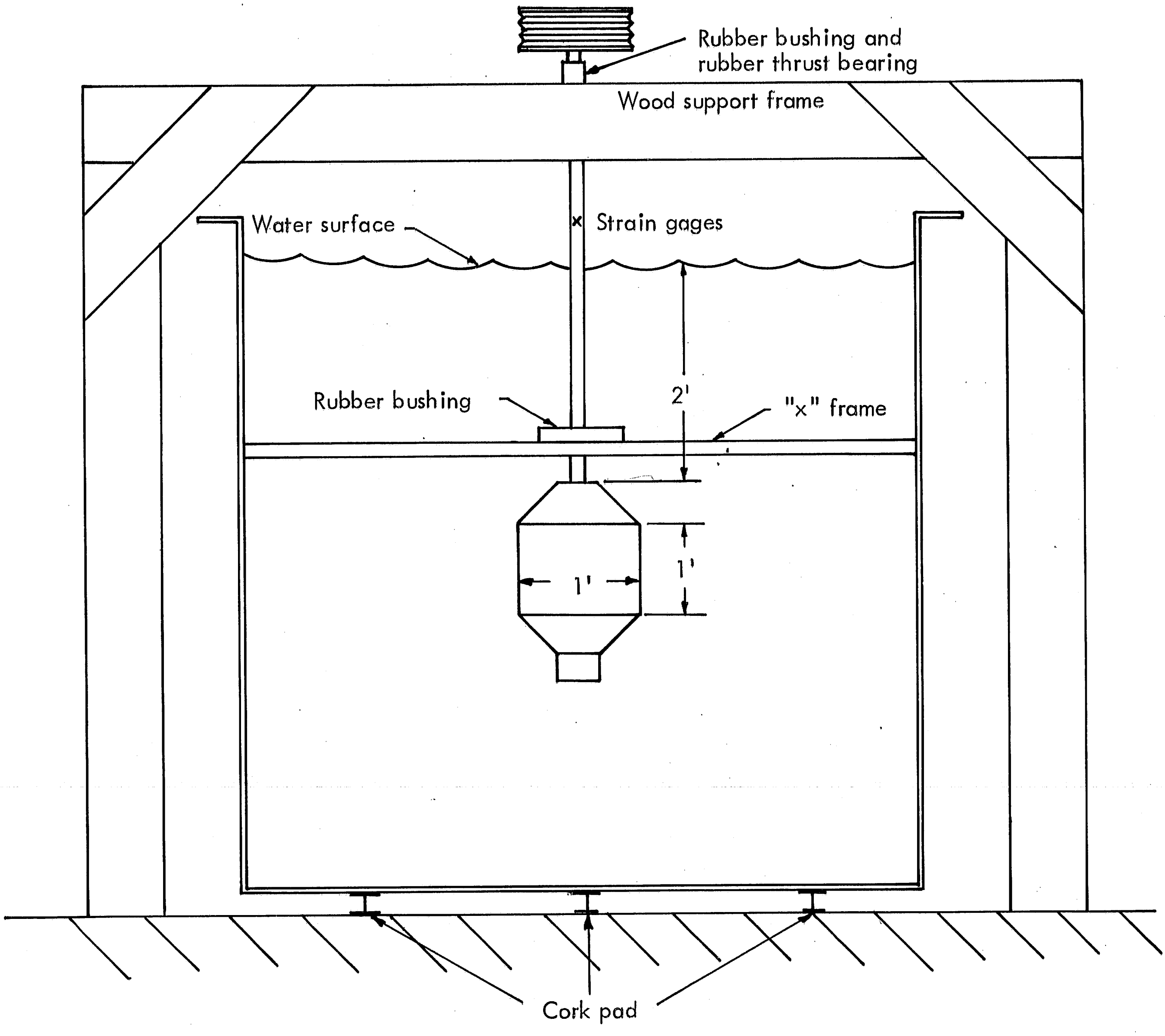

Fig. 1 - Sketch of Test Tank with Rotating Cylinder in Place

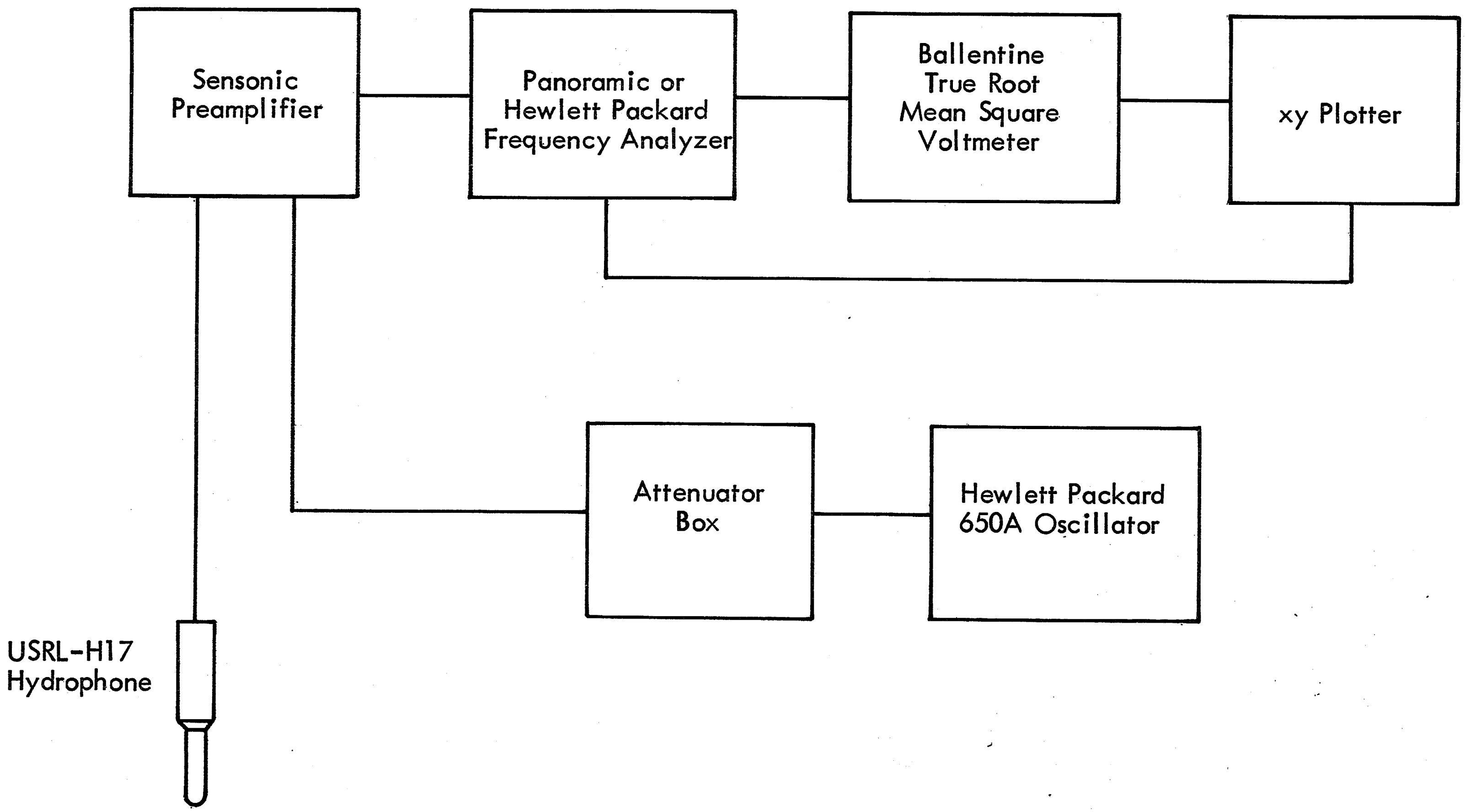

Fig. 2 - Block Diagram of Electronic Measuring Equipment

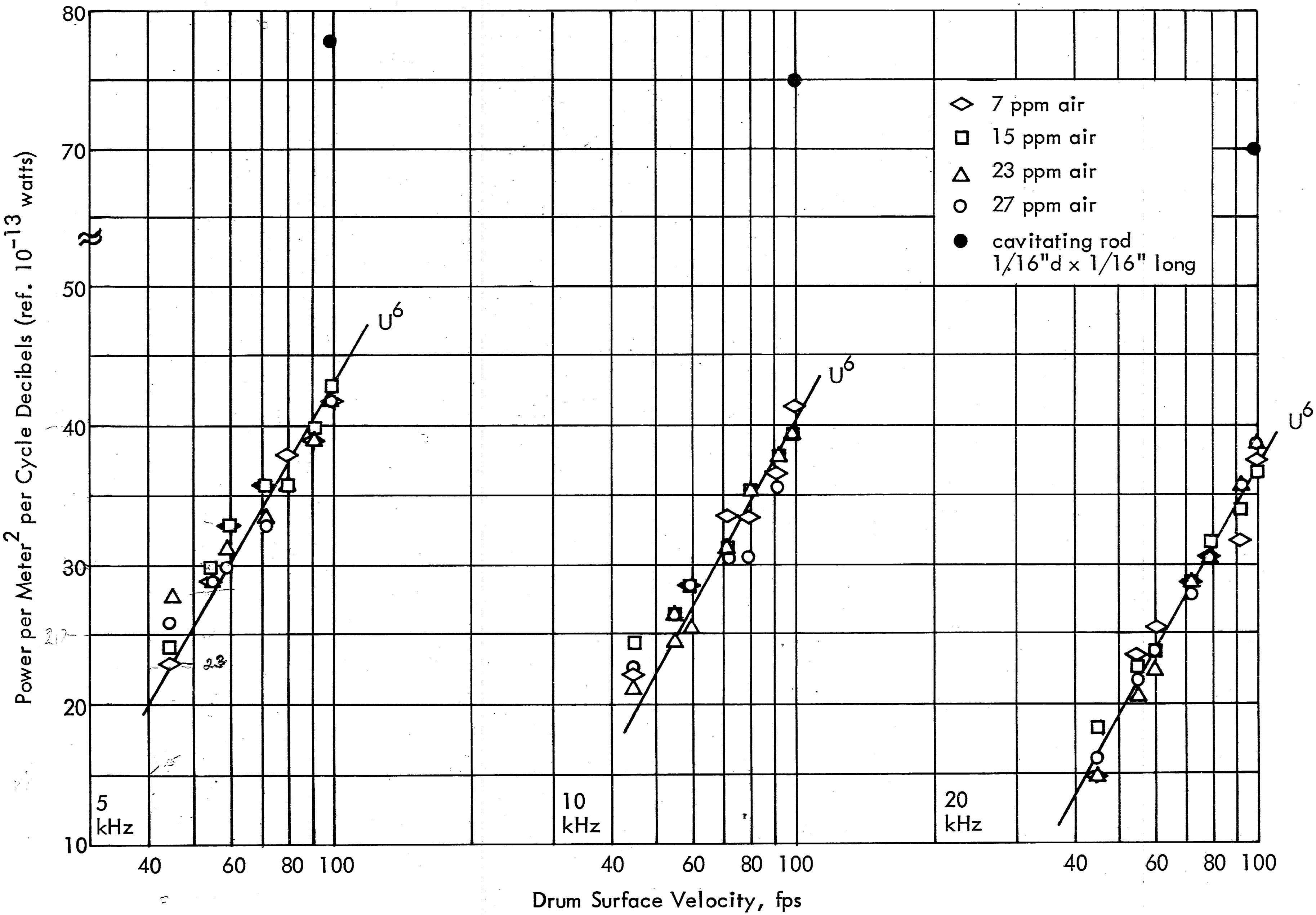

Fig. 3 - Flow Noise Power Measurements - 5 kiloHertz to 20 kiloHertz

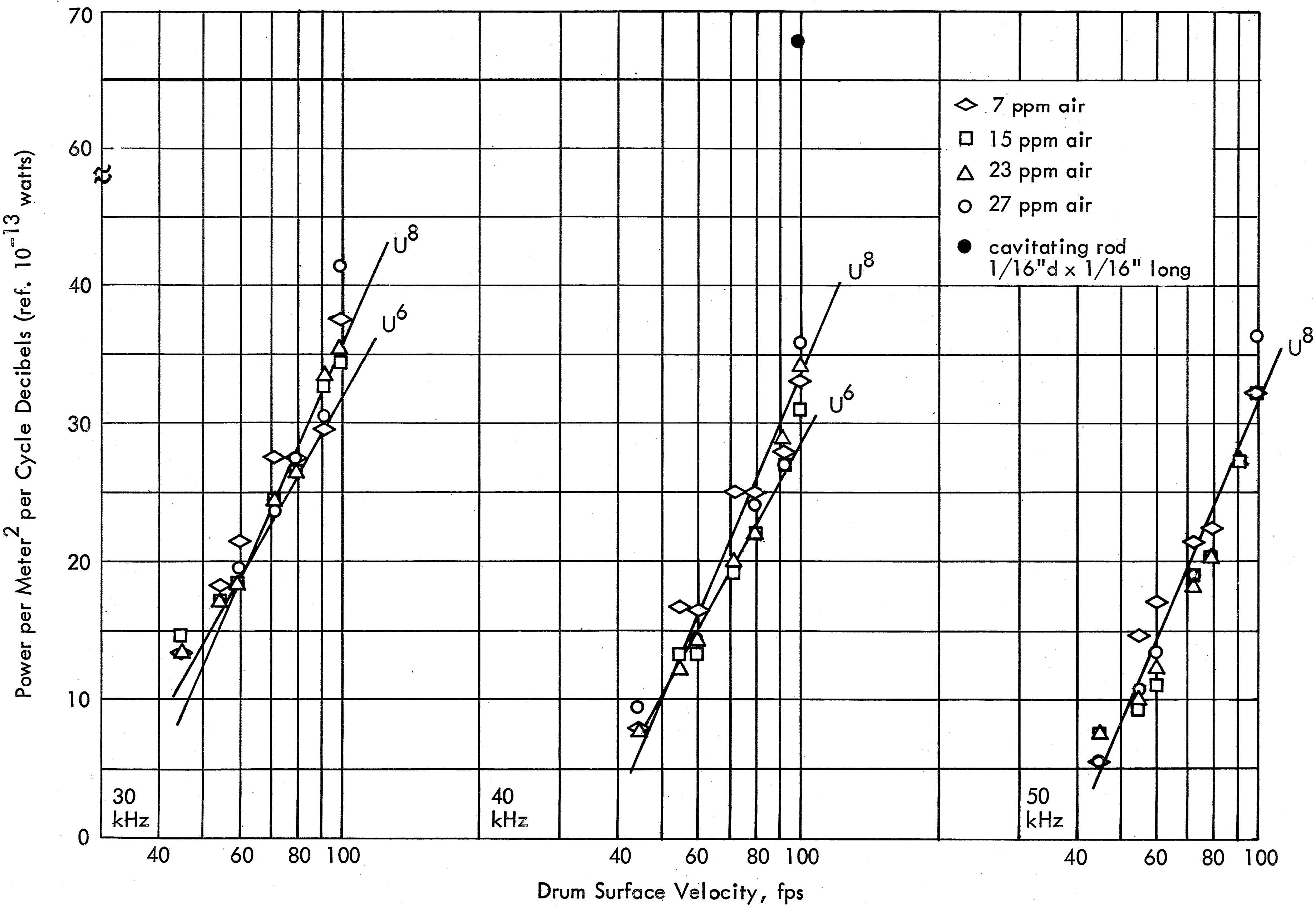

Fig. 4 - Flow Noise Measurements - 30 kiloHertz to 50 kiloHertz

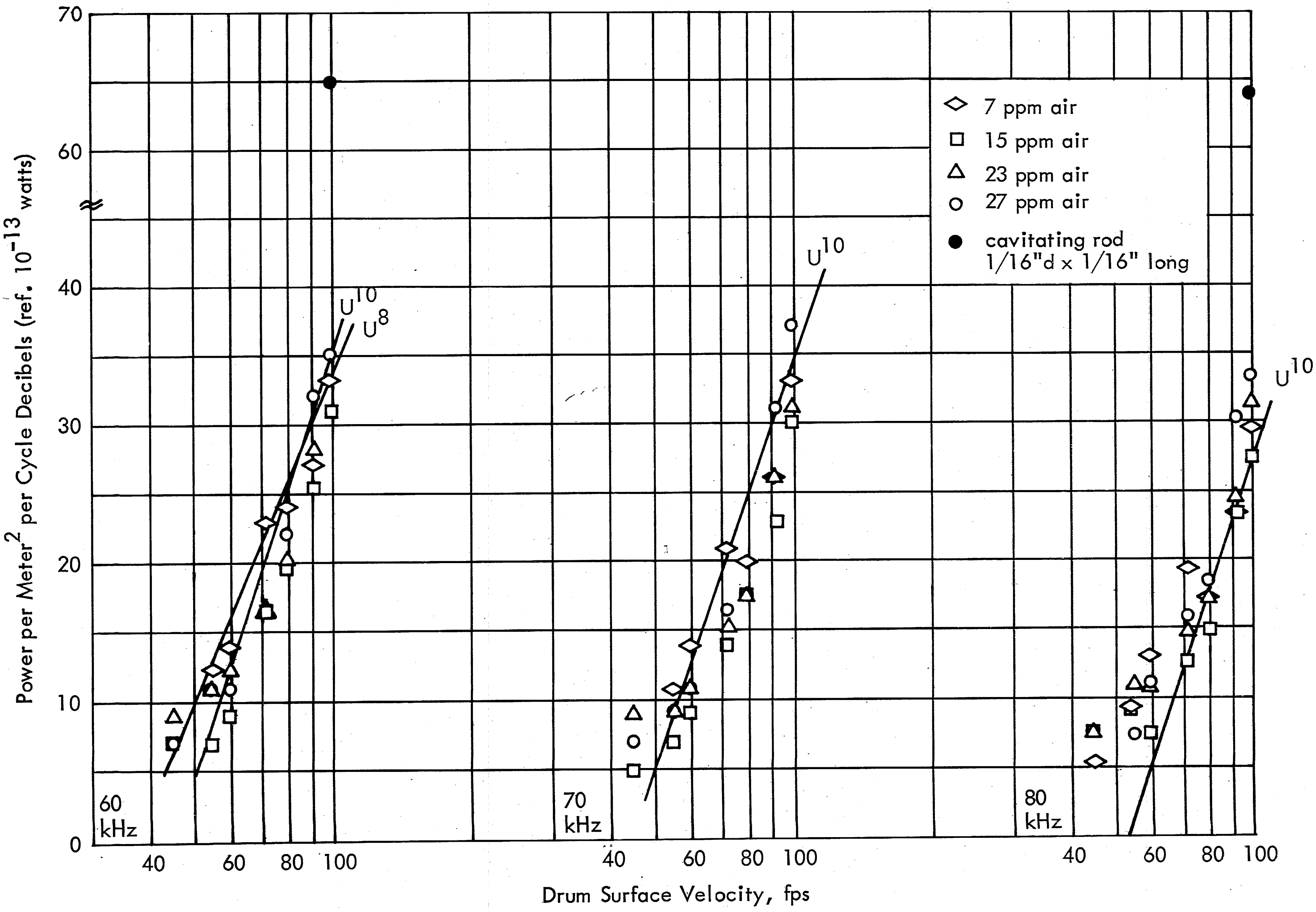

Fig. 5 - Flow Noise Measurements - 60 kiloHertz to 80 kiloHertz

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D (Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) St. Anthony Falls Hydraulic Laboratory, University of Minnesota	2a. REPORT SECURITY CLASSIFICATION Unclassified	
	2b. GROUP	
3. REPORT TITLE A STUDY OF THE INFLUENCE OF MICROBUBBLES ON HYDRODYNAMIC FLOW NOISE		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report		
5. AUTHOR(S) (Last name, first name, initial) Killen, John M. Crist, Scott D.		
6. REPORT DATE April 1966	7a. TOTAL NO. OF PAGES 19	7b. NO. OF REFS 15
8a. CONTRACT OR GRANT NO. Nonr 710(65) b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Project Report No. 82	
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10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY David Taylor Model Basin	

13. ABSTRACT

A test facility has been constructed for the measurement of flow noise generated by a rotating cylinder in water. Measurements were made of radiated flow noise in water for a frequency range of 5 to 80 kiloHertz. The surface velocities of the cylinder were varied from 44 to 100 fps. The total air content of the water was varied from 7 to 27 ppm. The radiated flow noise was observed to increase as the sixth power of the surface velocity for low frequencies. For high frequencies, the flow noise increased as the tenth power of the velocity. Release of air bubbles by shear had no effect on radiated flow noise other than to reduce the measured level of the noise.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Flow Noise						
Noise from Boundary Layer						
Boundary Layers						
Air Bubbles						
Rotating Cylinder						
Flow Noise Intensity Spectra						

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