AN INVESTIGATION OF CAVITATION NOISE AT THE INVERTED INTAKE OF A LIQUID BASIN

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ABSTRACT

Cavitation noise at the inverted intake of a liquid basin has been investigated, both analytically and experimentally. The analysis is based on the basic theories of hydrodynamically generated sound, implying Lighthill's acoustic analogy [1,2]. Results indicate that the onset of cavitation could be clearly identified from a simple monitoring of sound pressure level, close to the inverted intake. Flow intake mean velocity is shown to play a major role in defining the extent of cavitation zone, and consequently in designating the characteristics of acoustic radiation from the cavitating flow.

INTRODUCTION

The choice of the minimum submergence of an inverted intake of a pump sump is usually a critical decision since it defines the lowest point of pumping station and thus a major part of the civil engineering cost. In general, the submergence of an intake should be large enough to reduce the possible occurence of air entraining vortices, swirling flow and the effects of any surface waves which may arise. There is, therefore, a conflict in that a conservation hydraulic design with a deeply submerged intake costs more than a design in which the minimum submergence is only just adequate.

A limited amount of experimental data is available for the minimum submergence (Smin) [3]. The minimum submergence, usually defined as the submergence when air-entraining vortices form, is found to depend on the intake mean velocity (V_B) (i.e. flow rate (Q) devided by the bellmouthed area) and the bellmouth size (D). The general trend is that S_{min}/D increases as V_B increases and that for a given V_B , S_{min}/D is slightly less for larger intakes than for for smaller intakes. However, although an extensive amount of work has been done on the critical submergence, no attention was paid to the possible local cavitation at bellmouth intakes at relatively high intake mean velocity, even at adequate submergences.

The process of cavitation is the result of formation, transport and eventually collapse of cavities in the liquid. Neumerous literature is available which covers different aspects of this process in hydraulic equipment, [4-8].

However, in areas of flow through an inverted intake of a pump where the local pressure, due to high velocity, decreases to the vapour pressure of the liquid, the fluid becomes filled with bubble streams. These cavities are initially filled with air comming out of solution and then at a later stages of the cavitation process the voids are filled with vaporized liquid. These bubbles are carried in the liquid to areas of higher pressure downstream, where collapse starts to occur. At the pump suction eye no voids may be present. In this case although the liquid flow in the pump is vapour free at the intake to the impeller, the vapour formation in the intake tends to reduce pump efficiency.

In the present work and during the course of study of the effect of intake size and mean velocity on the critical submergence of an inverted intake, a strong correlation was observed between the onset of cavitation and the subsequent developement of the cavitation bubble inside the intake, with noise radiated due to the suction process.

The present work, however, aims at presenting noise level data that could be useful in monitoring the onset of cavitation at pipe intakes and the subsequent growth of the cavitation bubble size.

Two main parameters have been considered in the experimental investigation. These are the submergence of the intake pipe and mass the flow rate. Analysis is also made of cavitation noise , at pipe intakes, based on Lighthill's acoustic analogy and the principal cources of hydrodynamically generated sound.

ANALYSIS

In the present analysis, the hydrodynamic noise produced due to cavitaion at the inverted intake, of the suction pipe of a pump, is considered. The characteristic parameters of the flow are the pipe diameter, D, the average velocity of water flow, U, the cavitation bubble size, d, and the length of flow in which separated air or vapour bubbles are present.

It is anticipated that the flow pattern in the entrance region of the pipe will be very much affected by the inlet edge condition. For example, a properly designed bellmouthed inlet will produce an almost eddy free running full entrance, whereas a sharp-edged inlet would produce a flow with vena-contracta. The flow field in this region is expected to be dominated by large scale eddies whose chracteristic length is of the order of pipe diameter in addition to a broad spectrum of eddy sizes, ranging from this large scale down to the minute, viscosity like small scale, energy dissipating eddies.

If we considered a sharp-edged inlet, the flow pattern would be similar to that illustrated in Figure (1), where a vena contracta is the most probable feature of the flow. The depression produced at the minimum cross-section of the flow in addition to the negative pressure due to suction in the inverted intake will be added together, and cavitation becomes more likely to occur. Under these circumstances all the three principal sources of hydrodynamically generated sound would exist. These according to their efficiency, as a flow propagated audible noise respectively, are [1,9] :

a) A group of monopoles, resulting from the fluctuations of liquid mass injection within the oscillatory boundaries of air and/or vapour bubbles present in the flow .
b) A distribution of dipoles over the internal surface of the intake pipe (solid surface) due to fluctuating momentum exchange between the collapsing bubbles and the solid boundary.
c) A distribution of quadrupoles whose strength depends upon the fluctuating stresses within the fluid itself, away from the solid boundaries and the cavities.

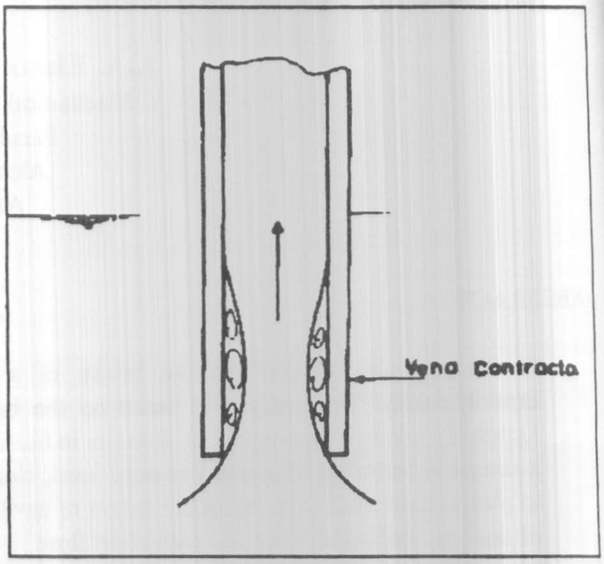


Figure 1. Flow through a sharp-edged intake.

Monopole Acoustic Power Output

Under conditions of fluctuating mass displaced within the source boundaries (the oscillating bubbles), the pressure disturbances induced by the resulting oscillations will propagate audible sound according to the classical wave equation [10]. The sound emitted by such sources (monopoles) has no directional preference and the acoustic power generated from a groups of monopoles is given by

$$W_m \sim \frac{\rho_o}{a_o} U^4 D^2 \qquad (1)$$

Where W_m is the acoustic power (watt), ρ_o is the density of ambient air (kg/m^3), a_o is the speed of sound in ambient air (m/s).

Dipole Acoustic Power Output

Following Curle's theory [11], it can be shown that sound power generated due to the presence of solid boundaries in the flow takes the form:

$$W_d \sim \frac{\rho_o}{a_o^3} U^6 D^2 \qquad (2)$$

Quardupole Acoustic Power Output

Lighthill [1] showed that free turbulence emits sound in proportion to the eighth power of the flow velocity. Based on dimensional analysis he concluded from an elaborate theoretical ground that the acoustic power generated from a turbulent field would take the form :

$$W_q \sim \frac{\rho_o}{a_o^5} U^8 D^2 \tag{3}$$

Acoustic Power Level

The acoustic power level of a noise sources, L_w , is defined as :

$$L_w = 10 \log_{10} \frac{W}{W_o} \quad dB \tag{4}$$

where W is the acoustic power, of the source and W_O is a reference power.

It is almost known that in a cavitation free flow, of the dimensions reported above in this section would mainly accomodate a distribution of quadrupoles. However, at the onset of cavitation, few tiny bubbles are likely to be formed in the flow, giving rise to powerful monopole sources. The sound power emitted would accordingly increase 8.Progressing towards cavitating flow necessiates the domination of the flow region with additional monopoles up to a certain saturation state. The collapse of bubbles at the inner solid surface of the pipe, which is more likely to occur, at bubble saturation condition, would result in some efficient dipole emission.

Applying the definition of sound power level as given by Eqn. (4) and the procedure adapted by Elshorbagy [12], the difference in power levels due to change in flow velocity, keeping all other flow parameters unchanged, are given by :

$$\Delta L_q \sim 80 \log_{10} \; (U_2 / U_1) \;\; dB \tag{5}$$

$$\Delta L_d \sim 60 \log_{10} \; (U_2 / U_1) \;\; dB \tag{6}$$

$$\Delta L_m \sim 40 \log_{10} \; (U_2 / U_1) \;\; dB \tag{7}$$

$$\Delta t_t \sim 180 \log_{10} \; (U_2 / U_1) \;\; dB \tag{8}$$

for the change in power levels due to quadrupole, dipole, monopole and total effects, respectively. The suffices 1 and 2 refer to the conditions before and after the change occurs, respectively.

Equations (5) to (8) can be used as a monitor to deduce the difference in sound power level accompanying a change in mass flow rate in an intake pipe of a given diameter, when any of the three sources or all of them are present, respectively.

EXPERIMENTAL WORK

Apparatus and Instrumentation :

The equipment used for the tests is shown in Figure (2-a) representing the general layout of the apparatus and defining the various features to which reference is made. The apparatus is illustrated in Figure(2-b).

The sump comprised a transparant plexiglass tank of internal diameter 0.87 mt and height of 50 cm. It could be filled with water to within few centimeters of its rim. The water was circulated through the tank, and to exclude any effect of circulation upon the flow, the liquid was admitted through a ring pipe of 2.5 cm diameter. The walls of the ring pipe were perforated by equally spaced small holes 2 mm. diameter distributed along the pipe wall. The pipe was laid in a ring channel, the space between the ring and the edge of the channel was packed with gravel so as to completely damp the kinetic energy of the incoming flow. This arrangement of in-flow distribution resulted in a quite free surface at inlet.

The inverted intake was provided with a pipe to which various sizes of pipes could be fitted, with provision for varying the projection of the pipe into the tank. The dimensions of the pipes used in the tests are 1.0, 1.9, and 2.5 cm in diameter. The inverted intake was also provided with a jet pump (the power fluid used is air) for priming the suction line of the pump.

The water discharge through the intake was measured by means of a calibrated venturie-contraction. The measured values of discharge are estimated to be accurate to within 2.5%.

Measurements of overall sound pressure level (OASPL) were made at 1 m distance from the axis of the vertical inverted intake, using a 451 American-made sound level meter with a built-in 1/2-inch ceramic microphone. The meter provides a direct reading of sound level over the

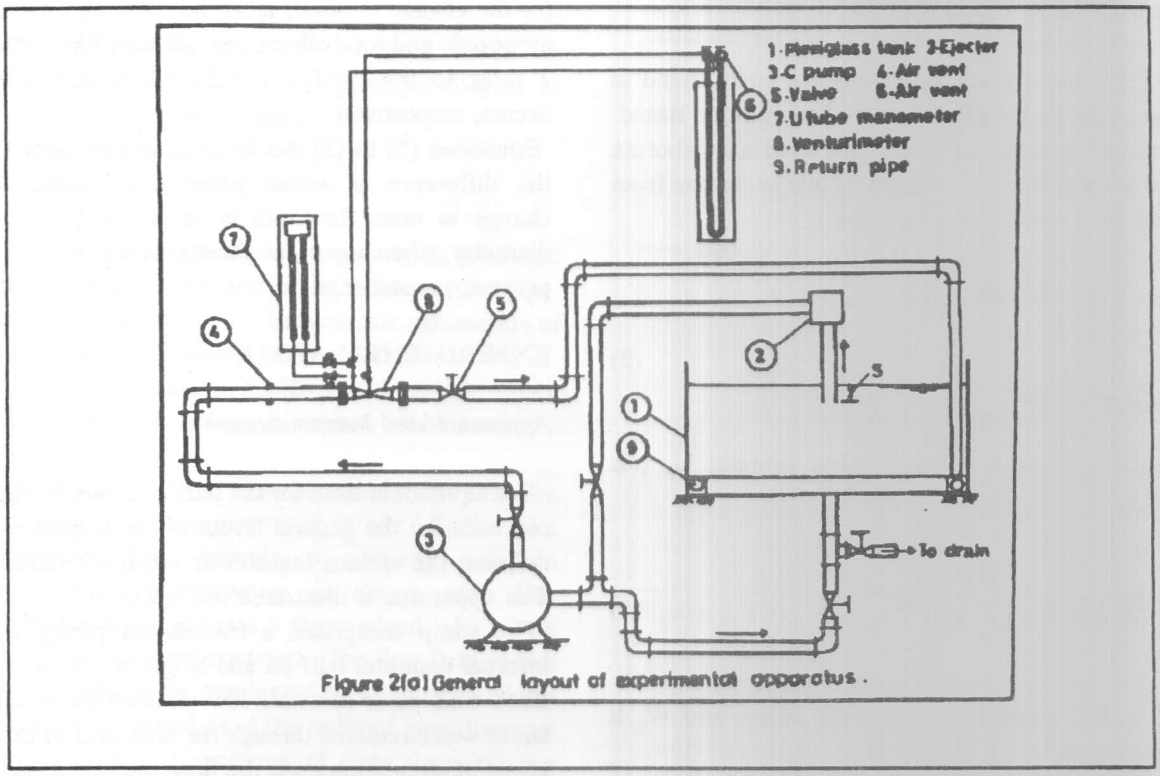


Figure 2a. General layout of the experimental apparatus.

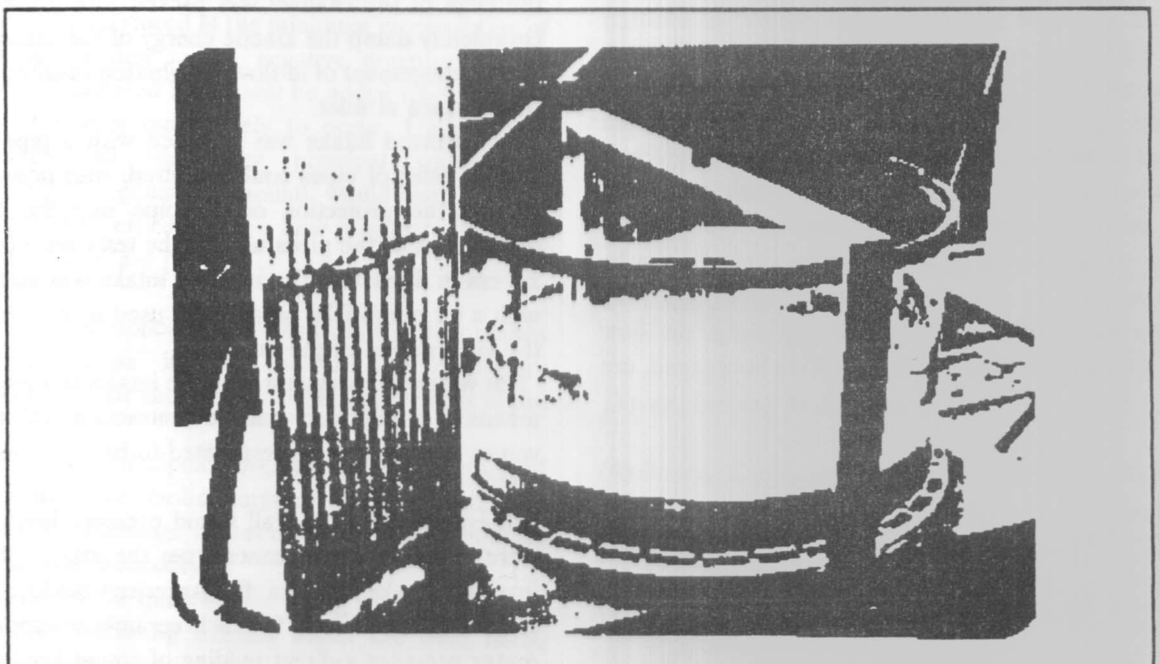


Figure 2b. A general view of the experimental apparatus.

range 45-130 dB(A) with a reference pressure of 0.00002 N/m^2 . A preliminary survey of sound levels was first carried out (at constant intake discharge) in a horizontal plane along the circumference of a circle of 1 m radius. The circle center was the intersection of the intake pipe axis with water surface in the tank. From this survey the acoustically best angular position of the sound level meter was procured. Precautions were taken to minimize the effects of extraneous noise and reflection from nearby objects. The background noise was also checked and found to be negligibly contributing to the recorded levels. OASPL measurements are believed to be accurate to within $\pm$ 0.5 dB.

Procedure for taking observations :

Before carrying out cavitation noise measurements and visual observation, the following procedure were adopted for determining the critical submergence for a given inverted intake and discharge.

The liquid was carefully filled into the tank and the associated pipe system using the jet pump. The centrifugal pump was started and the discharge gradually adjusted to the desired value (the inflow was measured by means of a calibrated venturimeter). Each run was started with a large depth of submergence, which was then reduced by draining some of the liquid, with the discharge remaining the same. The liquid surface was allowed to drop very gradually, until the air entrainment started. The pump was then stopped and the delivery valve was closed. Upon attainment of steady conditions the submergence was measured. The corresponding submergence was designated as the critical submergence. The entire range of mass flow rates was similarly investigated for each pipe.

Having obtained the values of critical submergence with different intake pipes and different mass flow rates, submergence values of much higher magnitudes were assigned for cavitation noise experiments

At a given intake static submergence the water discharge through the intake was gradually increased. At steady state conditions, the discharge was measured, OASPL was recorded and a series of still photographs were taken for the flow through the submerged tube. This procedure was repeated for ascending values of water flow rate, using inverted intake pipes of a nominal diameter 1 cm with a grounded, flat tip.

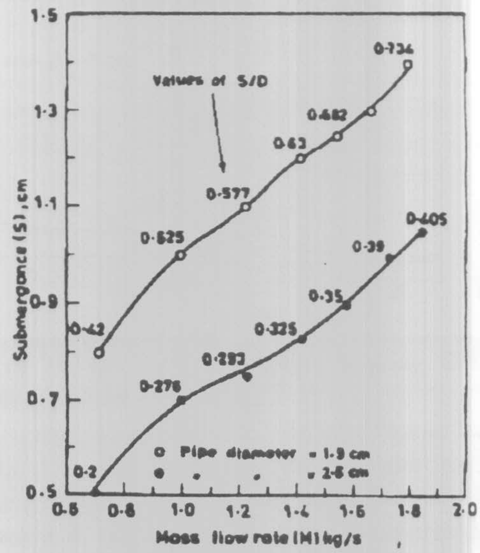


Figure 3. Variation of critical submergence with mass flow rate for two pipe diameters.

RESULTS AND DISCUSSIONS

Critical .Submergence

Figure (3) demonstrates experimental results showing the variation of critical submergence ,S, with mass flow rate, M, for the 2.5 and 1.9 cm pipe diameters. The results are based on visual observation of air bubble entrainment in the pipe intake. It is normal to notice that the critical submergence increases with increasing the discharge in the whole range of flow rates. Higher flow rates usually mean higher velocities, and thus lower pressures are likely to exist. In order to compensate for the resulting lower pressures, the static submergence should be increased.

It is also normal to have results showing higher values of the critical submergence for the smaller pipe of 1.9 cm diameter . At a given fixed discharge, with a smaller pipe diameter the flow velocity will be increased and consequently the resulting pressure willl be reduced. Again a larger submergence would be needed for pressure compensation, in order to avoid separation of air bubbles or cavitation. It is however, of interest to note that relative values of critical submergence , S/D, for the smaller diameter pipe are about twice the corresponding values for the 2.5 cm (larger) pipe.

The values of S/D for the small size pipe ranges between 0.2 to 0.405 whereas the corresponding range for the large

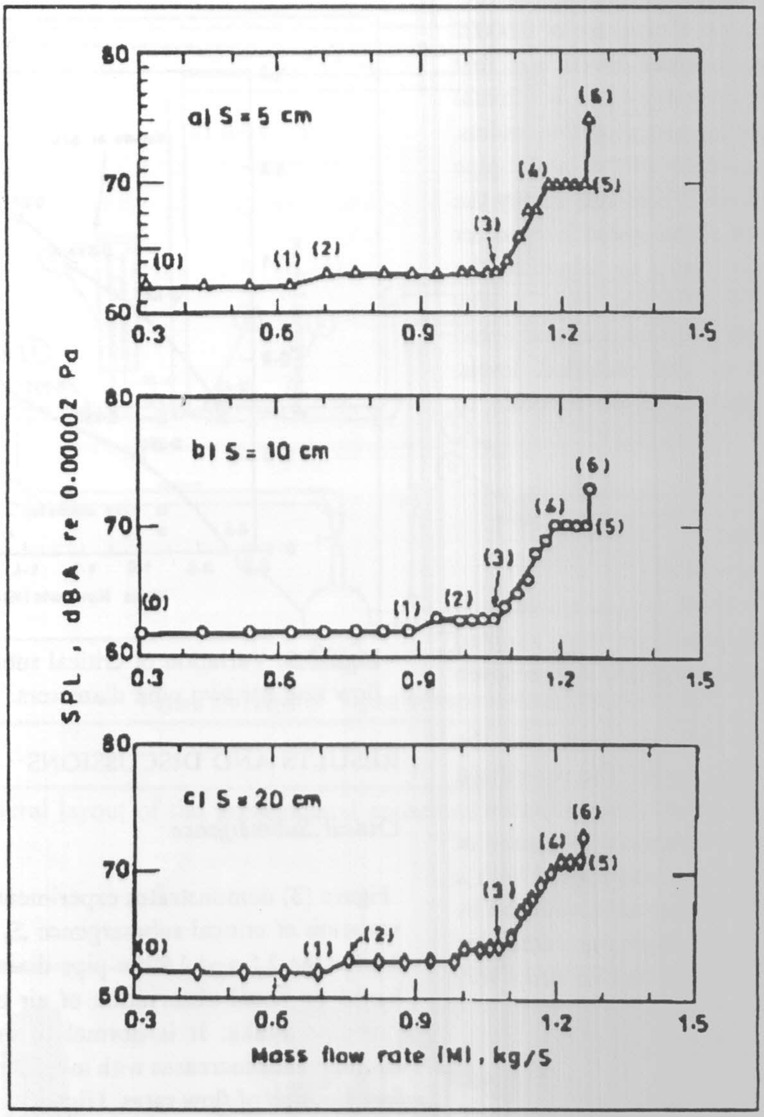


Figure 4. Variation of SPL with mass flow rate (Flat tip glass intake pipe, D = 1 cm).

pipe is 0.42 to 0.734. This would point out that in critical situations attention should be paid to the ratio S/D, especially with relatively small diameter tubes.

Cavitation Noise

Figures (4-a)-(4-c) show samples of the results of the variation of sound pressure level with mass flow rate through the intake pipe at three different values of static submergence, S, of 5, 10 and 20 cm, respectively. Knowing that the intake pipe diameter, D, for these results is 1.0 cm, it is clear that the ratio S/D for present investigations is much higher than the above reported corresponding values of critical submergence.

At any given value of static submergence,S, the variation of sound pressure level (SPL) with mass flow rate is characterized by six regions of variation, which can be recognized clearly in the figures. These regions are, respectively :

(0)- (1) first constant low level region.
(1)- (2) slightly increasing level region.
(2)- (3) second constant low level region
(3)- (4) region of, progressively, linear increasing level.
(4)- (5) constant high level region.

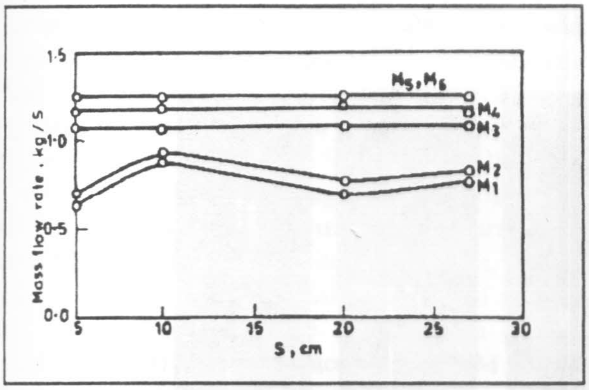


Figure 5. Limiting mass flow rates versus submergence.

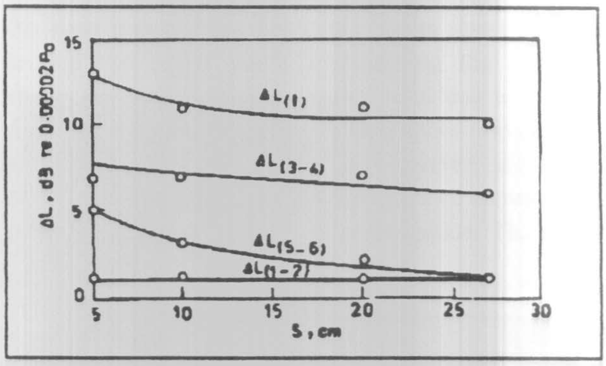


Figure 6. Variation of regions limiting SPL with submergence.

(5)- (6) Abrupt jump of noise level region.

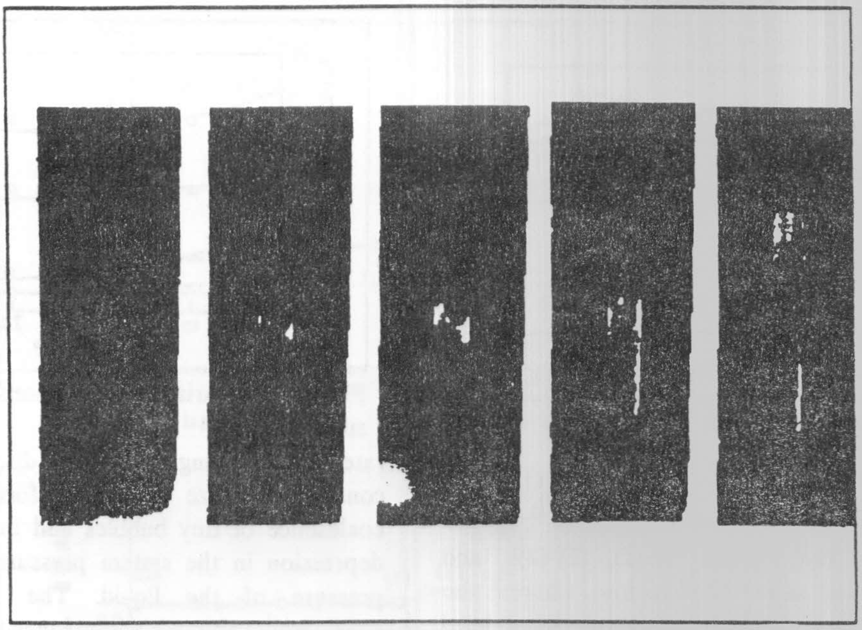
From the Figures, the regions (0)-(1), (1)-(2) and (2)-(3) can be assigned as low level regions, whereas the other last three regions could be assigned higher level regions.

It is, however, noticed that the extent of the first three regions, along the mass flow rate domain, differs according to the value of submergence, S. The extent of each of the last three regions (higher level regions), is seen to be independent of S. On the contrary, the limits of sound pressure levels bounding the first three (low level) regions are seen to be the same (independent of S); whereas those limits differ with S for the higher level regions. This behaviour is seen much evident from Figures (5-6). In Figure (5), the mass flow rate terminating each one of the above mentioned regions is plotted against the experimental static submergences. However, in Figure (6) the difference between limiting sound pressure levels, for regions (1)-(2), (3)-(4), (5)-(6) and the total level rise ΔL_t is plotted against S. The value of ΔL_t represents the overall rise in SPL between points (0)-(6).

The characteristic variation of SPL with mass flow rate, as it appears in Figures 4(a),(b) and (c) and described above, is thought of as being a flow and cavitation derived characteristics. It is believed that turbulent flow noise dominates in the region (0)-(1), where quadrupole sources resulting from turbulence are usually generated. In the region (1)-(2) it is believed that very small nucleate (non-observable) bubbles are liberated from the liquid due to the fall in system pressure, resulting from the increase in the stream velocity. The tiny bubbles produced give rise to possible monopole-like radiation. A saturation with such bubbles occurs at the limit (2), and subsequently no more rise in SPL occurs in the region (2)-(3). At the mass flow rate corresponding to point (3), discrete vapour bubbles of considerable size would be formed due to possible coalesence of tiny bubbles and more naturaly due to a depression in the system pressure, to approach vapour pressure of the liquid. The presence of discrete considerable size bubbles enhance the monopole radiation and SPL would start to rise. An increase in the mass flow rate, after that corresponding to point (3), means more formation of vapour bubbles and thus higher SPL would occur as in the region (3)-(4).

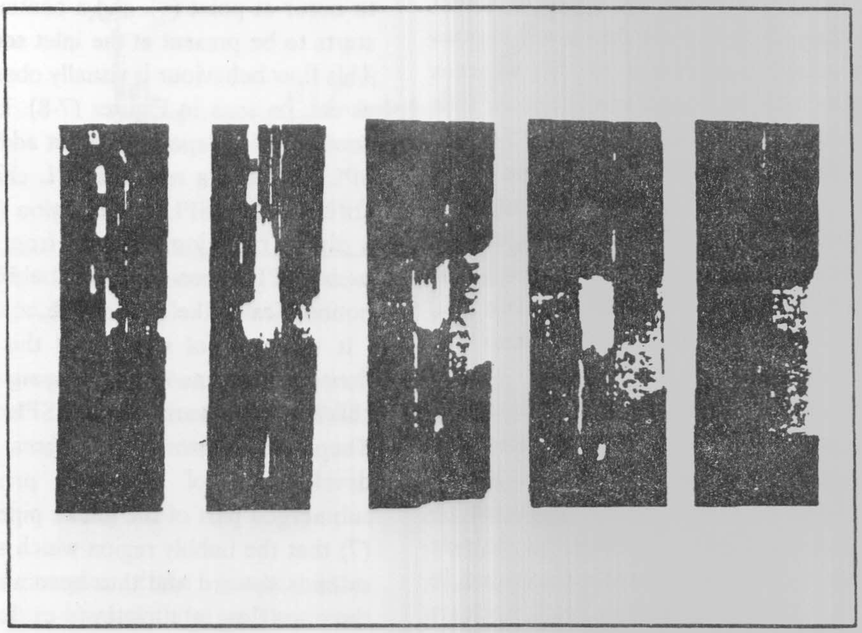
A saturation of the discrete bubble formation is believed to occur at point (4), and a continuum of vapour volume starts to be present at the inlet section of the intake pipe. This flow behaviour is visually observed and photographed as can be seen in Figures (7-8). In the region (4)-(5) the continuum of vapour does not add to the reached value of SPL and thus a constant SPL characteristic prevail. The abrupt rise in SPL in the region (5)-(6) is most probably a dipole radiation resulting from fluctuating momentum exchange between collapsing bubbles and the internal solid boundaries of the intake pipe.

It would be of interest, at this stage to recognize the flow phenomena accompanying the above elaborated characteristic variation of SPL with mass flow rate. Theplates shown in Figures (7-8) represent the development of cavitation produced bubble in the submerged part of the intake pipe. It is clear from Figure (7) that the bubbly region which starts at the inlet section extends upward and thus becomes longer with increasing the mass flow rate; plates (a-e). It can also be noticed that the recorded SPL exhibits an almost constant value with negligibly small increases of 0.5 and 1 dB in plates (b-c), respectively. It was also observed that the initiation of bubbly region and its progress as from plates (a-e) in Figure (7) occurs in the high constant SPL region; region (4)-(5) as shown in Figure (4).



	(a)	(b)	(c)	(d)
M, Kg/S	1.15	1.18	1.23	1.24
SPL, dB	69	69.5	70.0	69.0

Figure 7. Photographs of cavitation bubble in the submerged part of inverted intake pipe.



	(e)	(f)	(g)	(h)
M, Kg/S	1.25	1.26	1.26	1.26
SPL, dB	69.0	70.0	73.0	78.0

Figure 8. Extension of cavitation bubble above the reservoir water surface in the inverted intake.

The progress, in Figure (8), of the bubbly region, which extends above the submerged portion of the intake pipe, occurs at a constant mass flow rate of about 1.259 Kg/s. The sound levels associated with different photographs in this plate are observed to be produced in the region (5)-(6) of Figure (4-a). Although records of SPL were taken in this region, yet the certainity of accurate values there is questionable due to some instabilities, recorded and observed at the limiting maximum reached mass flow rate. According to the above interpretation one may consider point (1) on the characteristic SPL-M variation as beeing a criterion for the onset of cavitation, or simply the first sign for probable cavitation. The next limiting points for different regions of the variation designate progressive states of cavitation. The region (4)-(5) represents a development towards fully cavitating intake.

Finally in Figure (9), prediction is made of the sound power level changes according to equations (5-8). The level changes due to monopole, dipole and quadrupole effects are lablled ΔL_m, ΔL_d and ΔL_q, respectively. The total power change is designated ΔL_τ. Data points from experimental records are also included. It should however be noted that, based on experimental findings, the same value of 0.2 has been assigned as a constant to convert the approximation signs of equations (5-8) into equality signs. It should also be noticed that, on determining the experimental change in power level, the measured changes in sound pressure levels were directly substituted. This proved correct in the present situation since :

$$L_w = L_p + 10 \log A \tag{9}$$

in which L_w is the sound power level, L_p the corresponding sound pressure level and A is the area of a sphere whose radius is equal to the distance between the source and the microphone. The measurements, however, were all conducted at a constant spacing from the intake pipe (noise source) so that the difference due to surface area will be cancelled, leaving:

$$\Delta L_w = \Delta L_p \tag{10}$$

On determining the experimental changes in SPL due to flow velocity variation, the velocity corresponding to that at points (2), as base points, in Figures (4a-4c) is considered as initial velocity (U_1), and that corresponding to points (3),(4),(5), and (6) as final velocity (U_2).

Now, on considering the comparison made in Figure (9), the data points from the experiments appear to scatter around the upper curve representing the sum of the changes occuring in noise power level due to monopole, dipole and quadrupole effects. It is quite evident that the scatter of data is widely diversed. However, one would not expect a better prediction or even a more converging data points at the present stage of investigation. The fact that all data points are bounding the total change in power level line (ΔL_τ), which comprises changes due to quadrupole, dipole and monopole radiation, gives a substantial support to the present theory of cavitation noise.

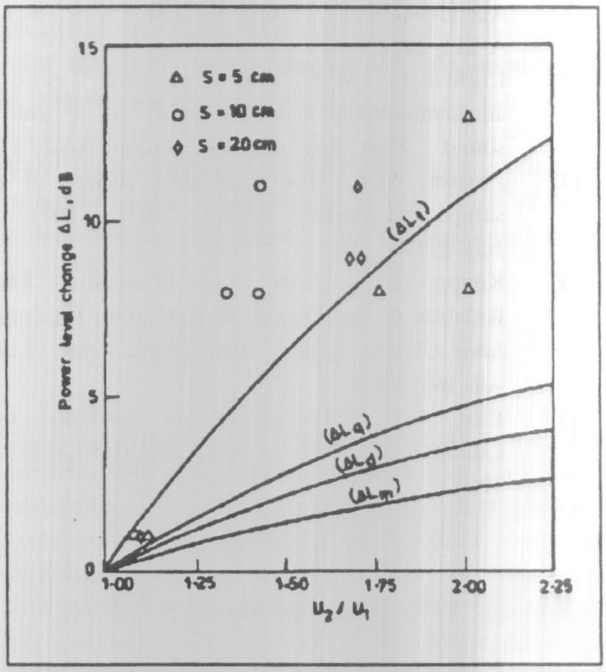


Figure 9. Power level dependence of flow velocity in the inverted intake.

CONCLUSIONS

1. Prediction of changes in sound power level due to cavitation noise at inverted pipe intakes are made on the basis of Lighthill's accoustic analogy and the principal sources of hydrodynamically generated sound.
2. Cavitation noise emitted from inverted pipe intakes could be used as a log for the recognition of the onset of cavitation as well as its subsequent stages.

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