Fluid-flow studies in water tunnels

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Water as a medium has certain specific advantages in fluid-flow diagnostics and, as a result, water tunnels are becoming more popular as research tools in a variety of fluid dynamics investigations. In particular, they are highly suitable for laser-based fluid-flow diagnostics, including flow visualization. They are also extensively used for scale-model investigations of devices like marine propellers and hydraulic turbines, the phenomenon of cavitation being one of the important aspects of these studies.

PROBLEMS of fluid motion arise in many branches of engineering and science. Fluid dynamics is mainly concerned with relative motion between a fluid and a solid boundary. All real fluid motions are influenced by the viscosity of the fluid, however small its magnitude may be. In certain situations, the influence is limited to a very small region near the solid surface and this region is commonly termed a boundary layer. In other cases, as in flow separation past a bluff body, more global effects result. In addition, most flows of interest in practical situations are turbulent and their features are not fully understood. As a result, it is not possible to predict the characteristics of real fluid flow fully solely on the basis of theory. Therefore theoretical work needs to be supplemented by experiments. It is both convenient and economical to conduct the experiments in a suitable device which can simulate adequately the flow of a fluid past a boundary.

The water tunnel

A device for producing a moving airstream for experimental purposes is known as a wind tunnel. An analogue of this, where water is the working medium, is a water tunnel. The use of a wind tunnel for development of prototype aircraft through extensive model testing is well-established practice. Similarly, prototype marine propellers used for ship propulsion and water turbines used in hydroelectric power stations are developed after model testing in water tunnel facilities. From cost and practical considerations it is seldom possible to simulate the conditions of environment exactly in a wind or water tunnel. This discrepancy can result in scale effects, which, if not fully understood, can be responsible for wrong extrapolations of model test results. The scaling laws required for correct extrapolation must also be derived on the basis of theory or experiments in a suitable facility. Therefore, in fluid dynamics research, wind and water tunnels can play a multipurpose role. They are being used for model testing, derivation of scaling laws to extrapolate model test results to prototype conditions, conducting experiments to verify theories, and carrying out fundamental research to understand the basic nature of fluid flow. Even though wind tunnels have been used more extensively for these purposes, water tunnels are now becoming more popular.

Flow-visualization studies have played a central role in the development of fluid dynamics as a scientific subject. It was Prandtl, considered to be the father of modern fluid dynamics, who realized that water is a better medium than air for such studies. With the help of towed models in a water channel he was able to beautifully demonstrate certain subtle features of viscous flow like flow separation and formation of vortical flows. These photographs have now become classic and are included in many textbooks on fluid dynamics. Further impetus to flow visualization using water as a medium was received with the development of the hydrogen bubble technique[1]. This technique has been used, for example, by Offen and Kline[2] to observe certain detailed structure of a turbulent boundary layer near the wall. With the advent of lasers and computer-aided image processing, new techniques are being evolved for fluid-flow diagnostics. It is now possible to measure fluid velocities in a plane, at the same instant, using laser speckle photography[3]. Fluid-flow diagnostics using lasers may be roughly divided into two categories: those that make use of light scattered by tiny particles in the fluid and those that make use of variations of refractive index. Again, water is a better-suited medium since it is simpler to seed particles in water (in many cases no seeding is required) than in air on a continuous basis, and the refractive index of water is a much more sensitive function of temperature (see Table 1). Thus, classical techniques of optical flow

Table 1. Refractive index properties of air and water (20°C and 1 atm).

λ (nm)	$\eta_{air} - 1$	η_{water}	$(d\eta/dT)_{air}$ $[(°C)^{-1}]$	$(d\eta/dT)_{water}$
546.1	2.733×10^{-4}	1.3345	-0.932×10^{-6}	-0.895×10^{-4}
632.8	2.719×10^{-4}	1.3317	-0.927×10^{-6}	-0.880×10^{-4}

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visualization like shadowgraph, schlieren photography and interferometry can be effectively used in water. Therefore, on the whole, it has been argued that water is the preferable medium for certain types of flow-visualization studies. Even though it was indicated earlier that prototype aircraft are developed after wind-tunnel testing, at ONERA in France, there is a water tunnel exclusively built for flow-visualization studies on aircraft models[4]. An excellent collection of flow-visualization photographs is contained in *An Album of Fluid Motion*[5]. Similarly, recent developments in flow visualization are covered in a series of proceedings of international conferences entitled *Flow Visualization*[6].

Another property of liquids which has not been exploited to the extent possible is the fact that they have a well-defined vaporization point in the presence of weak spots, known as nuclei. Commencement of boiling at the saturation temperature corresponding to the system pressure is an example of this. Similarly, in cold liquids (like water at 20°C), vaporization can begin as soon as the static pressure at any point in the flow falls to the vapour pressure corresponding to the bulk system temperature. This process is known as cavitation. Therefore presence of cavitation is a good marker of low-pressure regions in fluid flow. An example of this is given in the photograph of Figure 1, where a tip-vortex cavity is clearly visible. Tip vortices are also generated from the wings of an aircraft during flight.

The type of water tunnel required for research studies depends on the ultimate use: large facilities with high-speed capabilities are exclusively required for studying the phenomenon of cavitation itself and model testing of underwater bodies like projectiles; moderate-sized facilities are used for fluid-flow diagnostics using laser doppler anemometer and for flow-visualization studies. Therefore one can broadly classify water tunnels as those required for cavitation studies and those required for fluid-flow diagnostics including flow visualization; one could call these high-speed water tunnels and low-speed water tunnels. Since a clear-cut distinction between the two is difficult, low-speed tunnels used for certain types of cavitation studies will also be included in the former category.

Design features

The major components of a water tunnel are the same as those of a wind tunnel; however, certain special considerations, like prevention of rusting and leakage at all joints, need closer attention. Most water tunnels are of recirculating type and have the following essential features: (i) a working section in which the model is mounted and can be observed, (ii) a closed water circuit consisting essentially of a high-capacity pump and piping by means of which the flow of water through the working section is maintained, (iii) a control system which enables the water speed to be regulated over a wide range of operating conditions, and (iv) a system of instrumentation for required measurements. A water tunnel for cavitation observations must in addition have a control system enabling the static pressure in the working section to be varied over a wide range. A practical water tunnel circuit is schematically illustrated in Figure 2. Important aspects of each of the elements indicated in the figure are discussed below.

1. Test section: This is the region where the test models or objects are mounted. There are basically two types of test sections, namely closed-jet and open-jet. In some special cases a free surface is required and can be maintained. The size and maximum speed in the test section depend on the type of studies to be conducted. If, for example, a torpedo model is to be used for force measurements, then the minimum size of the model which can be accurately fabricated and the extent of solid blockage which is permitted determine the test-sec-

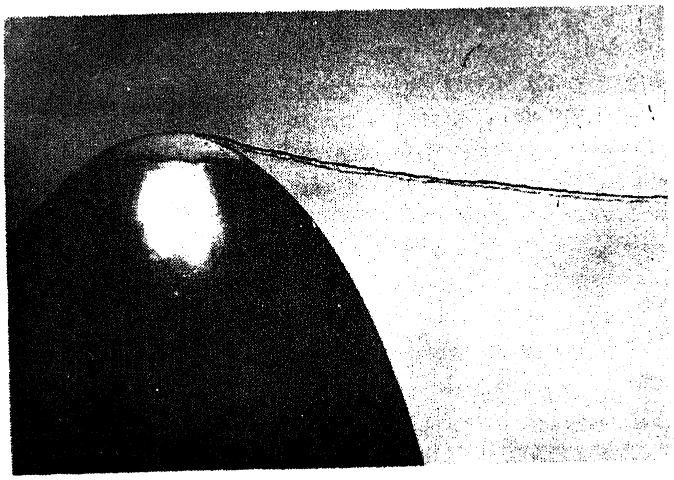

Figure 1. Tip-vortex cavitation from a lifting hydrofoil. [Photograph courtesy of Professor R. E. A. Arndt, Director, St Anthony Falls Hydraulics Laboratory, University of Minnesota, USA.]

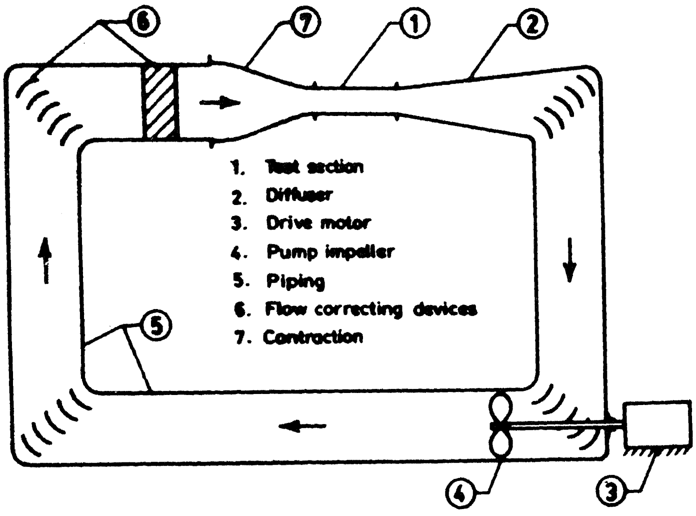

Figure 2. Schematic diagram of a basic water tunnel circuit.

tion size. The solid blockage, which is the per cent area occupied by a model, should not exceed about five per cent. It should be mentioned that test-section parameters like area A_T, maximum velocity U_T, and the operating static pressure P_T are important variables that have bearing on the overall size and other characteristics of the tunnel circuit. Therefore, in many cases, a compromise has to be made between the accuracy of measurements and economy in selection of test-section parameters.

2. Diffuser: The high velocities in the test section cannot be maintained in the rest of the circuit since this will result in high losses. Hence the purpose of the diffuser is to slow down the velocities by increasing the size. This has to be achieved as efficiently as possible and normally the included angle of the diffuser should not exceed 6°. In some cases, this may require continuation of the diffuser section past the first right-angle corner.

3. Drive motor: The power factor of a wind or water tunnel is usually defined as the ratio of the power input to the driving unit to the rate of flow of kinetic energy at the working section. Thus, if P is this power input (which is the drive motor output), the power factor λ is given by

$$\lambda = \frac{P}{\frac{1}{2}\rho_T U_T^3 A_T}$$

where ρ_T is the water density. The factor λ is also

$$\lambda = \frac{\Sigma \text{ losses}}{\eta \frac{1}{2}\rho_T U_T^3 A_T}$$

where η is the efficiency of the pump impeller and Σ losses is the sum of all the losses in the circuit. In computing the latter, it is important to include losses due to the placement of models in the test section. A well-designed circuit normally has a λ value of about 0.33 and can be used for preliminary estimates. For smooth speed variation, a DC motor is to be preferred.

4. Pump impeller: The pump impeller is normally of axial propeller type and has to be designed to provide the necessary flow rate and the head to overcome the losses. In addition, as far as possible, cavitation at the pump impeller should be avoided. For efficient operation over a wide speed range, pitch-controllable blades are sometimes used.

5. Piping: These are normal piping in most cases, made of mild steel. Rust-proofing is by internal application of coal-tar epoxy paint over a suitable zinc-based primer. For small water tunnels it may be feasible to adapt chemical methods through the use of additives in the water sample for corrosion inhibition.

6. Flow correcting devices: These consist of appropriately designed turning vanes at all the ninety-degree bends in the circuit and a honeycomb in the settling section, ahead of the contraction. Use of screens, a commonly found practice in wind tunnels, is not preferred in water medium since it can result in the phenomenon of 'singing'.

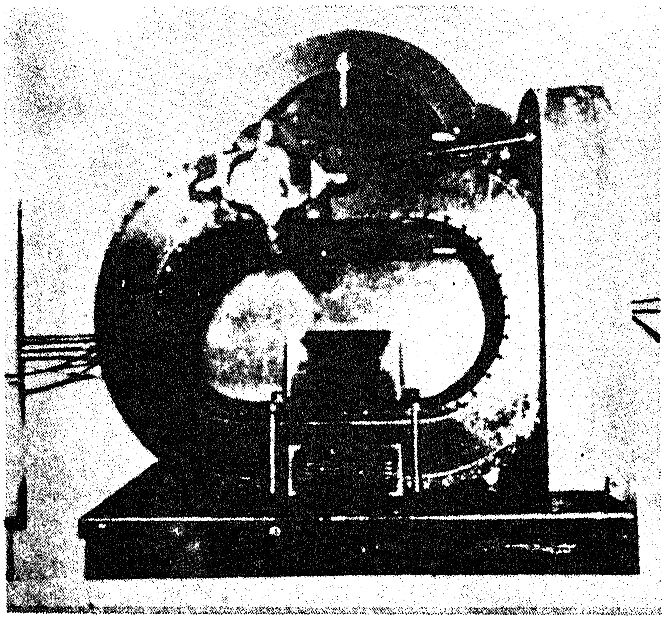

Figure 3. The water tunnel used by Parsons for cavitation studies.

7. Contraction: The purpose of the contraction is to smoothly increase the velocity from a low value existing in the settling section to the high value in the test section. The area ratio across the contraction is known as the contraction ratio and the typically used value is 9. It should be noted that, once the test-section size is chosen, it is the contraction ratio which determines the overall size and thus the cost of a water tunnel.

In addition to the above, it is also important to provide venting ports at key locations to release air during filling and normal operation. At a few points, the vents can be provided on the top of domes attached to the piping. In relatively large facilities it is convenient to provide access ports to the circuit interior.

Special considerations of a high-speed water tunnel

High-speed water tunnels are primarily used for marine propeller design, cavitation performance studies and hydroballistic studies. For cavitation studies maximum speed capability of at least 10 m s^{-1} is required. Design considerations of major high-speed water tunnel facilities in the world are contained in two proceedings of international symposia[7,8]. It was Parsons who first designed and used a water tunnel circuit for cavitation studies, and a photograph of his tunnel is shown in Figure 3. A photograph of a more modern facility, aptly termed 'Le Grand Tunnel Hydrodynamique', recently constructed in France, is shown in Figure 4. With the need for development of quieter and faster underwater vehicles, the more

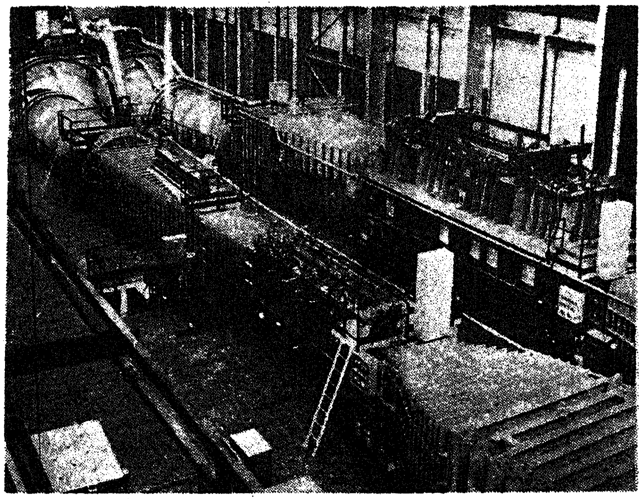

Figure 4. A modern water tunnel facility.

modern facilities contain several auxiliary units to the basic circuit of Figure 2.

The facility existing at the Indian Institute of Science in Bangalore[9] illustrates the typical configuration of a high-speed water tunnel. Its important characteristics are summarized in Table 2. The two distinctive features of the circuit, compared to the basic one shown in Figure 2, are the potential for static pressure control with the help of a dome on the top of the settling section, and the presence of an additional component in the lower leg, termed resorber. The function of the resorber is to dissolve out any air bubbles generated due to cavitation in the test section. Inclusion of a resorber in water tunnel circuits is an innovative idea of Knapp, who put it to practice for the first time in the California Institute of Technology high-speed water tunnel facility[10], which has become a trend-setter in the design of modern facilities.

Special considerations of a low-speed water tunnel

A low-speed water tunnel is primarily used for flow-visualization studies and can be of either horizontal or vertical configuration (a high-speed tunnel has to be of a vertical configuration). The test section of a low-speed tunnel must be equipped with optical-quality glass windows. Special attention must also be devoted to ensure that the water in the circuit is as clear as possible and that extremely low turbulence levels in the test section are achieved. Presence of foam downstream of a honeycomb and a series of screens can be an effective method of achieving these conditions. However, significantly higher losses are to be expected. Another method of achieving very quiet flow conditions is the use of gravity discharge through a large contraction in a vertical configuration[4]. Similar facilities are now being considered for certain types of underwater acoustics studies.

Table 2. Pertinent operating parameters of the Indian Institute of Science high-speed water tunnel.

Parameter	Closed-jet	Open-jet
Test-section size (diameter)	381 mm	460 mm
Contraction ratio	16 : 1	11 : 1
Maximum velocity	30.3 m s^{-1}	20.8 m s^{-1}
Turbulence level	0.2–0.3%	not measured
Maximum test-section pressure (absolute)	2.5 bar (2.5 × 10^{5} Pa)	
Minimum test-section pressure (absolute)	0.33 bar	
Capacity of the drive motor	447.4 kW	

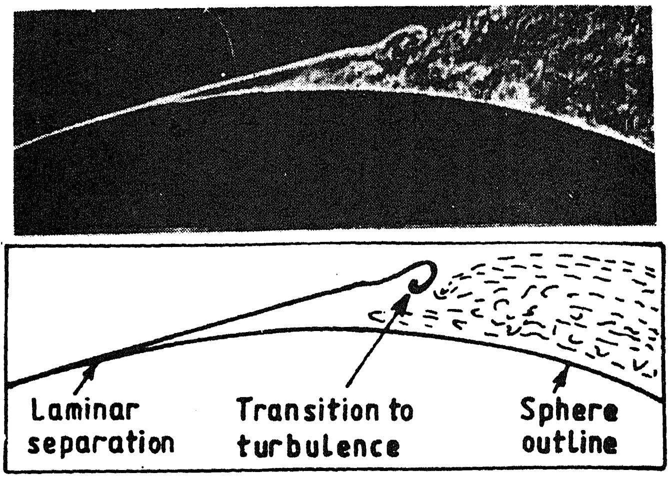

Figure 5. Schlieren photograph illustrating flow past a sphere near the separation zone.

Flow-visualization studies

The index of refraction of water is a sensitive function of temperature, and this fact can be taken advantage of in using optical methods of flow visualization. A schlieren set-up was developed to visualize flow past a sphere near the critical Reynolds number. The necessary density gradients required for flow visualization are generated by heating the sphere to a slightly higher temperature than the ambient. At the critical Reynolds number, the flow past a sphere goes through a substantial alteration in its structure. This was convincingly demonstrated, and certain details, which are otherwise difficult to probe, were made visible. A photograph from the study is shown in Figure 5, along with an explanatory sketch. As indicated, laminar flow separation is followed by transition to turbulence on the free shear layer and subsequent turbulent flow.

The second example of flow-visualization studies is the observation of tip-vortex structure from a delta-wing model aircraft configuration. This was done by injecting a coloured dye. A photograph of the visualized flow is shown in Figure 6. The roll-up process of the vortex from the leading edge of the wing is clearly defined.

Cavitation studies

The IISc high-speed water tunnel has been used extensively for cavitation studies on a series of axisymmetric bodies and model marine propellers. (The photograph on the cover of this issue shows tip-vortex cavitation from a

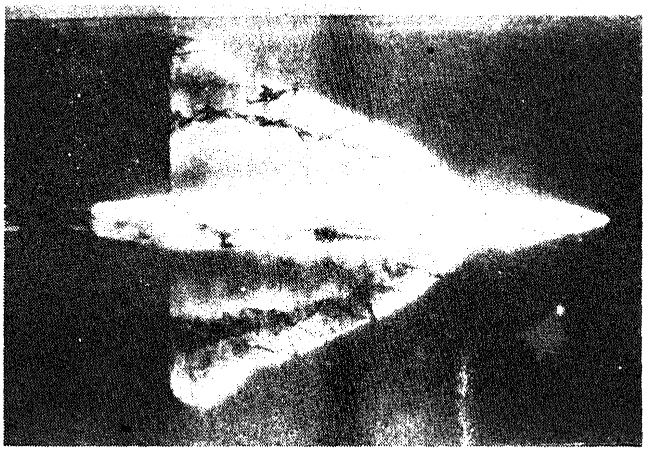

Figure 6. Tip-vortex structure visualized by dye injection from a delta-wing aircraft configuration.

model marine propeller operating in the open-jet test section of the IISc water tunnel.) In addition to characterizing radiated noise from marine propellers, investigations are being carried out to evolve techniques of reducing noise levels.

The studies on axisymmetric bodies have been of fundamental importance in characterizing the mechanism of cavitation inception and noise. In particular a technique has been developed to generate so-called synthetic cavitation by seeding artificial nuclei using electrolysis. The electrode configuration can be varied to generate cavitation at a desired location. Cavitation noise consists of sound radiated due to bubble growth and collapse as they travel in a spatially varying pressure field and is considered to be a monopole source of sound. On an axisymmetric body cavitation sound sources can be all around the body while the sensor is located at a particular orientation with respect to these sources. As a result there could be geometric effects, as shown in Figure 7, which compares the levels measured with cavitation directly facing the transducer and with cavitation where transducer is partly shaded by the body. It is clear that at high frequencies there is a definite geometric effect associated with sound diffraction.

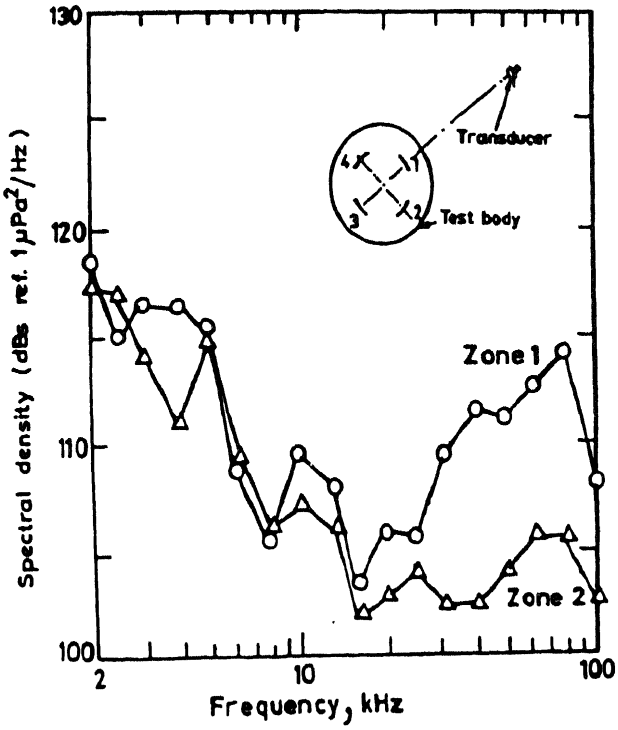

Figure 7. Illustration of geometric effect in radiated cavitation noise measurements. Zone 1 faces the transducer directly whereas Zone 2 is shaded.

Underwater acoustics studies

Sonar, an acronym for sound navigation and ranging, is the heart of communication systems used in underwater applications. Surface-ship to submarine communication is with the help of sonars. Similarly, acoustic homing torpedoes have a sonar placed in the nose region. From both safety and effective-detection points of view, radiated noise levels from a vessel and the 'self noise' levels of a sonar mounted on the vessel must be as low as possible. Major efforts are under way world-wide to achieve this goal. Recently the IISc water tunnel facility has been used to measure self-noise levels in the stagnation region of an axisymmetric vehicle configuration. Such measurements are extremely difficult to carry out and require very low background noise levels of the facility itself. Owing to size limitations of the facility only scale-model studies were possible. However, the necessary scaling methodology was developed to extrapolate model test results to prototype geometry and condi-

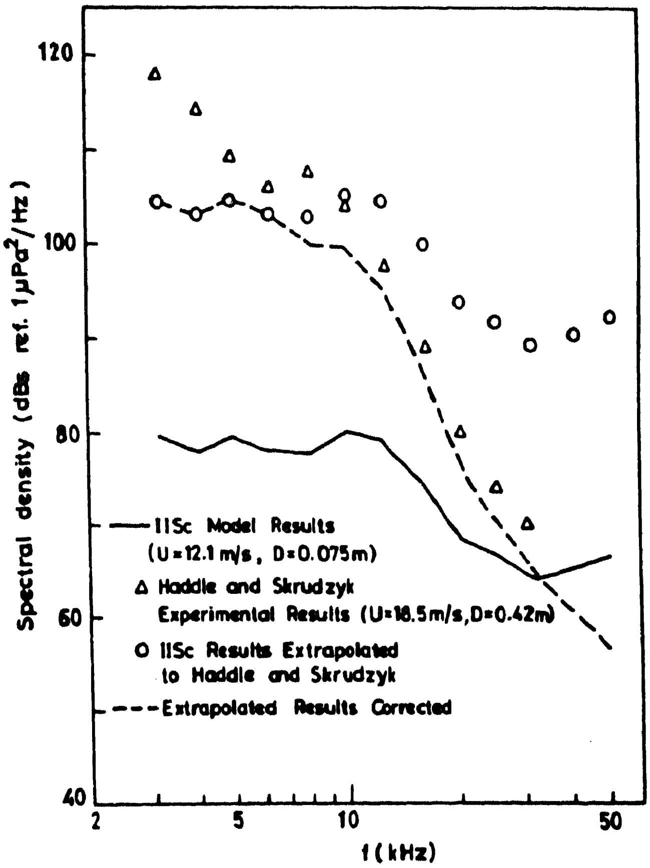

Figure 8. Comparison of extrapolated self-noise levels with those actually measured in prototype environment by Haddle and Skrudzyk[11]. U and D refer to velocity and maximum diameter respectively.

tions. As indicated in Figure 8, the procedure developed was highly successful. The figure compares the extrapolated results from the IISc model measurements with actual measurements from a prototype scale vehicle. At higher frequencies in the range of sonar operation, there is excellent agreement. It is worthwhile pointing out that the prototype measurements shown in the figure were made using a lake facility.

Concluding remarks

A water tunnel is a required facility for certain types of investigations such as observations related to the phenomenon of cavitation. With increasing use of lasers in fluid-flow diagnostics, it is becoming a research tool with wider applications. In particular, detailed probing of flows in air are being supplemented with flow-visualization studies using a water tunnel.

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