The Pennsylvania State University
Applied Research Lab
P. O. Box 30
State College, PA 16804

SENSOR FLOW-INDUCED SELF NOISE REDUCTION

FINAL REPORT

by
G. C. Lauchle
S. Park

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ABSTRACT

Boundary-layer transition and the fully-developed turbulent boundary are important contributors to sensor flow-induced self noise. The wall pressure fluctuations caused by these shear flows can be attenuated by localized fluid injection. Presented here is a vehicle forebody design concept that permits water to be injected into the transition region and adjacent turbulent boundary layer at prescribed volumetric flow rates. The injection flow rate may be tailored by a variable thickness porous shell made from powdered metal, or from a variable distribution of micro-hole perforations. Pressure to cause the injection is provided by the vehicle dynamic head. Up to 10 dB reduction of flow-induced self noise of sensors mounted in this forebody is demonstrated in small water tunnel tests.

ACKNOWLEDGMENT

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I INTRODUCTION

Acoustic sensors that are placed flush to the surface of a vehicle are typically used to measure acoustic energy originating from some distant source, such as in sonar applications. If those sensors are placed under the turbulent boundary layer (TBL) of the vehicle, formed because the vehicle is moving through the medium at some mean speed, U, then the effectiveness of the sensors in hearing the acoustic signals of interest is seriously diminished due to flow-induced sensor self noise. This self noise depends strongly on the speed of the vehicle, on whether the TBL is developing in a zero, favorable, or adverse static pressure gradient, and on the proximity of the sensors relative to the beginning and ends of the TBL. If placed near the end of the TBL, the resulting sensor self noise will have significant additional contributions due to trailing edge noise mechanisms including local flow separation. If the sensors are situated near the beginning of turbulent flow, as in the headforms of axisymmetric bodies, the laminar-to-turbulent transition zone noise mechanisms contribute. The wall pressure fluctuations generated by TBL's, transition zones, separated flows, and edge flows are stochastic fields that have spectral characteristics rich in both frequency and wavenumber content. Wall pressure fluctuations can couple efficiently to the structural modes of the vehicle supporting these flows if the structural modal frequencies and flexural wavenumbers correspond to those of the pressure fluctuations. This adds additional energy to the sensor self noise spectrum, and also to the radiated noise levels of the vehicle as a whole.

There is evidence in the contemporary open literature that local, turbulence-induced wall pressure fluctuations can be attenuated by various forms of boundary layer control. One that has proved quite effective[1,2] is area distributed fluid injection (blowing). The mechanism is quite simple: the blowing causes the TBL to become thicker which shifts the pressure producing motions away from the wall; the wall pressure fluctuations and corresponding correlations are reduced. The wall pressures in the high-frequency ranges of practical interest are thus attenuated.

The objective of the work described in this report is to consider area distributed injection of water into an axisymmetric water boundary layer for the purpose of reducing flow noise sensed by an acoustic transducer located in the laminar flow part of the forebody supporting this flow. The forebody is to be fabricated from porous, or perforated, material to a specification that allows the optimum injection coefficient for noise reduction to be achieved. The pressure required to achieve fluid aspiration is provided by the dynamic head of the moving vehicle. Prototype models are designed and evaluated experimentally in a small, high-speed water tunnel. The tunnel water is heated in some of these experiments in order to raise the model Reynolds number to values in closer alignment with full-scale operation.

II REDUCTION OF FLOW NOISE USING WATER INJECTION

Lyamshev, et al[1] were the first to show that injecting water into a water turbulent boundary layer results in significant reductions of local wall pressure fluctuations. They varied the blowing coefficient, defined as $C_q = v_n/U_\infty$ from 0 to 0.027, where v_n is the normal velocity of the injected fluid and U_∞ is the free-stream velocity. The spectrum levels of the local wall pressure fluctuations measured immediately downstream of a porous injector on a flat plate operating in a water tunnel under zero pressure gradient conditions continually decreased as C_q was increased. The magnitude of the space-time correlation functions of the wall pressure fluctuations showed analogous reductions with increasing fluid injection rate. Figure 1 is reproduced from Reference 1 to show that the level reduction is 20 (or more) dB for $C_q = 0.027$.

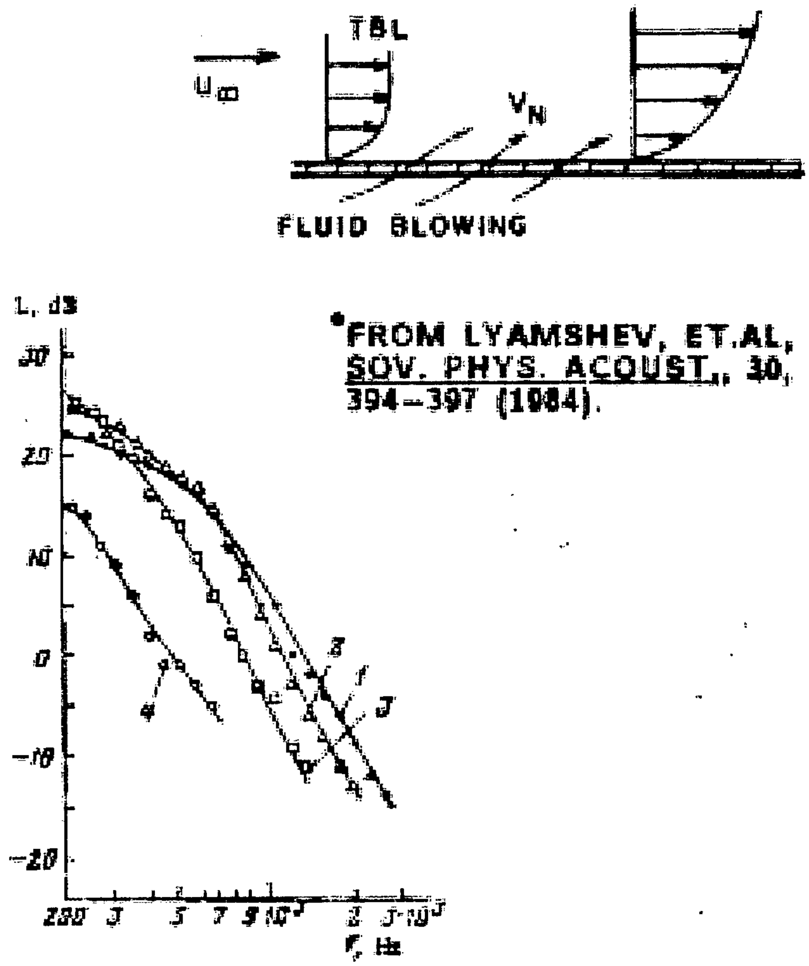

FIG. 1. Influence of liquid injection through a band of porous material on the spectrum of wall pressure fluctuations, $U_\infty = 3$ m/s. 1) $v_n/U_\infty = 0$; 2) 0.0055; 3) 0.0108; 4) 0.027.

Figure 1 The effect of fluid blowing on TBL wall pressure fluctuations (reproduced from Lyamshev, et al[1]).

The wall pressure fluctuation reductions shown in Figure 1 take place despite the increase in TBL thickness, and the increase in boundary layer turbulence intensities in the core region of the TBL during injection. The principal causes of the observed reductions appear to be the detachment of turbulence from the wall and the formation of a near-wall layer of reduced velocity fluctuation. These have lower correlation with the turbulent velocities in the main core region of the TBL.[1]

Shortly after the publication of the Soviet data, Schloemer and Payne[2] conducted their own experiments in order to verify the reported findings. The mean flow and boundary layer characteristics in the Naval Underwater Systems Center Acoustic Water Tunnel matched quite well those of the water tunnel used by Lyamshev, et al.[1] The TBL wall pressure level reductions were also repeated, as indicated in Figure 2. They found that if $C_q > 0.027$, the flow noise reduction is destroyed. The persistence of the reductions (for $C_q \leq 0.027$) as one moves downstream from the injection site was also investigated and found to be at least 25 boundary layer thicknesses. The injection process adversely affects the flow noise at only very low frequencies. Schloemer and Payne[2] confirm the Soviet hypothesis that a separation of the turbulence from the wall just aft of the injection region causes the dramatic reduction in wall pressure fluctuations.

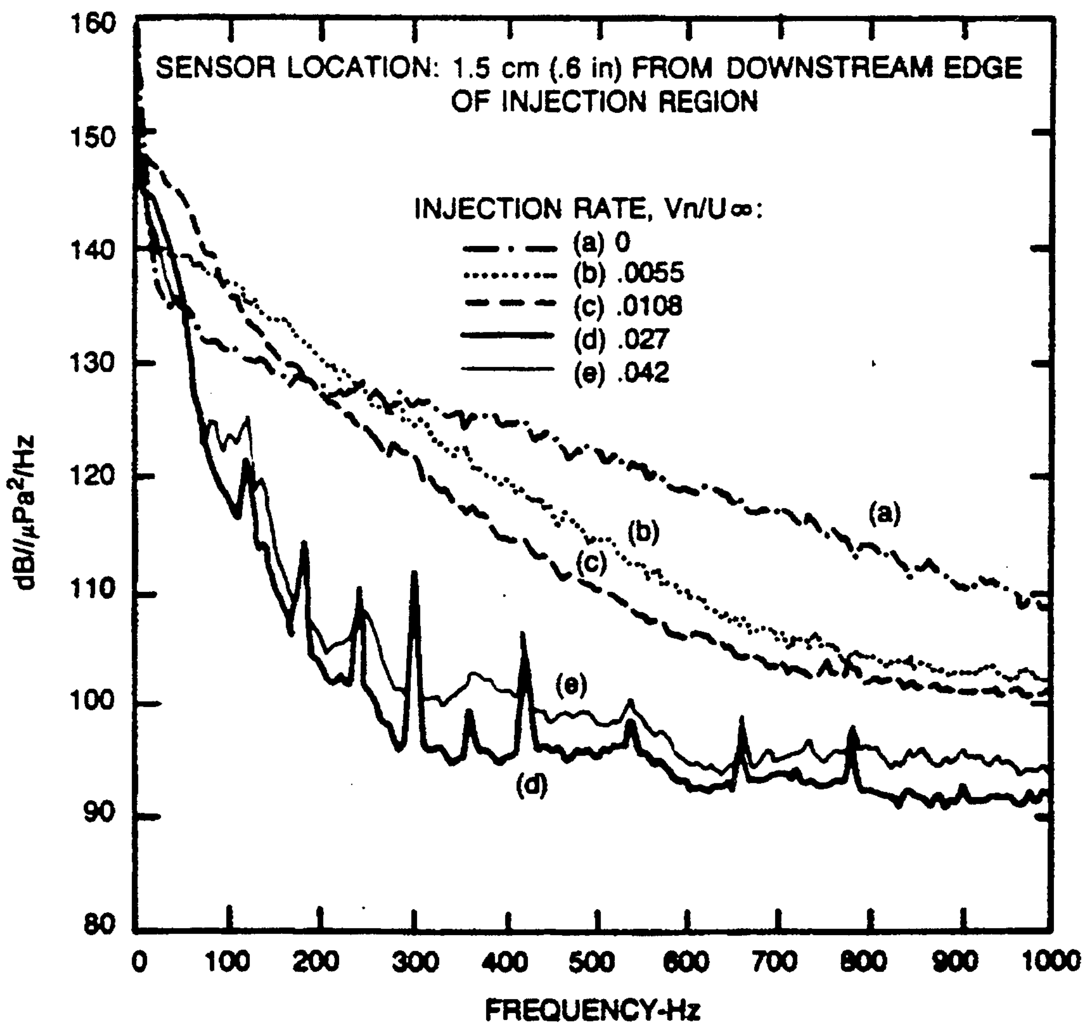

Figure 2 TBL wall pressure fluctuation spectra measured just aft of a porous section on a flat plate where water is injected at the noted values of C_q (reproduced from Schloemer and Payne[2]).

III IMPLEMENTATION ON AN AXISYMMETRIC BODY

With modern powdered metal fabrication technology, it is now feasible to manufacture porous materials of prescribed permeability in any shape that can be specified by a stereo-lithography coordinate file.[3] The design and manufacture of a reduced flow noise headform for use on an undersea vehicle equipped with a standard acoustic sonar transducer can be accomplished using porous metal (bronze or stainless steel) for the outer shell.[4] The hydrodynamic ram of the vehicle provides the pressure required to force the water through the porous shell. The normal ejection velocity is given by:

$$v_n = \frac{\alpha \Delta P}{\mu t}, \qquad (1)$$

where α is the material permeability, ΔP is the pressure differential across the shell, μ is the viscosity of the fluid, and t is the shell thickness.

A reduced flow noise headform design concept considered in this investigation is given in Figure 3. The nose contour is a modified ellipse defined by a flat area in the forward stagnation region that fairs into the cylinder by way of an elliptic contour.[5-7] A ring slot exists between an inner cylinder and the porous outer shell to allow water to enter the internal cavity. The hydrodynamic pressure head of the vehicle ($q = ½\, \rho U_\infty^2$) produces an internal pressure that is larger than the external static pressure, P. Potential flow codes are used to predict this external static pressure distribution.

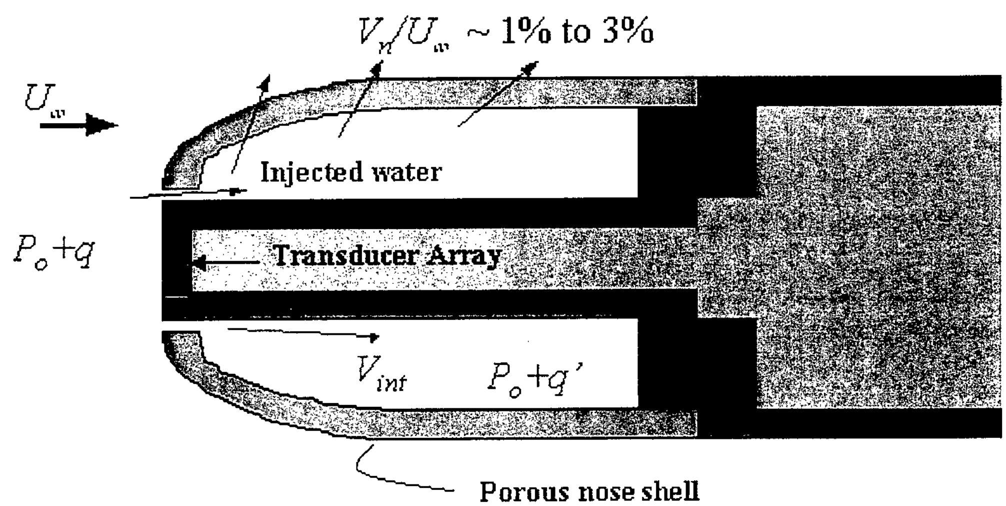

Figure 3 Self noise reduction concept. The vehicle velocity (U_∞) is used to force water into a cavity around the transducer array. The velocity of the water immediately adjacent to the array is reduced because the flow noise scales to a high power of the flow velocity. This results in reduced sensor self noise.

The fluid velocity close to the array is substantially lower than it would be if all of the external flow was permitted to pass over the array face, as in a normal closed body design. Flow noise scales on a high power of local velocity.[6,7] Specifically, denote the mean velocity of the internal flow near the array as V_{int}. Now if $V_{int} < U_\infty$, and if the TBL is the assumed source, we would expect a reduction in self noise ~ $(V_{int}/U_\infty)^6$. (A 7.5 power would be used if the transition of laminar-to-turbulent boundary-layer flow were the assumed dominant flow noise source[7]). Thus, we see for example, that if the local velocity next to the array were halved, an 18 to 22 dB noise reduction would be realized. In addition to this effect, if the blowing coefficient were in the desired range of 2 to 3%, there would be a reduction of the local wall pressure fluctuations on the external shell. Typically, 5 dB at $C_q = 0.0055$, and up to 20 dB for $C_q = 0.027$. This could lower the flow-induced structural excitation of the outer shell, which could also lead to reduced self noise. Structurally-induced radiated noise might also be lowered.

In Figure 4 the potential self noise reduction due to the combined effects of these two mechanisms is presented. The curved line represents the reduction due to $(V_{int}/U_\infty)^6$, while the horizontal lines are the reductions due to water injection into the external TBL. The chart helps us to see that if a 20 dB self noise reduction is required, the design of the ring slot that exists between the outer shell and the inner cylinder must be such that $V_{int}/U_\infty \lesssim 0.5$.

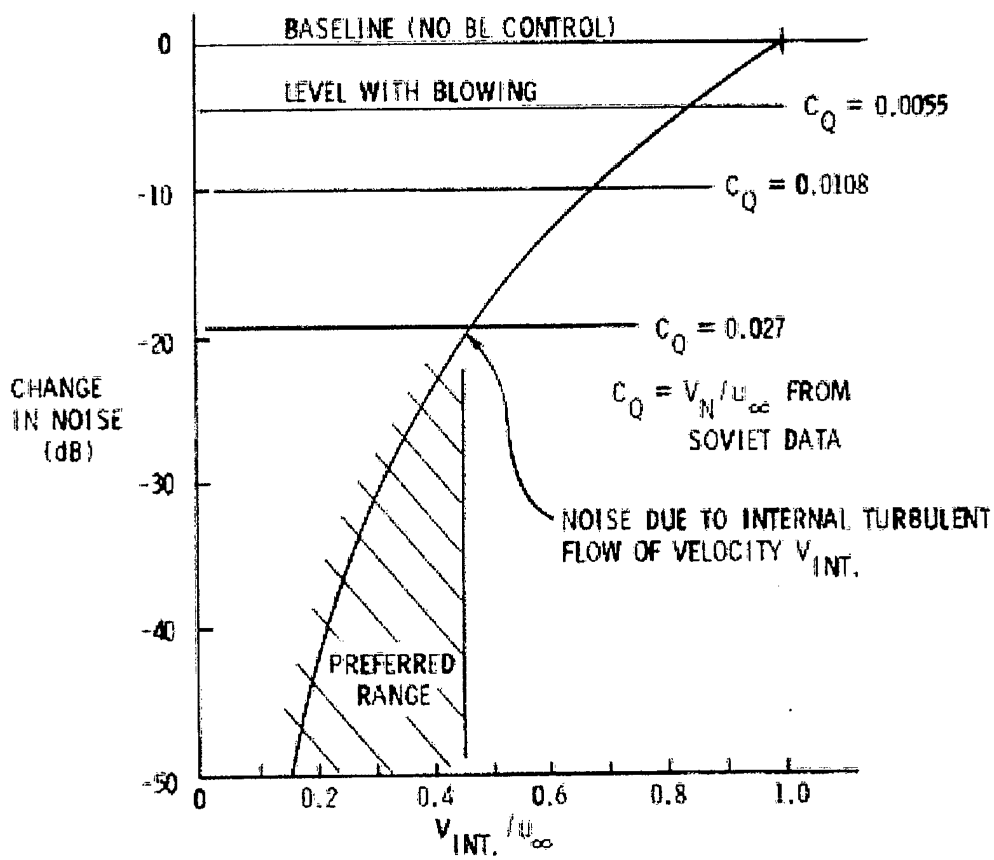

Figure 4 Potential self noise reductions due to the combined effect of external water injection into the TBL, and a lowering of the mean velocity adjacent to the acoustic transducer.

IV EXPERIMENTAL PROGRAM

The overall goal of the present research is to reduce the flow-induced and structure-borne self-noise of a torpedo sonar. Two separate 12-inch diameter water tunnel tests have been performed to experimentally demonstrate the self-noise mitigation techniques developed. Field tests are proposed for FY03. In the first series of water tunnel tests, conducted in FY01, the 3.4-inch diameter model outer shell was fabricated from porous sintered (powdered) stainless steel to a specification and thickness that allows the optimum injection coefficient for noise reduction to be achieved.[4] Figure 5 shows the cut-away views of one of these porous shells. The dynamic head of the free-stream water flow passively and robustly provided the pressure required to achieve fluid aspiration.

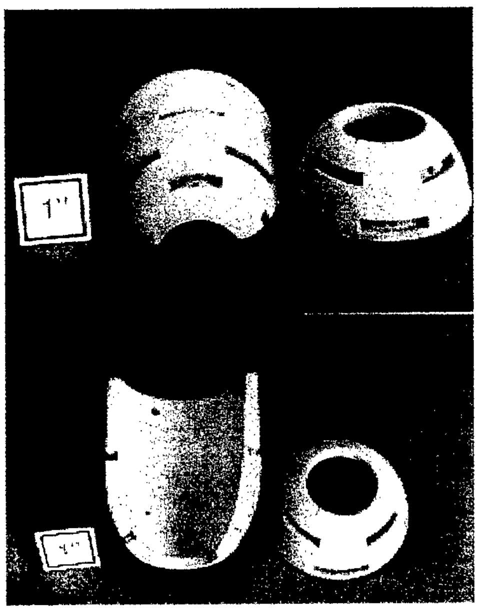

Figure 5 Photographs of the sintered stainless steel porous nose sections used in the first water tunnel test program.

An acoustic tonpilz pressure transducer is located at the forward stagnation point of the test model. Several circumferential arrays of 1:3 composite wall pressure transducer material were situated in the slots of the porous shell. The most forward array is under the laminar boundary layer, the middle one is intended to be under the transition zone, and the one located farthest downstream is under the TBL. The signals from all transducers are monitored and analyzed in the usual way to determine auto- and cross-spectral density functions. Tunnel background noise was found to contaminate many of these measurements, particularly at low frequencies.

The majority of the first experiment was with the sintered forebody that has the least permeable surface ($\alpha = 2.31 \times 10^{-12}$ m^2) of the three that were available. This model has design C_q values of ~ 1, 2, and 3 % at 30, 40, and 50 ft/s flow speed, respectively. The initial experiments were to determine the location of transition. This was accomplished by injecting fluoresceine from a small hypodermic needle from a location between the inner and outer shells. If the fluoresceine is visible under ultraviolet light on the outside of the model, then little of it is being injected through the porous shell. Figure 6 shows a typical streakline pattern observed at 30 ft/s. The dye streaks are clearly visible indicating 1) little dye is going through the shell because $C_q \sim 0.01$, and 2) the flow in the external boundary layer is laminar until about the third axial row of pressure transducers (here the dye gets dissipated by the turbulence in the TBL). Visualizations at progressively higher tunnel speeds showed the trend expected: less and less dye was visible indicating that more and more of the dye was being forced through the shell. Unfortunately, most of it stayed in the shell because, after all, the shell is nothing more than a filter. This particular nose ultimately became clogged and un-usable for flow noise control. Some limited flow noise data were collected from it, however, before the dye visualization tests.

Figure 6 Fluoresceine injection from a tube located between the inner and outer shells. Ultraviolet lighting renders the streaklines visible. Transition is where the lines disappear.

Figure 7 shows spectra of the flow noise signals measured at 30 ft/s by the nose tonpilz transducer and the three flush-mounted 1:3 composite transducer arrays located at the forward, mid, and aft locations (shaded areas of Figure 6) of the porous nose. The blowing was stopped by placing a special ring between the inner and outer shells of the model that blocked the flow from entering the internal pressure chamber. Figure 7 reveals that the low-frequency wall pressure fluctuations are increased due to blowing at the forward location. This might be due to the tripping of the turbulent spots that can increase the noise, but the visualizations of Figure 6 do not support this hypothesis. The mid-body transducer shows little effect due to the blowing, while the aft transducer array, which is under the TBL shows a slight decrease in wall pressure fluctuations due to the blowing. A significant reduction at the nose transducer suggests that the fluid blowing may have potential in reducing sonar sensor self noise. Data measured at 40 ft/s show similar trends, but the flow noise reductions are unexplainably less.

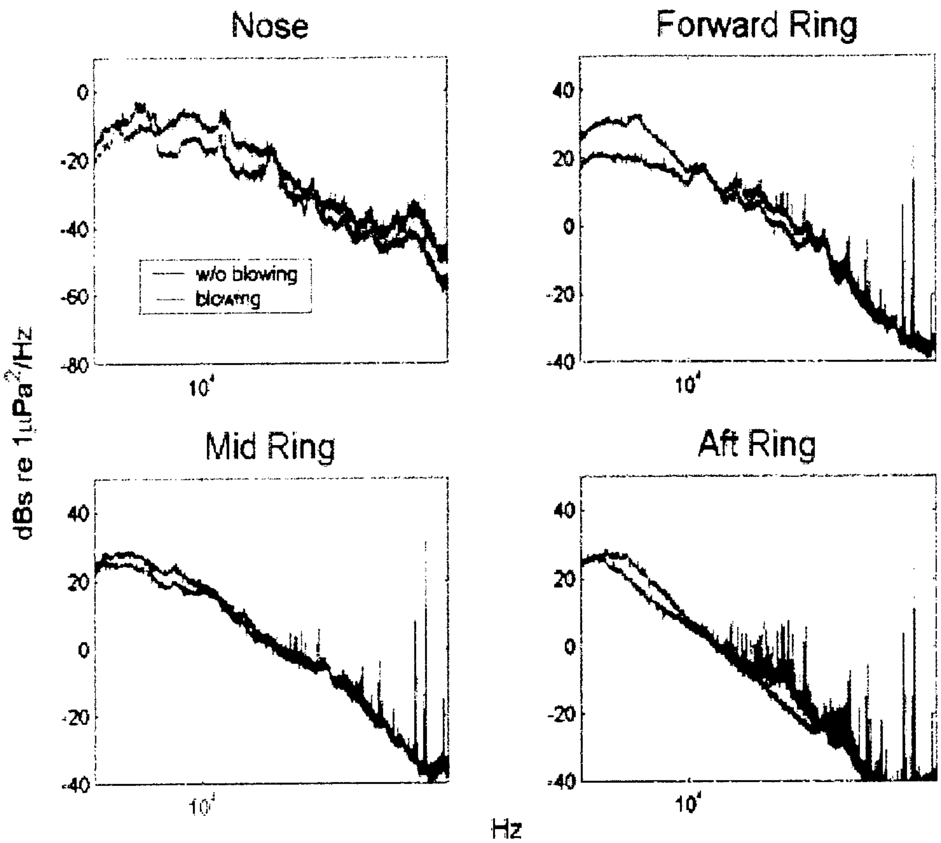

Figure 7 Flow noise spectra measured on the porous headform at 30 ft/s.

Although the data of Figure 7 are encouraging, they are far from conclusive. It is possible that the 1:3 composite transducer arrays do considerable spatial averaging of the local wall pressure fluctuations. The model was therefore re-instrumented with point receivers rather than the larger 1:3 composite transducers.

A. FY02 Measurements

In FY02 a new model was fabricated, as shown photographically in Figure 8. The acoustic tonpilz pressure transducer (transducer #1) was located at the forward stagnation point of the model, as in the first model tested in FY01. The sintered porous shell was replaced with one made of plexiglass. The 0 to 180° sector of this outèr shell was perforated with hundreds of holes for water injection. The 180 to 360° sector was left smooth to provide a baseline test configuration. Downstream of the porous section, three BB transducers[8] were spaced such that one was in the transition zone (#2), and the remaining two (#3 & #4) were under the TBL. During the experiments the water velocity was set and the spectra of the various transducers were measured with and without water injection. The baseline, no injection case, was achieved by rotating the porous section such that the perforated sector was opposite the flush mounted pressure transducers. Placing sponge material in the plenum between the inner and outer shells varied the ejection coefficient.

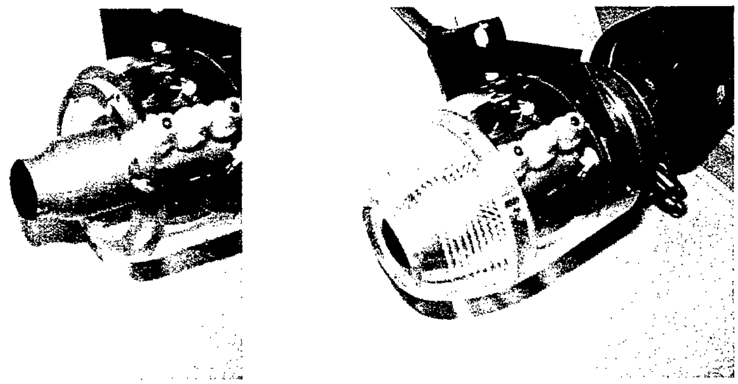

Figure 8 Photographs of the water tunnel test model showing the porous section that surrounds the tonpilz transducer. The three "plugs" contain the BB transducers.

One water tunnel test was conducted with the model of Figure 8. At 40 ft/s free stream flow velocity; C_q values of 2 and 3 % were achieved. As discussed in Section III it is important to keep the velocity at the inlet to the plenum lower than 50% of the free stream speed in order to realize 20 dB or better self noise reduction at transducer #1. Unfortunately, transducer #1 failed during the test so we cannot prove this hypothesis directly. The inlet velocity was determined from the measured pressure rise inside the plenum. Figure 9 shows the measured pressure rise and corresponding calculated inlet velocity. Note that at 40 ft/s, the inlet velocity (ordinate) is about 50% of the free stream speed (abscissa). This means that if an actual sonar transducer were in place on the inner body, its flow noise response would be ~ 20 dB lower based on a conservative 6th power law for self noise as a function of local flow speed.

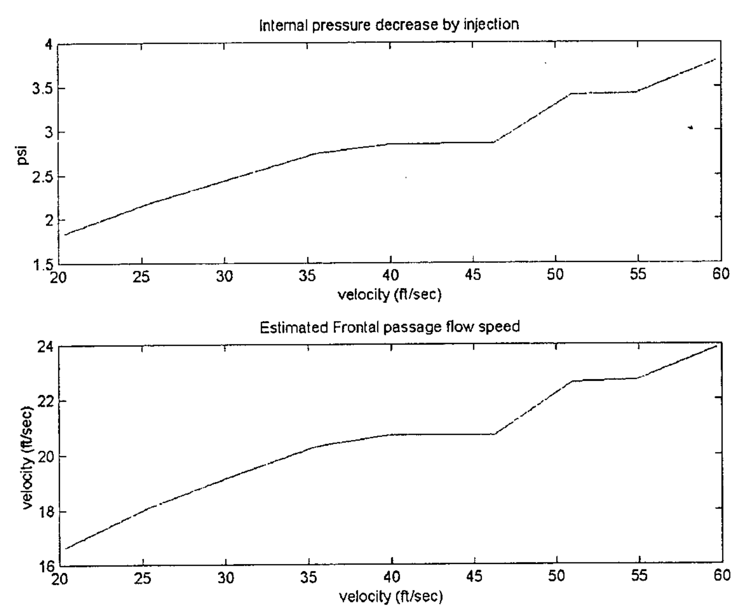

Figure 9 Measured pressure inside the plenum of the model, and the calculated inlet velocity. A low frontal passage velocity indicates that the flow-induced self noise of a transducer located on the inner shell may be reduced by 10 to 20 dB.

The local wall pressure fluctuation spectra measured downstream of the injection zone are given in Figure 10 for 30 and 40 ft/s and $C_q \sim 0.02$ and 0.03, respectively. In agreement with the published flat plate results,[1,2] these results show significant local TBL-induced pressure fluctuation reduction due to water injection into the TBL. Tests conducted at higher speeds and higher Reynolds numbers (through tunnel water heating) were invalid because the injection holes cavitated (the model design would not permit operating the tunnel at a higher pressure to suppress this cavitation). Regardless, the goals of the project have been reasonably well met.

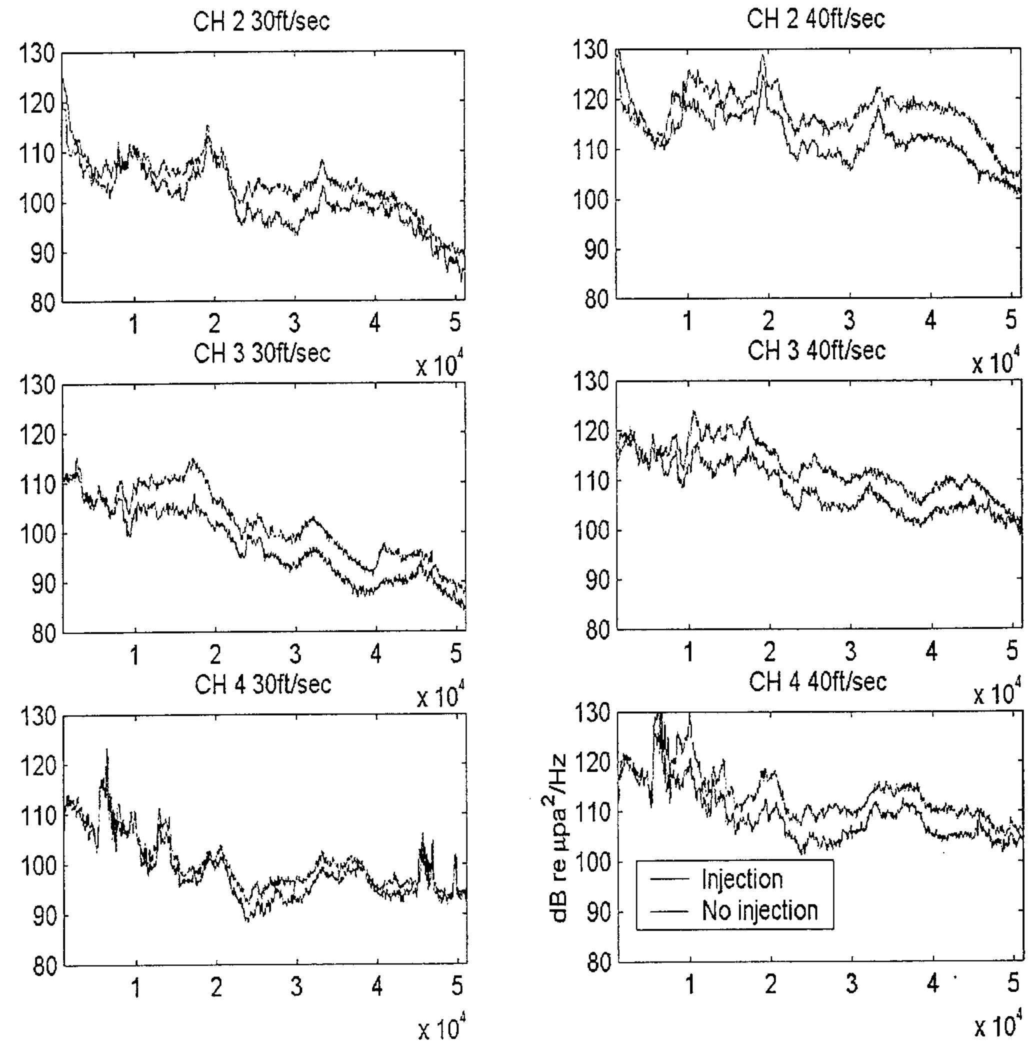

Figure 10 Spectra of the local wall pressure fluctuations on the axisymmetric body with and without water injection; 5 to 10 dB of pressure fluctuation reduction is observed meaning that the TBL structural forcing function will be reduced by this amount resulting in potential self and radiated noise reductions.

V CONCLUSIONS

- Local transition zone and TBL wall pressure fluctuation reductions (5 to 10 dB) have been demonstrated using fluid injection through a porous section of an axisymmetric forebody.
- These are the first such data for an axisymmetric body flow.
- The hydrodynamic ram of the body has been used as the supply pressure for the fluid injection.
- The reductions in local wall pressure fluctuations will translate directly into a reduced shell forcing function that will contribute to self noise reduction and will also reduce the *radiated noise* of the body.
- The local flow velocity around the inner shell of the body - the shell that contains the sonar transducer – has been reduced to 50% of the free stream speed. This should translate into a 20 dB flow-induced self-noise reduction on an actual vehicle.

VI RECOMMENDATIONS

A full-scale test of these principles is recommended and has been proposed for FY03 (Van Tol and Hughes of ARL Penn State). The existing transducer array to be used is one designed for a 12.75-inch diameter body. The outer porous shell will have the contour of a standard 21-inch body. It may be constructed of composite materials or perforated aluminum. Laser-boring methods exist to produce thousands of micro holes to produce the porous outer shell. The array with flow control outer shell should be tested in the field on an electrically-powered free-running vehicle, such as the ARL Penn State eXperimental Test Vehicle (XTV).

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