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Metering of Fluids at High Velocities with Vortex Shedding Flowmeters

J.D. Siegwarth

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J.D. Siegwarth

Physical and Chemical Properties Division
Chemical Science and Technology Laboratory
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80303-3328

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J.D. Siegwarth
Physical and Chemical Properties Division
National Institute of Standards and Technology
Boulder, CO 80303

Vortex shedding flowmeters have been designed and tested for measuring liquid and gas flows to the maximum velocities found in the ducts of the Space Shuttle Main Engines. The flow velocities found in these ducts are several times greater than found in conventional metering applications. The shedder bar was narrowed relative to conventional vortex shedding flowmeter designs to reduce the head loss introduced at the extreme flow velocities. The presence of bends in the duct near the flowmeter, while expected to degrade the meter performance, rather improved it in terms of signal quality relative to the performance in a straight duct. The performance also improved with a decrease in viscosity of the measured fluid. The signal quality obtained approached that of the modified commercial vortex shedding meters used to provide flow calibration.

Keywords: flowmeters; high velocity; hydrogen; LOX; vortex shedding

1. Introduction

The objective of this work was to develop vortex shedding (VS) flowmeters that can measure fluid flows in the ducts of the Space Shuttle Main Engines (SSME) to high velocities but without large pressure losses. Commercially available VS flowmeters measure liquid flows to about 6 m/s and gas flows to 76 m/s. At these maximum velocities, the pressure loss introduced by the flowmeter is less than 50 kPa (0.5 bar). Because pressure loss increases as the square of the flow velocity, the pressure loss across a conventional VS flowmeter could become unacceptably high at high flow velocities. The intended application of these flowmeters is the measurement of flow under the conditions found in selected ducts of the space shuttle main engines (SSME) where higher than normal velocities are encountered.

Flow measurement in the ducts of the SSME is needed both for monitoring the health of the engines and for controlling them. Venturi and turbine meters have been used in the past for this application. The linearity of VS flowmeters offers an advantage over venturi meters. Vortex shedding flowmeters have the advantage over turbine meters in that they are unharmed by high velocity gas flows encountered during cool down that can destroy a turbine meter.

Flow measurement in the SSME ducts has the added complication that the ducts lack straight sections of sufficient length in which to place flowmeters. Installation guidelines for VS flowmeters, like many other types of flowmeters, recommend a 20 diameter long straight section upstream in the absence of a flow straightener and a 5 diameter long straight section downstream. Straight sections in the ducts of the SSME are less than 8 diameters long.

2. Vortex Shedding Flowmeter Description

The operating principles of VS flowmeters have been discussed in numerous papers but usually not in depth. Miller provides a brief review [1]. Cousins et al. have delved into shedder design in some detail and discuss design parameters and the impact on meter performance [2].

The VS flowmeter consists of a bar of uniform cross section spanning a duct on a diameter. In uniform flow, vortices shed alternately from the sides. For a bar with a suitable cross sectional shape, the spacing of these vortices remains approximately constant in the moving frame of the liquid. Then the number of vortices shed per unit time is proportional to the flow. The vortex shedding can be turned into a time varying electrical signal by either sensing the pressure against, or the lift forces on, the shedder bar that are generated by the shedding process. Cousins et al. [2] have found that vortex shedding from a body of uniform cross section is most stable when D/w, the body length (meter diameter) over the body width, is in the range of 3 to 7, depending on the cross sectional shape of the shedder. A shedder width around 0.3 times the duct internal diameter, again depending somewhat on the shape, minimizes the sensitivity of the flowmeter calibration to the shedder width [2].

In this work, liquid flowmeters were developed for three sizes of duct inside diameter, 58.5, 51, and 28 mm (2.3, 2, and 1.1 in). These diameters correspond to the RS007035, RS007031 and the RS007032 ducts, respectively, of the SSME (NASA duct numbers). Gas flowmeter tests were carried out only in the 51 mm inside diameter duct corresponding to the 7034 duct of the SSME. Three of these four SSME ducts were obtained and retrofitted with ports to install flowmeters as illustrated in Figure 1.

The maximum liquid flow velocities exceed those of commercial applications by as much as a factor of 5 (7035 duct) and the gas flows by more than a factor of 3. The pressure drop in the 7035 duct that would be introduced by a conventional meter could be as high as 0.86 MPa (125 psi). In addition, the duct pressures are much higher, up to 53 MPa (7700 psi), and the temperatures lower than the applications for which most commercial vortex shedding meters are designed. The problems introduced by the low temperature and high pressures are minor compared to those presented by the bent ducts and the high velocities. The presence of liquid oxygen (LOX) limits the materials that can be placed in contact with the duct contents for safety reasons.

A means of testing flowmeter designs at high flows and in duct configurations like those of the SSME was needed to determine whether a vortex shedding flowmeter could be designed that would satisfactorily measure the duct flows.

3. Test Facilities

The cryogenic liquid flow facility at NASA Marshall Space Flight Center can produce LOX and liquid nitrogen (LN_2) flows at high velocities. This facility was eventually used for some cryogenic tests. However, water is close to LOX in most properties except viscosity, and tests can be done at lower cost. Unfortunately, most water flow test facilities are not built to provide flow at the high pressures needed to achieve the high flows required.

With permission from the City of Boulder Water Utilities, a water flow test facility was connected to the penstock of a hydroelectric plant that is part of the city water system. This test facility takes water from the penstock through a 4 in line at pressures of 3.2 to 3.9 MPa (470 to 570 psi) depending on the flow to the hydro plant. After the water passed through a 4 in or 2 in reference VS flowmeter, the line diameter was reduced to that of the test meter. These reference flowmeters determined the flow through the test flowmeters. The water then returned to the city water treatment plant. The pressure in the penstock was sufficient to achieve the desired flows.

The 4 in reference meter could measure flows to 9.3 m/s according to the manufacturer. This flow was sufficient to achieve the desired maximum flow velocity of 28 m/s in a 58.5 mm diameter duct. This 4 in vortex shedding flowmeter was assumed linear for these tests even though it was not perfectly linear even over the calibrated portion of its flow range. It had been calibrated only up to about 4.5 m/s (15 ft/s). It appeared to be linear up to 10 m/s flow velocity in water tests relative to a 4 in turbine flowmeter calibrated by NASA though some hysteresis was noted in the data. The 2 in reference meter was calibrated against the 4 in reference meter. Differential pressure transducers that measured the transverse pressure difference across the shedder bar replaced the original thermal type sensors of both reference flowmeters. The unfiltered signal spectrum from the 2 in reference flowmeter is shown in Figure 2 for a low and high flow. The spectra shown are the average of 10 measurements by the spectrum analyzer. The signal-to-noise power ratio from these sensors was 30 to 40 dB. The width and signal-to-noise ratio of these spectrum lines served as a performance to strive for in developing the high velocity flowmeters.

4. Signal Processing

The signal frequencies of both the reference meter and the test meter were measured first using counters. During the later testing, a fast Fourier transform (FFT) analyzer was used to measure both the test meter and the reference meter frequencies.

The meter performance was analyzed qualitatively by examining the signal frequency spectrum and the fade in the real time signal with a FFT spectrum analyzer using the flat top filter to compensate for the finite time of the measurement. A spectrum line with a width of 3 percent or less of the line frequency and a signal-to-noise power ratio greater than 30 dB was sought along with the absence of any mechanical resonance spectrum lines of comparable magnitude in or near the vortex shedding frequency range. Harmonics of the vortex generated signal, though often present, are not a problem for signal processing.

The vortex shedding signal amplitudes of the test flowmeters were less regular and steady relative to commercial VS flowmeters in the flow range up to 6 m/s and their signal stability usually did not improve with increasing flow above 6 m/s. The output signals were modulated often with the degree of modulation increasing with increasing flow. The signal spectrum lines broadened with increasing signal fade until they eventually split into multiple lines. When a flowmeter gives narrow spectrum lines and the signal fades infrequently, the flowmeter was said to show a "good performance". Signal fade, when it occurs, usually lasts for about a cycle for a good flowmeter.

Measurement uncertainty and linearity of meters designs tested in this work have been examined but not extensively. The test system was not well suited to define the uncertainty and linearity because of the hydro plant. The flow into the hydro plant could vary during the measurement interval because of the flow adjustments made to maintain the generator frequency. At high flows through the hydro plant, flow adjustments, even though small, alter the penstock pressure because of the large friction loss in it. A change of pressure in the penstock changes the flow in the flowmeter test system. The degree of this variation could change from day to day. The test and reference meters were read sequentially with the FFT analyzer. In addition, the measuring time of the 4 in reference flowmeter was long at low flows because of the low signal frequency. The spectrum lines from the reference meters did not show any obvious effects from flow variation over the course of a measurement. However, when the 2 in reference flowmeter was calibrated against the 4 in reference meter, data scatter observed could have resulted from variations in the flow to the hydro plant.

The meter factor of a 28 mm bore flowmeter was tested during this calibration as shown in Figure 3. For the circled data points, both the 2 and 4 in reference flowmeters were read along with the 28 mm flowmeter. Only the 2 in reference flowmeter and 28 mm flowmeter was read for the rest of the data points. The meter factor of the 2 in meter was determined from the 2 and 4 in data from the circled points assuming both flowmeters had linear flow dependencies. The meter factor of the 28 mm test flowmeter showed appreciably more scatter at low flows when the 4 in reference flowmeter was also read than when only the 2 in reference flowmeter was read. The Reynolds number for the lowest flow point was below 10^4 for the 4 in flowmeter, the minimum flow specified by the meter manufacturer. The solid curve was fitted only to the 2 in reference meter data at low flows plus the data at the five highest flows where both reference meters were read. The total scatter of the calibration data, excluding the lowest two points, was 0.7 percent. The greater scatter at low flows of the data when the 4 in reference meter was read, Figure 2, suggests that the flow varied a detectable amount over the measurement time.

5. Flowmeter Design

To reduce pressure drop introduced by the VS flowmeter at high flows, the area of the shedder bar facing the flow can be decreased either by narrowing the shedder bar or shortening it so that it does not completely span the duct. The first decreases the shedding stability and the second the uniformity of the flow along the bar. Either modification combined with the absence of straight duct sections of sufficient length could result in an unacceptable degradation of flowmeter performance.

Shedder bars that partially spanned the duct were tried early on to reduce the pressure drop across the meter [3-6]. This concept proved marginally successful in a 1½ in nominal flowmeter but failed to scale up to the 58.5 mm size. Flowmeters with narrowed shedder bars performed much better [3-6]. The narrowed shedder bar had the advantage that a satisfactory shedder bar assembly could be inserted through an opposed pair of standard SSME duct instrumentation ports for ducts up to at least the 58.5 mm bore. These ports are 11.2 mm diameter. While narrowing the shedder bar reduces the pressure drop, it carries the disadvantage that the ratio D/w of the shedder bar is near the limit if not out of the region of stable vortex shedding.

The maximum liquid flow velocity that can be measured is presumably the velocity at which cavitation occurs. Flowmeters for the SSME must measure to the highest required duct flows without cavitating. Since the flow at which they cavitate depended on flow velocity and pressure, not the Reynolds number, the maximum velocity to which the flowmeter can measure is the quantity of interest. Thus, the meter factors, the signal frequency per meter per second of

Table 1. Reynolds number for 1 m/s flow.

Duct inside diameter	Fluid	Reynolds No. at 1 m/s
58.5 mm	Water	3.9×10^4
58.5 mm	LN_2	2.6×10^5
51 mm	Water	3.4×10^4
51 mm	LN_2	2.3×10^5
51 mm	Air	5.7×10^4
28 mm	Water	1.9×10^4

average velocity, are shown as a function of flow velocity. The pipe Reynolds numbers at the flowmeter can be obtained by multiplying the average flow velocity in meters per second by the appropriate factor found in Table 1. Some of the Reynolds numbers approached 10 million.

The development of these flowmeters has been in progress since the early 1980's. The previous results have been reported periodically [5-10] and reviewed twice [3,4]. The previous work showed that for the 51 and 58.5 mm ID ducts, a narrowed shedder bar that inserts through an opposed pair of SSME duct instrument ports could measure liquid flow to the required flow velocities without upstream flow conditioning. The best performing of these flowmeters, however, was still inferior to that obtained from a properly installed commercially available flowmeter in its normal operating flow range. The best performance was obtained even when the shedder bar was placed perpendicular to the plane of the preceding duct bend [3,4,7].

6. Test Results

6.1 The 58.5 mm Bore Flowmeter

Much of the development work was done with this meter size because it is subjected to the highest liquid flow velocity. Most of the determination of best shedder shape and the suspension and vortex sensor design were worked out concurrently on this flowmeter size. Only a few of the more successful designs tested will be discussed here.

A straight 59 mm bore test duct was used for the earliest water flow tests, and flowmeter 85-4-9, Table 2, gave a good performance. The performance of 85-4-7 was similar but the meter factor of 85-4-9 was more nearly constant over the flow range of interest. In the first water flow tests involving the 7035 duct, the flowmeter was placed at the outlet of the duct, a few diameters downstream of the final duct bend. The performances of 85-4-7 and 85-4-9 were again similar and acceptable, but here the meter factor of 85-4-7 was more nearly constant. For this reason, 85-4-7 eventually became the preferred shedder design for the 7035 duct.

The head loss across a shedder bar was determined by differential pressure measurements across the meter location with and without this shedder bar in place. The difference between these two measurements is the head loss due to the shedder bar. For the 85-4-7 and shedders of similar cross section, a value of 0.18 MPa (26 psi) was measured for the head loss at the maximum flow of 28 m/s (92 ft/s). This is about a factor of 5 lower than the pressure loss would be across a commercial flowmeter at the same flow velocity.

Three later versions of a flowmeter with shedder dimensions close to those of 85-4-7 were built and tested with water flow: flowmeters 88-7-2, 87-9-1, and 91-6-2. The suspension of the shedder bars all differed [3-8] from each other as well as from 85-4-7. The latter two were similar to 85-4-7 in that the vortex sensor was outside the duct and driven by the axial motion of an O-ring sealed shaft passing through the duct wall. This shaft transmitted the transverse motion from an extension of the shedder bar out to the sensor. The sensor of 88-7-2 was inside in contact with the fluid in the duct. The spectrum lines of these three were similar though mechanical differences were substantial. All spectra were narrower than those of 85-4-7 since the vortex sensors had improved. The meter factors of the three agreed within 1 percent. That meter factor of 85-4-7 was about 2 percent higher can be attributed both to its slightly smaller width and to the lack of sharp corners on the shedder bar. Rounded front corners on the rectangular-shaped cross section shedder bars have previously been shown to increase the meter factor [4].

A flowmeter design consisting of a shedder bar formed of two sections cantilevered in from the opposite flowmeter ports and nearly touching end to end in the center of the duct was developed as a means of avoiding a shedder bar rigidly spanning the duct. A flowmeter of this design, 86-4-2, was tested with water in the straight duct [4,7] while the 7035 duct was being installed in the NASA Marshall LN_2 flow facility. It performed well and was selected for the LN_2 flow tests in the 7035 duct at Marshall. It was one of only two flowmeters tested with both water and LN_2 and performed well in LN_2. When the 7035 duct was returned to Boulder, 86-4-2 was tested in it with water. Its performance in the 7035 duct was inferior to that in the straight test duct. The vortex signal often contained multiple lines. When the meter factor proved sensitive to the width of the gap between the cantilevered pair, the concept was abandoned in favor of a single piece shedder bar provided with axial relief.

6.2 The Final 58.5 mm Flowmeter Design

Flowmeter 88-7-2, Figure 4, has a spring mounting on the end opposite the sensor so the shedder does not form a rigid coupling across the duct. This flowmeter gave one of the best performances of the 7035 duct flowmeter designs tested. The design can be made LOX compatible by replacing the O-ring sealing the mounting flange with a cryogenic seal and placing a LOX compatible coating over the sensor to eliminate contact between LOX and ignitable material. No rubbing contacts are present. The meter inserts through an opposed pair of standard SSME instrument ports eliminating the need to do a duct redesign.

Table 2. Liquid flowmeters tested.

Flowmeter	Shape and dimensions, mm		In ducts:	
85-4-9	Rectangular, 7.5 wide by 5.1 deep		Straight, 7035 exit	58.5 mm dia.
86-4-2	Rectangular, 7.6	by 6.5	Straight, 7035	"
85-4-7, 87-9-1 88-7-2, 91-6-2	Rectangular, 7.6	by 4.1	7035	"
86-2-1	Rectangular, 6.4	by 4.9	Straight, 7034	51 mm dia.
93-4-1	Rectangular, 8.4	by 5.6	Straight, 7034	"
87-10-2	Rectangular, 4.3	by 3.3	Straight	28 mm dia.
87-11-2	Rectangular, 4.3	by 2.5	Straight	"
89-5-3, Widened	Rectangular, 6.4	by 3.3	Straight	"
91-3-1	Rectangular, 6.6	by 4.3	Straight	"
91-3-2	Rectangular, 7.1 length 16.5, centered	by 4.1	Straight, 7032 Side branch	"
92-6-1	Circular, dia. 7.6	slit 0.22	7032 Side branch	"
92-6-2A	Circular, dia. 7.6	slit 0.37	7032 Side branch	"
92-9-1	Circular, dia. 6.3	slit 0.29	7032 Side branch	"
93-10-1	Circular, dia. 6.3	slit 0.32	7032 Side branch	"
93-10-2	Circular, dia. 5.8	slit 0.32	7032 Side branch	"

The vortex-sensing transducer is a lead zirconium titanate (PZT) bimorph. It is a thin flat plate that, when bent, produces a voltage difference between the electrodes on its faces. The PZT was clamped to a flat surface that spans a transition from a rigid post to a spring section. It acts as a strain gage sensor that detects bending at the transition. The alternating strain produced by the shedding produces a nominally sinusoidal voltage across the PZT electrodes though harmonics are often present.

The meter is shown in place in the paired instrument ports added to the 7035 duct in Figure 4b. The port location on the duct is shown in Figure 1. The port plugs restrict the flow of liquid through the ports bypassing the shedding element. Their diameter is undersized relative to the port to allow the transverse forces generated by the shedding vortices to displace the shedder bar slightly sideways.

The end of the shedder bar opposite the sensor is fixed in the directions perpendicular to the shedder bar but allowed to move axially by the axial relief springs. These springs allow the duct and shedder to expand and contract relative to each other without axially loading the shedder bar. The 19 mm long spacer placed between the mounting flange and the instrument port provides space for the sensor portion of the meter.

The FFT analyzer was used to analyze the output signal frequency, bandwidth, and signal-to-noise ratio during most of the tests. Each measurement contained 10 sweeps of the spectrum analyzer. Several measurements of the frequency spectrum were made as the shape and center frequency of the spectrum line obtained varied from one measurement to the next. Only the first signal spectrum measured was stored as representative to try to minimize bias that would otherwise be introduced if the experimenter selected the spectrum. The spectra were recorded for a window width of 0 to f, where f was in the range of 1.2 to 2 times the meter frequency. An acceptable performance was a line width that was about 3 percent of the line frequency over the test range. To reduce the effect of line broadening by the flat top window of the analyzer, the widths in one set of tests were examined using windows 40 to 200 Hz wide approximately centered about the line frequency. These narrower frequency range measurements of the signal from flowmeter 88-7-2 gave an average line width of 1.8 percent, while 0 to f bandwidth measurements during the same test gave an average line width of 3.1 percent. The filter added about 1.3 percent to the 0 to f bandwidth.

Narrow band logarithmic and linear spectrum lines from 88-7-2 are shown in Figure 5. These are typical spectrum lines. Occasionally wider lines would be obtained. The signal spectrum lines were at least 30 dB above the background and dominated any other line in the spectrum up to 10 kHz, the maximum frequency measured. This is considered to be a good performance even though the signal lines are wider than the spectrum lines of the 2 in flowmeter.

Figure 6 shows the meter factor of 88-7-2 as a function of flow relative to the 4 in reference meter. The measurements were made in 1989 and 1996 in the 7035 duct using water. The change in sensitivity of the reference meter with increasing flow is included in this curve. Removing this dependence would increase the slope of the curve in Figure 6.

The abrupt increase in meter factor above 30 m/s (100 ft/s) average flow is presumed to be cavitation at the 7035 duct meter. The meter factor increases gradually with decreasing flow below about 5 m/s. The full width of the scatter of the meter factor as a function of flow was less than 0.6 percent for the 1989 test.

The meter factor measured in the first 1996 test, Figure 6, showed hysteresis at low flows between the increasing and decreasing flow test points. Hysteresis had been noted before. It was not observed when the test was started in the mid-flow range as it was in the 1989 tests. The higher curve was obtained when the first 1996 test was started from lowest flow and the lower curve is obtained when the flow was decreased. Hysteresis was seen only on the first time the flow was increased. The original sensor was replaced in an unsuccessful attempt to improve the magnitude of the output signal, and a second flow test was done with the intent of further examining the hysteresis. The meter factor of 88-7-2 with this new sensor showed much greater scatter, in excess of 1 percent. If any hysteresis was present, scatter masked it. A third 1996 test at a limited number of flows, but with several data points taken at each flow, showed a hysteresis but it was inverted relative to the hysteresis seen in the first 1996 test. This higher scatter seen during the second and third of the 1996 tests cannot be attributed to the hydro plant causing pressure fluctuations because it was shut down during both tests.

This hysteresis was often seen. Perhaps some mechanical relaxation of the test meter installation occurred. However, it was also seen when the 4 in turbine meter used at Marshall on the LN_2 tests was compared to the 4 in reference meter on the water flow facility. This suggests that the hysteresis is associated with the reference meter.

Martinez-Piquer [11] reported a superior performance obtained with a vortex shedding flowmeter whose shedding element consisted of a circular cylinder with a full length diametrical slit through it transverse to the flow. Two shedders of this design were fabricated for the 7035 duct and tested. The performances were poor, and no further effort was made to improve the 7035 duct design. The results eventually achieved with the 28 mm flowmeter design, discussed below, suggest that a successful flowmeter of this design could be developed for the 58.5 mm duct.

A pair of ports was placed on the 7035 duct of an SSME test bed engine for the purpose of testing a flowmeter in the engine environment. Unfortunately, the port pair was oriented 90° from the correct position relative to the upstream elbow and located at a point along the duct where the vibration was too great for the flowmeter to meet the fatigue requirements. Further development of the 58.5 mm 7035 duct flowmeter was deferred to develop a 7031 duct flowmeter for a location with less levels of vibration and a better orientation.

6.3 The 51 mm Bore Flowmeter

A successful flowmeter for the 51 mm duct and the last flowmeter tested was 93-4-1 shown in Figure 7a. It was a modification of the 88-7-2 design that eliminated the need for both a sensor coating and for the larger diameter seal.

The maximum flow velocity that the 51 mm flowmeter experiences is lower, 16 m/s (52.5 ft/s) so the shedder width of 93-4-1 was increased to 0.165 of the duct diameter, II. The ratio d/w, where d is the shedder dimension in the flow direction, was 0.67, the value recommended by Cousins et al. [2]. The depth could be reduced if found necessary. The sides were specified to be parallel to 0.025 mm. Stress calculations by NASA staff showed that the design had sufficient fracture toughness to survive measuring LOX flow in the 51 mm bore SSME 7031 duct. The shedder assembly of the flowmeter was successfully pressure tested to 69 MPa (10^4 psi).

The main difference between the meter designs of Figure 4 and Figure 7 is in the spring section. Between the shedder bar and the mounting flange of 93-4-1 was a 11.4 mm long spring section of rectangular cross section 8.9 mm by 3.2 mm. Centered within this spring section is a 1 mm by 6.4 mm rectangular hole extending the length of the spring section. The slot was cut using a wire electrical discharge machine (EDM) after which the shedder bar portion was welded to the lower end of the spring section. Both of the parts were made of Inconel 625. The weld closes the interior end of the slot so that LOX cannot access it. A PZT bimorph was potted into this slot with epoxy so that it spanned the transition from the flange to the spring. The sensor detected bending at the face of the mounting flange in this design. The design is LOX compatible.

In Figure 7b, the meter is shown inserted in the instrument ports fabricated for the 7034 duct. Not only is the sensor removed from any contact with the fluid in the duct, but also the overall mass of the meter has been reduced because locating the sensor partially into the top flange shortens the spacer between the top flange and the duct. The slot containing the sensor could be made using a sinker EDM rather than a wire allowing the flowmeter to be made from a single piece of metal. Eliminating the weld would reduce the length of the port plug. This modification could eliminate the spacer entirely.

Since a 7031 duct was not available, the 51 mm bore liquid flowmeters were tested with water first in a straight test duct and then in the 7034 duct. The 7034 duct was assumed to be a tougher test of the flowmeter because it has sharp out-of-plane bends and shorter straight sections than the 7031 duct.

The straight duct had 22.5 diameters of straight section upstream of the meter and 7.5 diameters downstream. The upstream end was preceded by reducers stepping from 4 in to 2.5 in pipe to the 51 mm ID straight test section. The performance of 93-4-1 in it was poor. The spectrum lines were broadened. As many as four overlapping lines of similar amplitude appeared during the recording of 10 averages, showing that the shedding frequency was unstable. Examples of the spectra at high and low flows are shown in Figure 8. Based on the experience with flowmeter 86-4-2, the performance of 93-4-1 was expected to be better in a straight test duct.

However, a review of earlier testing revealed that one 51 mm flowmeter, 86-2-1, gave a poor performance in a straight duct but a very good one in the 7034 duct. Also, the meter factor was constant over a wide flow range [3,4,7]. The performance, based on comparable spectrum lines, was similar to that of 88-7-2 in the 7035 duct. It was retested with water in 1993 in both a straight duct and the 7034 duct, and the earlier performances obtained in both ducts repeated.

Flowmeter 93-4-1 was then tested with water in the 7034 duct. Figure 9 shows the narrow band spectrum lines obtained there. Figure 9, bottom right, shows the 0 to 10 kHz band at maximum flow. A flow independent line, probably a mechanical resonance, appears at 2.2 Hz. Its frequency is well above the maximum of the measurement range, and its magnitude is well below the level of the vortex-generated line. The performance surpassed that of 88-7-2 in the 7035 duct. The average width of a line measured by the FFT spectrum analyzer in the 0 to f band width mode using the flat top window was 3 percent, slightly better than obtained with 88-7-2. Though the vortex-shedding signal was modulated, complete fade occurred less often and lasted for fewer cycles than for 88-7-2. In part, the better performance probably resulted from the lower maximum flow. The spectrum line width approached that of the commercial flowmeter, Figure 3.

The meter factor of 93-4-1 in the 7034 duct is shown in Figure 10. It is not nearly as linear as 86-2-1 in the 7034 duct was or as 88-7-2 in the 7035 duct, but the scatter relative to the fitted line (a fifth-order polynomial) is smaller. Hysteresis was absent in these data, possibly because data acquisition was started at a flow velocity above 10 m/s.

6.4 Duct Geometry

Two flowmeters of very different dimensions had performed much more poorly in the 51 mm bore straight duct relative to the 7034 duct. This suggested that the differing performances were associated with the duct. Some tests were carried out to locate the cause of this difference. Four possible causes of the poorer performance in the straight test duct were examined:

- a distorted flow pattern from the reducers upstream,
- noise from the flow control valve downstream,
- roughness of the duct wall,
- lack of duct bends.

The addition of a flow straightener upstream of the straight test section to remove any effects from the reducers produced no improvement in the flowmeter performance. Adding the 7034 duct between the straight test section and flow control valve to serve as an isolator for any downstream valve effects gave no improvement. The straight duct was tested with the duct reversed as well as forward. The only configuration of the straight duct that showed any improvement of the flowmeter output signal was that with the duct reversed so the short straight section preceded the meter. The meter factor of 93-4-1 in this configuration is shown in Figure 10. Meter 86-2-1 when tested in the reversed straight duct, also showed some improvement in performance based on line width. The straight test section was then honed to remove the wavy surface of the inner wall. The performance of 93-4-1 in the honed duct, if anything, was worse.

Elbow effects were examined by placing an elbow three diameters ahead of the straight test section first with the long straight section upstream. Some improvement was noted; however, the lines narrowed somewhat from just the straight duct but the performance still remained poor. When the duct was reversed, the meter moved from 25.5 to 10.5 diameters downstream of the elbow. The performance of 93-4-1 improved dramatically. The performance became comparable to that in the 7034 duct. Spectrum lines are shown in Figure 11. Apparently, the flow pattern introduced by the elbow stabilizes the vortex shedding process. Part of these data was taken with the shedder axis rotated about 10° from the vertical of the plane of the preceding bend. This rotation had no apparent effect. The averaged vortex-generated signal, the highest peak in each spectrum, dominates all the other lines present from less than 1 Hz to 10 kHz. The instantaneous output signal is typically modulated, and, on rare occasions, the signal fades completely. The faded portions of the signal are short, about one cycle.

The meter factor of 93-4-1 in the straight duct, Figure 10, left, in the forward and reversed configurations differed in flow dependence but the average magnitudes were similar at higher flows. The meter factor was higher for the straight duct relative to the 7034 duct. This could be caused by a difference in duct bores. However, the close agreement between the meter factor of 93-4-1 in the 7034 duct and in the reversed straight duct preceded by an elbow suggests that the duct bores are close to the same and the bends are similarly modifying the flow in both ducts. The close upstream elbow lowered the shedding frequency slightly.

It was anticipated, when this work started, that the meters would only be adversely affected by the presence of nearby upstream bends. Instead, the flowmeters giving the best performance in the 7034 duct actually require the presence of nearby upstream bends. Similar elbow effects have apparently been seen but not reported by other workers [12].

6.5 Tests of 94-3-1 in LN_2 Flow

A flowmeter with a dimorph vortex sensor had not been tested cold to assure it would still function. Flowmeter 94-3-1 was tested in LN_2 flow in the NIST liquid nitrogen flow facility. The straight test duct with the long straight section preceding the flowmeter was used. A long 3 in straight section followed by a 3-to-2 in transition preceded the test section.

The signal amplitudes for water and for LN_2 flow are compared in Figure 12. The signal amplitude for LN_2 flow was about 1/6 of that for water at the same velocity. The signal amplitude variation for water was a function of v^2, as expected, where v is the velocity, but was about $v^{2.5}$ for LN_2. Though some of the reduction in signal at 77 K relative to ambient temperature probably arises from the lower density of LN_2 and increased stiffness of the shedder material, most of it is assumed to be a loss of sensitivity of the PZT at 77 K. Though it might be desirable that the signal amplitude did not decrease with temperature, the signal-to-noise ratio is not diminished by the sensitivity loss.

The maximum obtainable flows in the NIST LN_2 flow facility, as Figure 10 shows, were significantly less than available in the water test facility. The spectrum lines obtained for 93-4-1 in LN_2 flow, Figure 13, were single and narrow though not as narrow as those obtained with water when the duct was reversed and preceded by an elbow. However, since the presence of upstream reducers had very little effect on the meter performance for water flow, they would not be expected to have any greater effect on LN_2 flow. Different performances of the flowmeter for water relative to LN_2 were observed in the earlier tests of 86-4-2 in the 7035 duct [4,7]. The earlier test results, covering the full velocity range, were assumed at that time to stem from the particular meter design. The similar result for 93-4-1 in the straight test duct suggests that the poorer performance for water flow measurement relative to LN_2 might be caused by fluid properties. The 93-4-1 spectrum lines, Figure 13, were far superior to those obtained for water flow measured with the same test section configuration when compared at equal flow velocities. Between flows of 1.02 and 2.2 m/s for LN_2 and 7 to 14.6 m/s for water, the Reynolds numbers overlap. The performance of 93-4-1 in LN_2 is also far superior to that in water at the same Reynolds number. The improved performance seen for LN_2 flow, then, must be a viscosity effect. The narrowed shedder bar may have magnified the difference seen in the performance of the flowmeter in the two fluids. The discrepancy does not seem to be noted for the commercial designs. Viscosity effects are seen in the meter factor for commercially available meters [13].

The meter factor for 93-4-1 was higher in LN_2, Figure 10, in agreement with the tests of 86-4-2 in the 7035 duct. The meter factor curves are nearly parallel when plotted as a function of velocity though the data from the reversed straight duct merges with the 7034 duct data at low flows. The 7034 duct data and the reversed straight duct with a preceding elbow are close in magnitude even though the flow dependence differs slightly. The meter factor is sensitive to the duct configuration, Figure 10, left. It varies by as much as 2.5 percent for the configurations tried.

The LN_2 meter factor as a function of Reynolds number for water and LN_2 are shown in Figure 10, right. The reference meter for the water flow tests was calibrated and read low compared to a calibrated turbine meter by about 1.5 percent. The LN_2 test system is specified accurate to about 0.25 percent. The uncertainty in the measurement is well below the differences in meter factor seen in Figure 10, right. The data do not correlate with Reynolds number.

The testing was insufficient to establish that the shedder shape of 93-4-1 for the 51 mm duct was the best attainable. Judging from the meter factor and performance of 86-2-1, a narrower shedder could give a better performance than 93-4-1. A flowmeter with a reduced depth from that of 93-4-1 or 86-2-1, judging from the 7035 duct tests, could have an improved linearity.

6.6 The 28 mm Bore Flowmeter

The 28 mm flowmeter was designed for the side branch of the 7032 LOX duct, Figure 1. Obtaining a satisfactory performance from a 28 mm duct flowmeter proved to be more difficult than for the two larger flowmeters. The 28 mm bore meters were tested with water only. The results of the LN_2 test results for 93-4-1 suggest that the designs discussed below that performed poorly in water may have performed satisfactorily in LN_2 or LOX flow.

The first 28 mm bore flowmeters tested were cantilevered from one side of a straight test duct but spanned the diameter of the duct. Two of these meters, 87-10-2 and 87-11-2, Table 2, produced acceptably narrow spectrum lines in the first tests. Their meter factors as a function of flow had pronounced negative slopes. But when the tests of 87-10-2 and 87-11-2 were repeated about 1½ years later, their performance was very poor and remained poor despite attempts to improve it. A satisfactory explanation for the initial success and subsequent failure has not been found. Meter 89-5-3 had similar dimensions to 87-11-2 but attached to the duct on both ends. Though it performed slightly better, its performance was still poor. The vortex shedding was unstable. The vortex-generated signal appeared in bursts. Otherwise the amplitude faded completely as much as 75 percent of the time.

The performances of two wider shedders, 89-5-3 and 91-3-1, were satisfactory in the straight test section. Only 91-3-1 was tested in the 7032 side branch where it performed well. The flow velocity in the side branch of the 7032 duct is 22 m/s (72 ft/s). Increasing the width of the shedder bar to increase the width-to-length ratio improved the signal spectrum but introduced a pressure loss across the meter at maximum flow in excess of 320 kPa (47 psi) for water.

Shortened shedding sections were tried again here, but this time the shortened section was centered in the duct. Narrow streamlined posts supported each end of the shedder section. Six flowmeters of this design with increasing width and length were tried. The widest was 91-3-2. The wider three gave good performances in the straight test duct but flowmeter 91-3-2, when tested in the 7032 side branch, gave an unsatisfactory performance. Further work on shedders with rectangular cross sections was discontinued when better results were obtained with a round shedder design.

The mounting design of the first 28 mm flowmeter with a circular cross section and a cross slit [11], 92-6-1, was like that shown in Figure 4. This meter produced a fade-free signal for flows up to about 20 m/s average velocity. The meter factor showed a strong flow dependence including a sudden change in slope at about 5 m/s flow. Flowmeter 92-6-1A, meter 92-6-1 with the slit widened to 0.37 mm, no longer had the sudden change in slope of the meter factor as a function of velocity. The flow dependence also decreased.

Flowmeter 92-9-1 was similar to 92-6-1 but with the diameter reduced and the cross slit widened. This meter produced narrow spectrum lines over the required flow range. Little signal modulation was present until the higher flows were obtained. The meter factor, shown in Figure

14, again varied with flow.

The final two flowmeters tested were slotted circular cylinders but used an earlier suspension design. The vortex-shedding portion was a separate piece attached to the sensor and mounting flange assembly by a clevis pin [4,6]. The opposite end terminated in a round shaft that pushed into a tight fitting socket in the port cover. This design has the advantage that only one mounting plate and sensor needed to be fabricated. Various shedder shapes could be fabricated at a much lower cost from ½ in round stock, quickly attached to the sensor assembly, and inserted into the duct for testing. The sensor assembly used for the tests of the final two was encapsulated in the spring section like 93-4-1. One of the two, 93-10-2, had almost the same dimensions as 92-9-1. The other, 93-10-1, was smaller, Table 2.

The dimensions of meter 93-10-2 were held close to those of 92-9-1 to try to define the effects of the different shedder suspensions. The combination of differences in the shedder dimensions and suspension were enough to lower the meter factor curve, Figure 14, more than 1 percent and change the shape, especially at low flows. The data point at about 5 m/s appeared to be too high and was not included in the line fit. The performance of meter 93-10-2 in terms of line width was superior to any other flowmeter tested. The time signal almost never faded out even at the highest flow. The spectrum lines, Figure 15, were the narrowest obtained from any of the flowmeters tested, approaching the widths found for the commercial meter, Figure 2. The wide band spectrum shows a broad low-amplitude resonance peak near 4 kHz and several sharper harmonic lines of the vortex signal. Measurements using 92-9-1, thus by inference 93-10-2, showed that a head loss for water flow introduced by the flowmeter was 145 kPa (21 psi) for water at the maximum flow of 22 m/s (72 ft/s).

Widening the slit of 92-6-1 to that of 92-6-1A raised the meter factor curve, whereas the wider slit of 93-10-2 relative to 92-9-1 decreased the meter factor. This could result from a minimum in the meter factor as a function of slit width, from the fact that the clevis pin mounting was apparently stiffer than the 91-9-1 mounting, or from the slightly larger diameter of 93-10-2. It may be some combination of these three factors.

The meter factor of 93-10-1, whose shedder at 5.8 mm was smaller in diameter than that of 93-10-2, is also shown in Figure 14. The meter factor as a function of average flow seems to have a more linear flow dependence than the other round shedder bars tested. Its performance was poorer than that of 93-10-2, but still good.

The tests completed on the shedder bar consisting of a transversely split circular cylinder have shown that a narrowed shedder design can be made that performs well in the 7032 duct. While rectangular cross sectioned shedders retain a more linear meter factor as a function of flow when narrowed, the cross-slitted cylinder does not. The flow dependence in the meter factor can again be removed in the signal processing.

These results suggest that the performance of the meter is sensitive to the dimensions of the shedder bar; thus, a round shedder bar with reduced diameter might be very sensitive to the properties of the measured fluid. To obtain a similar performance to 93-10-1 with a lower viscosity fluid like LN_2 or LOX, the flowmeter may require a narrower slit through the shedder bar.

Since the tests of both 86-4-2 and 93-4-1 with LN_2 suggest that lowering the viscosity of the measured liquid improves the performance, good performance might be easily attained for a slitted cylinder measuring LN_2 and, by inference, low viscosity fluids such as LOX.

6.7 Gas Flowmeters in the 51 mm Bore Duct

In the SSME duct locations where fuel metering is desired, the hydrogen is a gas. The maximum flow ranges from 100.6 m/s (330 ft/s) to 241.5 m/s (792 ft/s). Commercial VS flowmeters are designed to operate to 76.2 m/s (250 ft/s) of airflow. At flows much above this, Mach 1 is exceeded in regions around the shedder bar. The velocity of sound in hydrogen exceeds that of air by a factor of 4 to 5. Therefore hydrogen flow velocities can exceed airflow by the same factors without exceeding Mach 1.

A test facility capable of providing calibrated hydrogen flow at high pressures and high mass flow rates was not available at the time of these tests. Hydrogen flow was simulated to the extent possible with compressed air at a pressure giving the same density as hydrogen gas. The viscosity of air under these conditions is higher,.up to about twice that of hydrogen. The largest difference in properties, however, is the velocity of sound.

Because of the high velocities in the SSME ducts and the low temperatures and high pressures, the pressure loss in the 7034 duct for a conventional meter could be around 2.34 MPa (340 psi). Narrower shedder bars are needed in the fuel flowmeters. Design testing was carried out using air at a local calibration facility in which choked nozzles are used as flow standards. The first tests, using a straight test duct, indicated that a shedder bar of the conventional triangular cross section with truncated corners gave a satisfactory performance, Figure 16. All subsequent gas flowmeters tested had this cross section. Even with the narrowed triangular shedder bar, airflow would choke above about 150 m/s (500 ft/s). With a velocity of sound for hydrogen at least four times greater, the VS flowmeter tested should be able to measure hydrogen flows up to 600 m/s before choking. At flow velocities of 150 m/s, the shedding frequency was about 3.4 kHz.

The later fuel flowmeters tested had the shedder bar suspension shown in Figure 4. A wire strain gage sometimes replaced the PZT as the vortex detector. The first shedder bars tested were steel. When their signal spectra were found to include rather strong flow independent lines, shedder bars of lower density material, aluminum and titanium, were built and tested. The less dense material reduced the flow independent spectrum lines in the output signal. The aluminum shedder bars have less fatigue strength than steel, and one broke at a point near the center of the duct during a test. The failure of the shedder bar probably occurred after the flow choked at the test flowmeter as the tests were run up to the choked condition. The titanium shedder bar, 89-5-1, though it was tested more than once, did not fail. The sensors and sensor leads on the shedder bars were also prone to break. The sensor leads would have been more fatigue resistant had alloy wire been used instead of copper.

Even though the meters could not be tested to the maximum flow rate, the ability of the flowmeter to measure gas flow in an engine duct could be inferred. Meter 89-5-1 was tested in the 7034 duct. The shedder bar suspension was like that shown in Figure 4 but its cross section was triangular. Representative wide and narrow band spectra through the flow range are shown in Figure 17. Like the liquid flowmeters, narrow spectrum lines can be obtained in the SSME ducts without the use of a flow conditioner preceding the meter. The spectra are relatively free of any other significant lines other than somewhat broadened harmonics of the vortex shedding frequency. An exception is the broadened line accompanying the 3 kHz vortex generated signal line, Figure 17. The spectrum lines were mostly narrow. In spite of the narrowed shedder bar, the output signal amplitude showed little fade. The absence of fade may again result from the low viscosity of the measured fluid.

The 7034 duct lacked the instrument ports near the flowmeter needed for the temperature and pressure measurements to convert the flowmeter reading to a mass flow. A pressure measurement was required to hold the test pressure constant to maintain the density constant as the flow was varied. The closest duct port available for the pressure tap was 1.1 m upstream. For some flowmeters a port was available on the flowmeter itself. The flowmeter port measured the average pressure at the circular gap around the shedder bar at the sensor end. The pressure at this gap is some average of the pressures before and after the shedder. When the flowmeter port was used to hold the test pressure constant, the meter factor for flowmeters like 89-5-1 was relatively constant. When the pressure was held constant at the port 1.1 m up stream of the flowmeter, the meter factor was flow dependent above about 50 m/s. The meter factor increased by 10 to 20 percent because of the gas expansion between the pressure port and the flowmeter.

A preliminary set of tests was done using a straight 51 mm duct ported to permit additional pressure measurements. The pressure measurements at high flows were inconsistent probably because of localized compressibility effects. The pressure loss across the flowmeter for hydrogen at maximum flow was estimated to be 0.6 MPa (87 psi).

Some of the early gas flowmeters were tested in water prior to the air flow tests. The meter factors had different Reynolds number dependencies for air and gas and if extrapolated to the same Reynolds number the meter factors could differ by more than 10 percent [3].

Development of hydrogen gas flowmeters for the higher velocity applications is going to require a test facility that can use hydrogen gas. Because of the high flow velocities in these ducts, the flowmeter, thermometers, and pressure transducer will need to be calibrated as a unit for best accuracy.

7. Discussion

7.1 Liquid Flowmeters: Water Flow Tests

The results of these flowmeter tests show that vortex shedding flowmeters can measure water flow to the expected maximum velocities in the 28 mm, 51 mm, and 58.4 mm bore LOX ducts without upstream flow conditioning. For SSME applications, the duct vibrations might add interfering lines into the signal spectrum. This needs to be examined.

The head loss introduced by using VS flowmeters to flows well above the conventional 6 m/s maximum can be reduced by narrowing the shedder bar. Doing so, however, reduces the stability of vortex shedding. The signal instability usually increased rather than decreased with increasing flow. The occasional signal fade resulting from the unstable flow did not obviously degrade the flowmeter performance in terms of the linearity and scatter of the meter factor as a function of flow.

The nearby duct bends upstream and downstream of the flowmeters were expected to adversely affect the meter performance. Instead, the presence of close upstream duct bends seems to be necessary to sufficiently stabilize the vortex shedding of the flowmeters, especially for 93-4-1 when measuring water flow. The limited testing of a flowmeter in both the straight and SSME ducts with water indicates that a flowmeter designed to perform acceptably in one duct will probably perform poorly in the other. Thus, the duct bends are necessary for good performance of a flowmeter designed for the engine ducts.

If the flow in the 51 mm bore 7031 duct is to be measured with a flowmeter of the 93-4-1 design, then it should be placed within 10 diameters of the nearest upstream bend according to the water flow test results. Possibly, the poorer performance produced by 93-4-1 relative to 85-4-7 in straight ducts for water could result from 93-4-1 being both wider and having a larger d/w.

The 28 mm bore meters with a width-to-duct diameter ratio similar to 88-7-2 performed poorly in most water tests. This suggested that the absolute width w as well as D/d, factors into the signal stability.

A way around the paradox of achieving lowered head loss at the sacrifice of shedding stability is to use a shedder geometry consisting of a cylinder with a cross slit. For water flow tests in the 28 mm duct, a flowmeter of this design approached the performance of the commercial flowmeters used for reference in terms of line width. However, linearity of the flowmeter is sacrificed to achieve the better performance. Even though the preliminary attempt to use the slit circular cylinder in a 58.5 mm duct flowmeter was unsuccessful, slit cylinders of the appropriate design still might improve the performances of the 51 and 58.5 mm bore flowmeters. This has yet to be confirmed experimentally.

These flowmeters with narrowed shedder bars are more sensitive to geometry and fluid properties than conventional VS flowmeters. For best accuracy, it will be necessary for them to be calibrated in the duct with the duct fluid as demonstrated by the changing meter factors shown in Figure 10.

7.2 Liquid Nitrogen Tests

Ultimately, more extensive testing of the flowmeter designs in cryogenic fluids should be done. The work done so far just shows that the VS flowmeter design tested is suitable for cryogenic applications.

No flowmeter with the 88-7-2 dimensions was tested with cryogenic fluids. Only two meters, 86-4-2 and 93-4-1, have been tested with cryogenic liquids, both in LN_2. Test results for both flowmeters showed better performance with LN_2 than with water. The improvement was relatively less for 86-4-2 but it was tested in the 7035 duct, while 93-4-1 was tested in a straight duct. This is consistent with upstream bends improving the flowmeter performance. Based on this, it seems likely that 88-7-2 would perform better in the 7035 test duct for LN_2 flow than for water.

Vortex shedding flowmeters commercially available tend to correlate through Reynolds number. The SSME duct flowmeters tested in both water and LN_2 or water and air did not. Finding why they do not was outside the scope of this work.

More tests of flowmeters in LN_2 are needed to confirm the expectations of better performance there. The amount of LN_2 testing was insufficient to confidently predict a good performance. Since LOX has a similarly low viscosity, the flowmeter performance with LOX should be similar to that with LN_2. LOX differs from LN_2 mainly in density. Density has not yet been demonstrated to alter flowmeter performance. LOX flow testing needs to be done to substantiate the presumption that the performance is the same as that for LN_2.

The other best flowmeters from water flow testing need to be tested with LN_2 to ascertain that changing fluids does not degrade the performance of the flowmeter obtained for water. More tests with LN_2 are needed to determine to what extent elbows improve the metering of low velocity fluids. Viscosity obviously has a strong effect on the performance of these reduced width shedder bars. Perhaps a different shedder bar shape, such as the cross slitted cylinder, could improve the performance of the flowmeter measuring low viscosity fluids. The testing done so far in LN_2 flow was insufficient to provide any definition of the flow region where the VS flowmeter gives a satisfactory performance or whether a better cross sectional shape of the shedder might be found.

7.3 Gas Flowmeters

The development of gas flowmeters for hydrogen has been hampered by the lack of a suitable hydrogen gas flow facility. Airflow simulation of hydrogen flow is limited to maximum flow velocities of about 150 m/s by compressibility effects. However, localized compressibility effects are having an impact at lower velocities. The test results suggest that the VS meter with a narrowed shedder bar can also measure flow in the SSME engine ducts without any flow conditioning upstream of the flowmeter. The shedder bar should be narrowed further, if possible, to reduce the pressure loss.

The response of the sensor could prove to be the major limitation to measuring flows to 250 m/s. It is not clear that detecting the strain on the shedder bar will be a satisfactory vortex sensor up to 250 m/s flow. The testing of alternate sensor designs offering higher frequency response could still be done with air up to near Mach 1 but testing to 250 m/s flow and flowmeter calibration will eventually require a high pressure, high flow hydrogen test facility. A more rigidly mounted shedder bar with pressure ports connecting to a diaphragm sensor outside the flow stream may be a better sensor design. That approach has worked well for the reference flowmeters used in the water flow tests, but the frequency was much lower and the fluid coupling the transducer to the shedder was incompressible. It needs to be demonstrated that this sensing method can be applied to the fuel flowmeters. Employing piezo-resistive pressure transducers close to the end of the shedder bar so the porting is short may make pressure sensing a viable vortex detection method.

Igarashi [14] has found that for airflow at lower Reynolds numbers the round cross slitted cylinder provides the strongest vortex shedding signal. Though it has not been tried for this application, the success of the design in the 7032 duct suggests it could also improve the performance of the gas meters. In addition, a round shedder bar can further reduce the pressure loss across the flowmeter.

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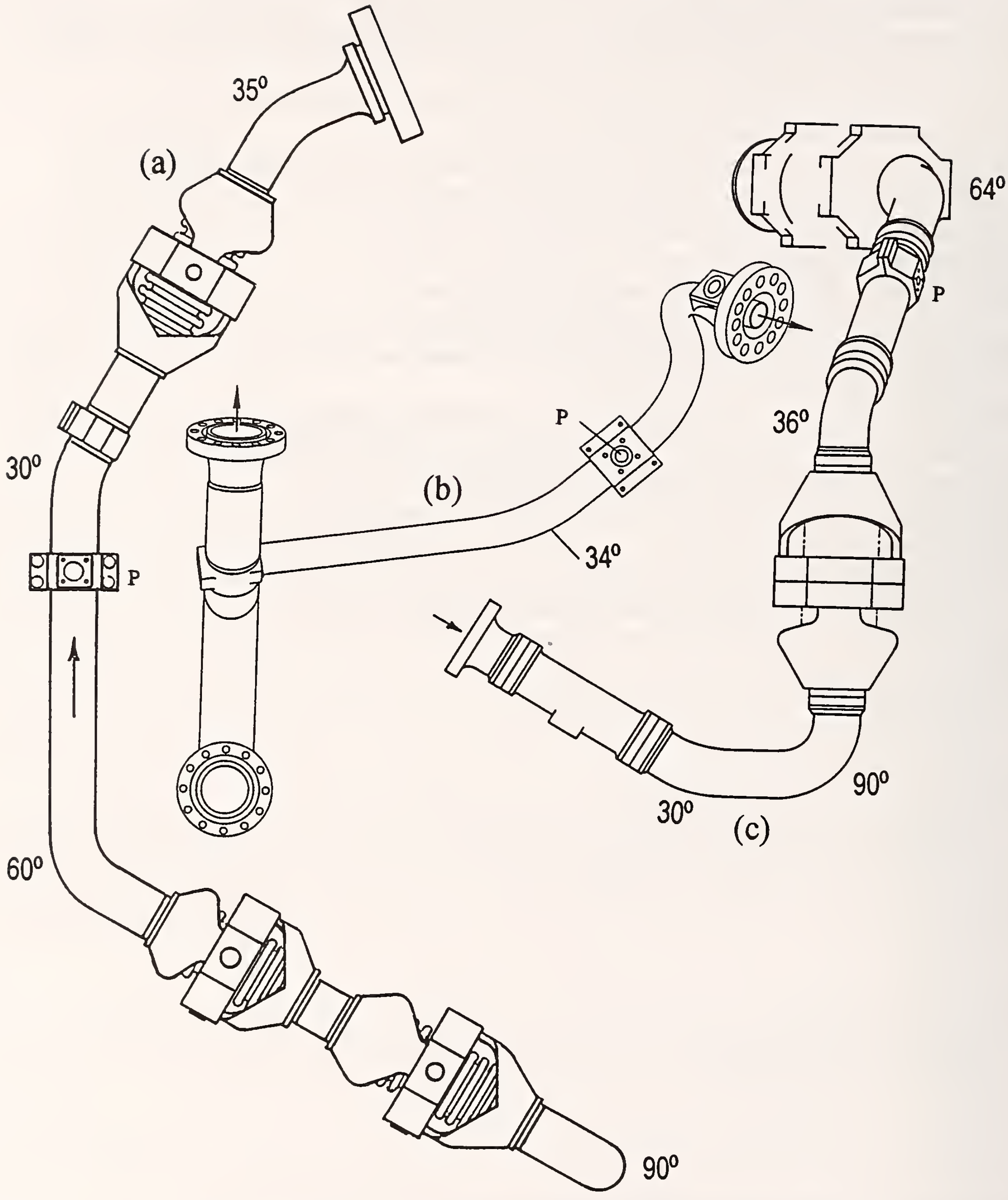

Figure 1. a. The exit section of the RS007035 LOX duct of the SSME. The duct makes a 90° bend into the page. This bend is preceded by three 45° out-of-plane bends preceded by a 90° bend. P – Flowmeter ports.
b. The RS007032 LOX duct with its 28 mm ID side branch.
c. The RS007034 GH_2 duct.

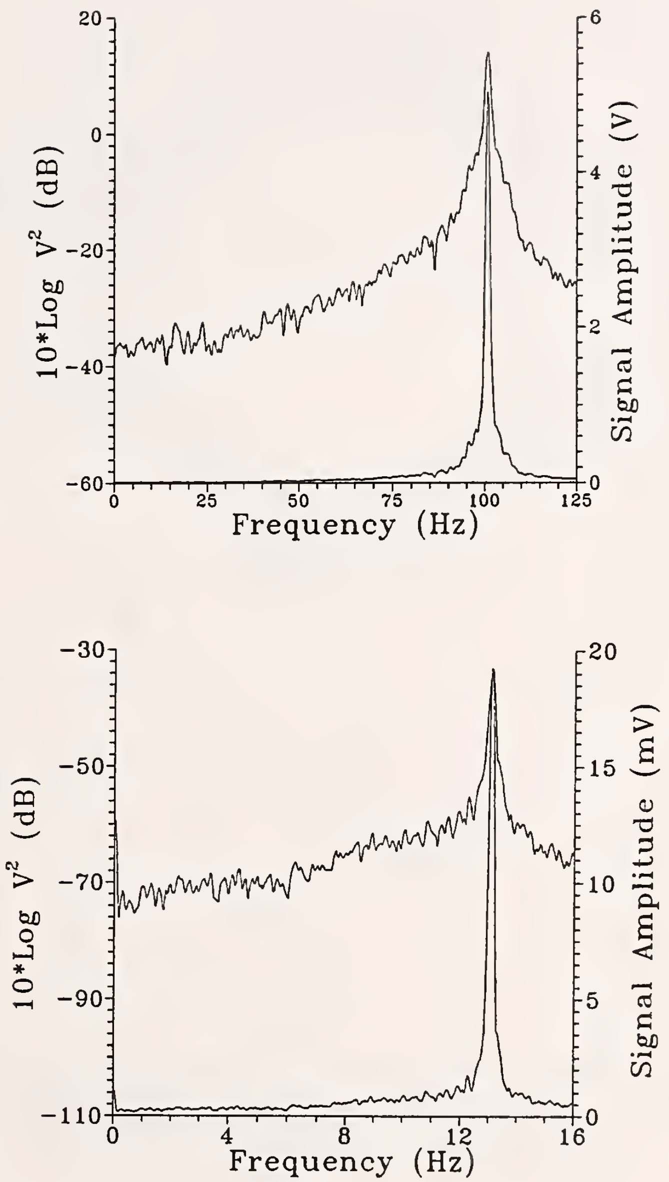

Figure 2. Spectra from a 2 in commercial vortex shedding flowmeter for water. Upper curve, Log V^2 in dB, lower curve, the signal voltage. The data in subsequent spectra are similarly shown.
Top: 0.78 m/s average flow.
Bottom: 6.03 m/s average flow.

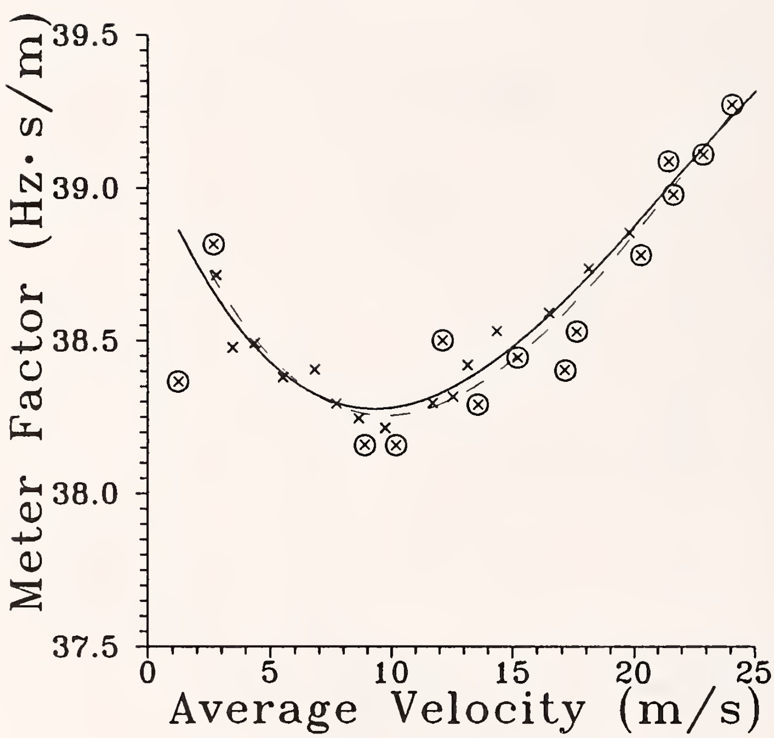

Figure 3. Meter factor of meter 92-9-1 using both the 4 in and 2 in reference meters. Circled X, both reference meters read; X only the 2 in reference read. The dashed line is a fourth-order polynomial fit to all the data. The solid curve is a fourth-order fit to the 2 in data plus the highest four flows where both flowmeters were read.

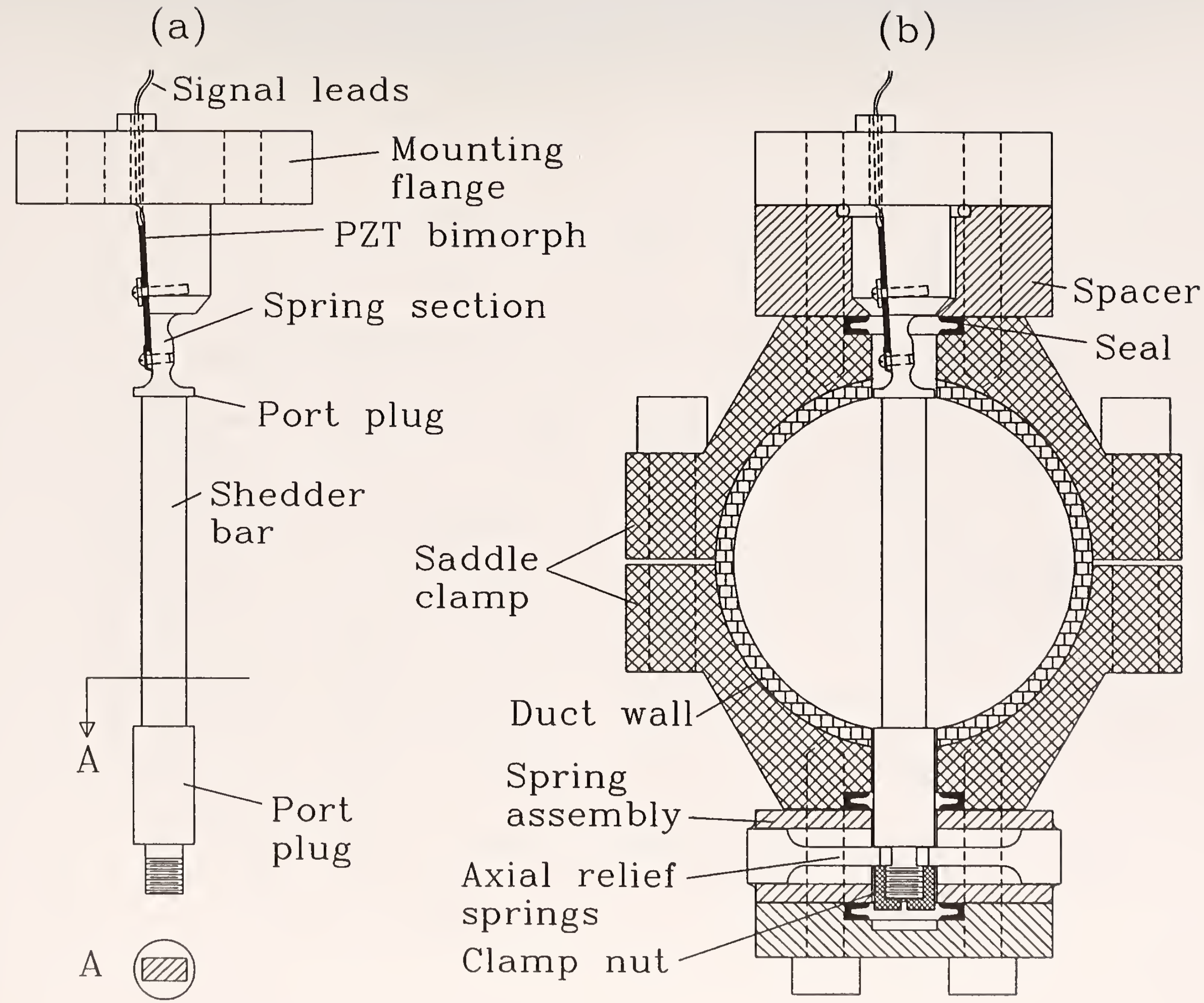

Figure 4. a. Scale drawing of the 88-7-2 flowmeter assembly.
b. The flowmeter in the fabricated meter ports of the RS007035 duct.

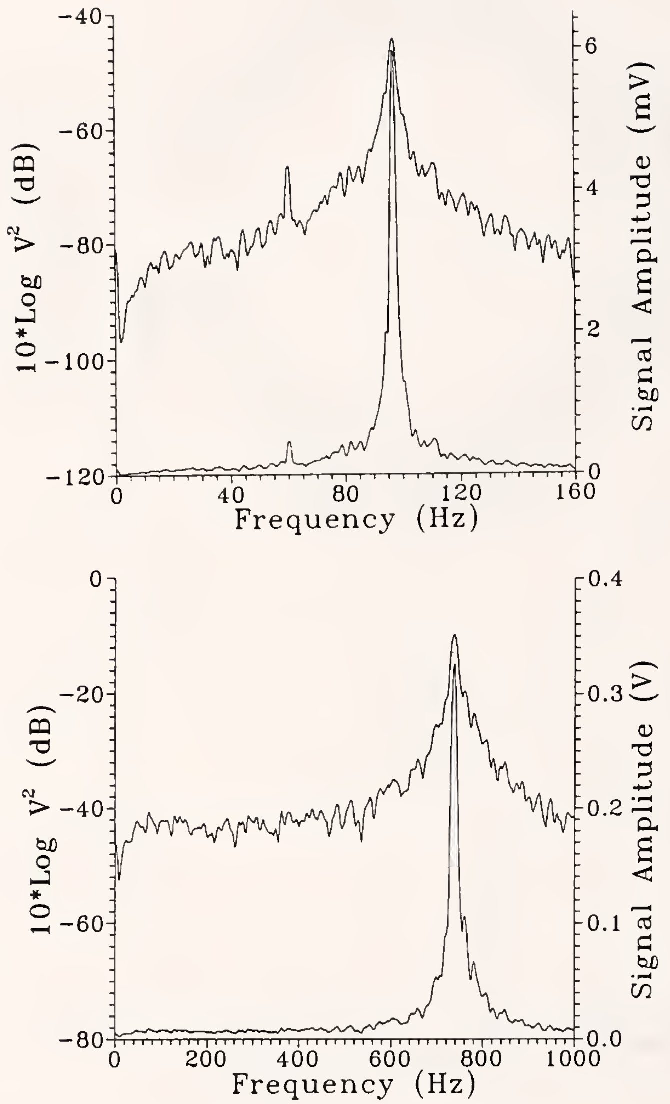

Figure 5. Spectra of 88-7-2 in the RS007035 duct for water flow.
Top: 4.44 m/s average flow.
Bottom: 33.17 m/s average flow.

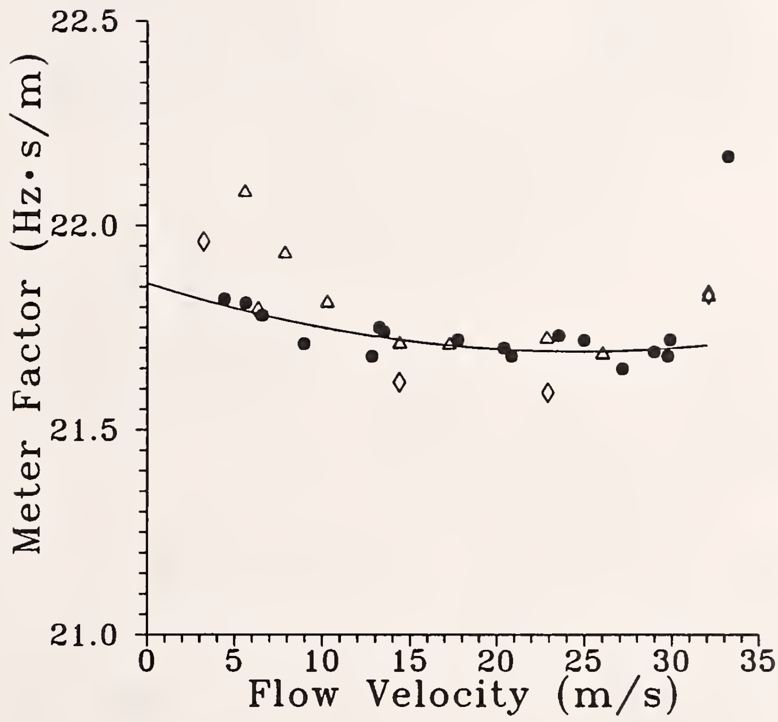

Figure 6. Meter factor measured for 88-7-2 for water in the 7035 duct. The curve is a second order polynomial fit. Solid circles, the 1989 test data. Triangles, the 1996 retest for increasing flows. The diamonds are the data acquired in 1996 for decreasing flow showing the hysteresis that is often seen on start up. The curve is fit to the 1989 data.

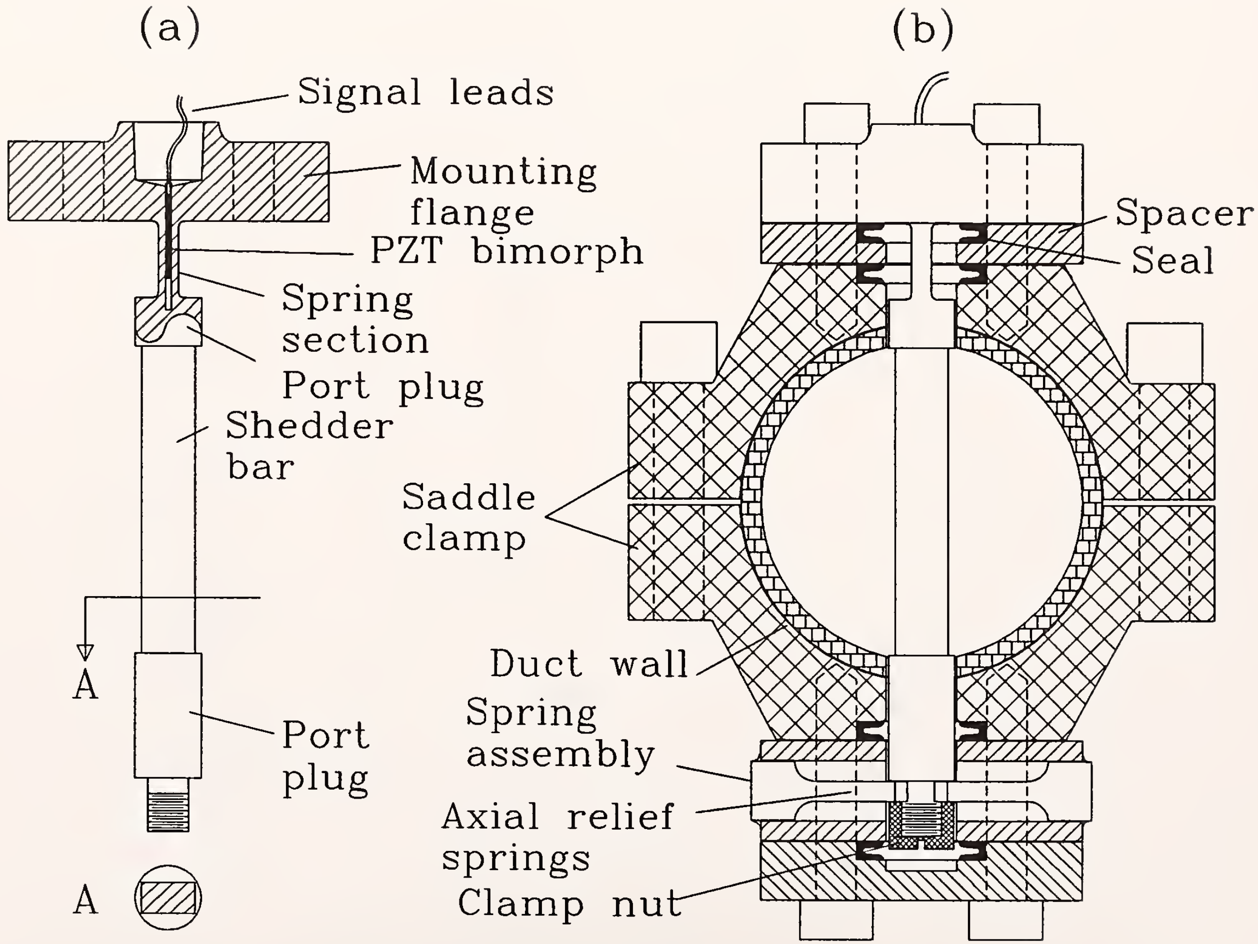

Figure 7. a. Scale drawing of the 93-4-1 flowmeter assembly.
b. The flowmeter in the fabricated meter ports of the RS007034 duct.

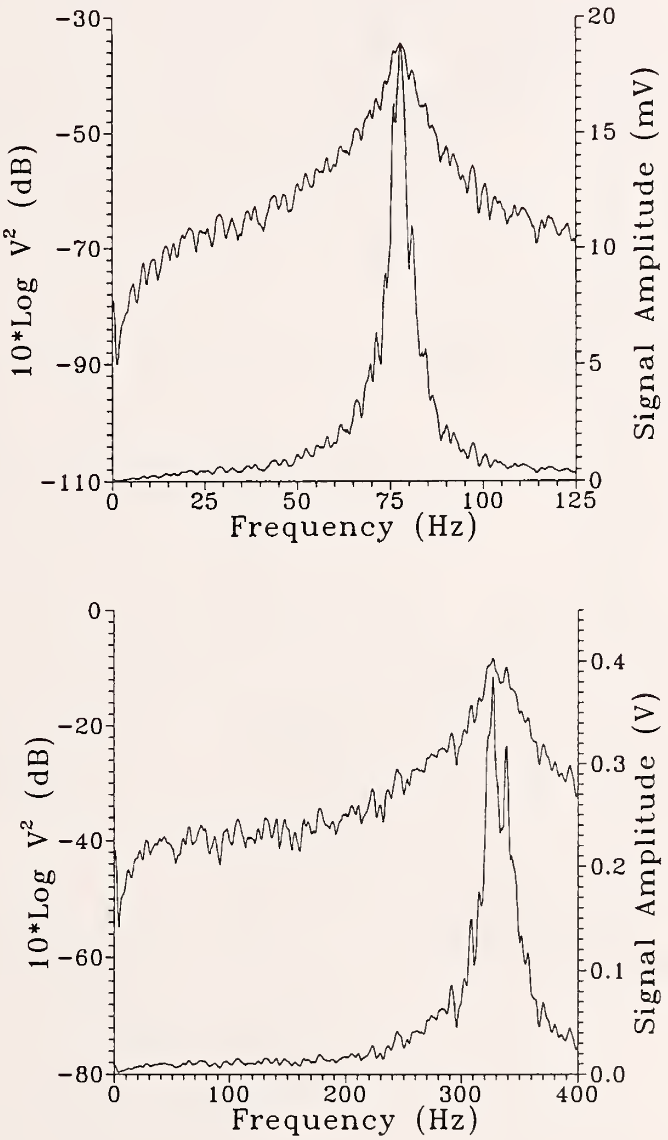

Figure 8. Spectra of 93-4-1 in the straight test duct for water flow.
Top: 3.67 m/s average flow.
Bottom: 16.03 m/s average flow.

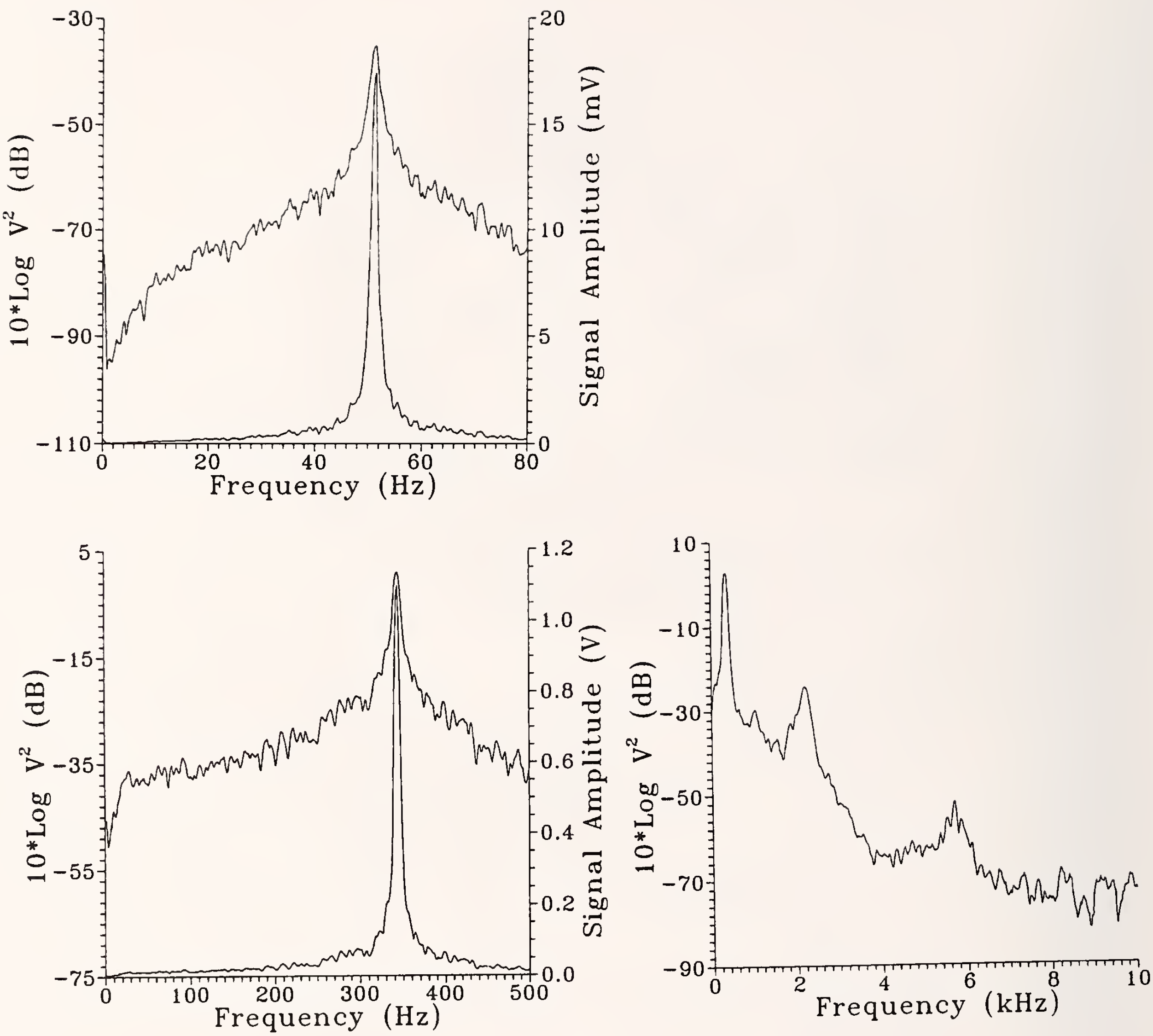

Figure 9. Spectra of 93-4-1 in the 7034 duct for water flow.
Top: 2.43 m/s average flow.
Bottom left: 16.88 m/s average flow.
Bottom right: 16.88 m/s broad band spectrum.

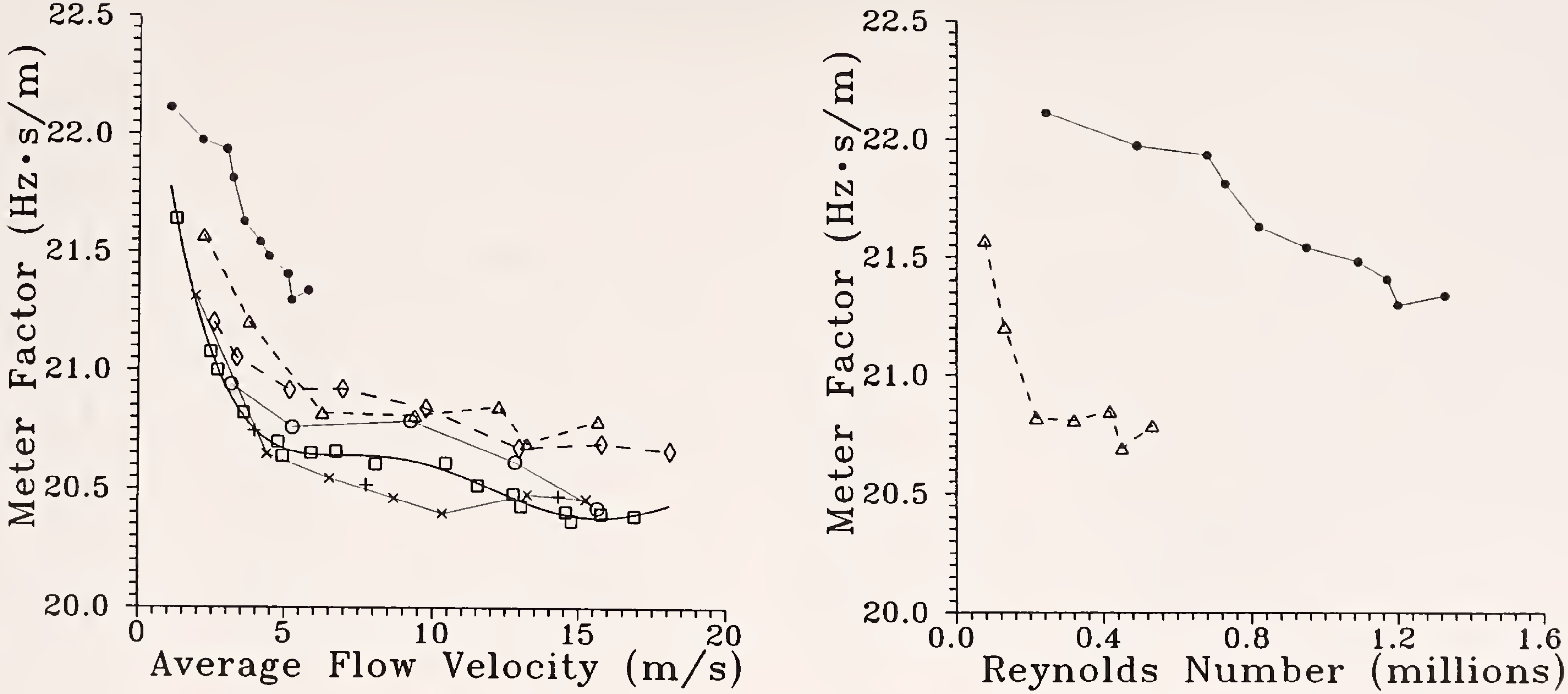

Figure 10. Left) Meter factor of 93-4-1 for different fluids and different ducts and duct configurations. Squares, water flow in the 7034 duct. The solid line is a 5th order polynomial fit. Triangles, water flow in the straight test duct. Diamonds, water flow with the straight test duct reversed. Circles, water flow in the honed straight test duct preceded by a 90° elbow. + and x, water flow in the reversed honed straight test duct and preceded by a 90° elbow. Solid circles, LN_2 flow in the honed straight duct.

Right) Meter factor as a function of Reynolds Number for 93-4-1. Triangles, water in the straight test duct. Solid circles, LN_2 flow in the honed straight test duct.

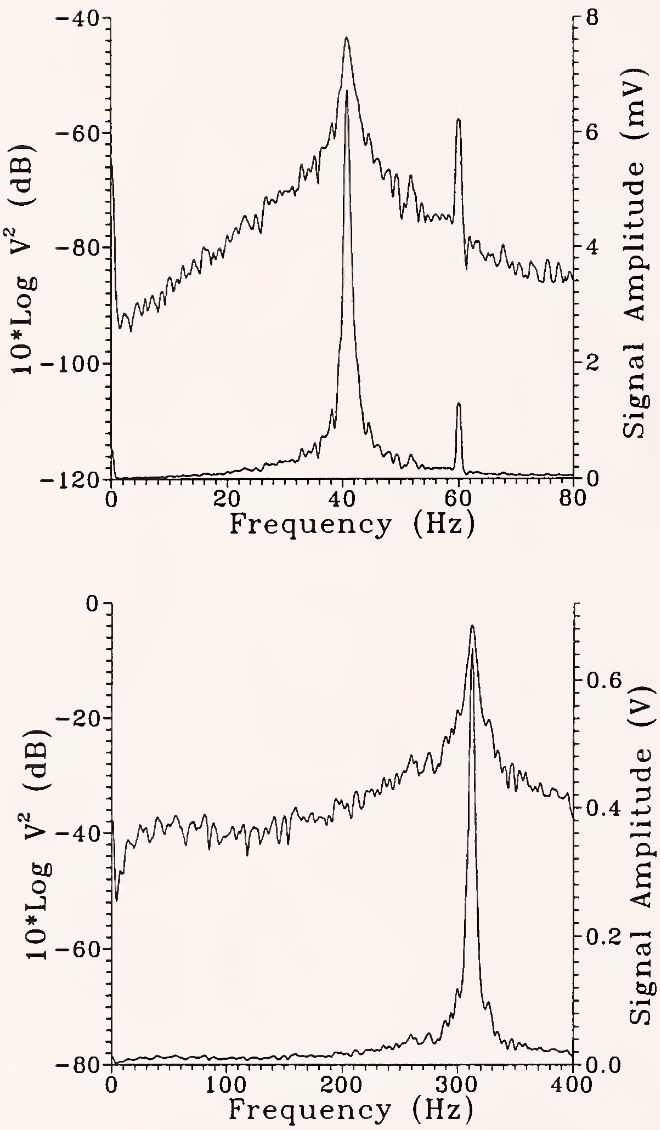

Figure 11. Spectra of 93-4-1 for water flow in the reversed straight test duct preceded by a 90° elbow.
Top: 1.915 m/s average flow.
Bottom: 15.24 m/s average flow.

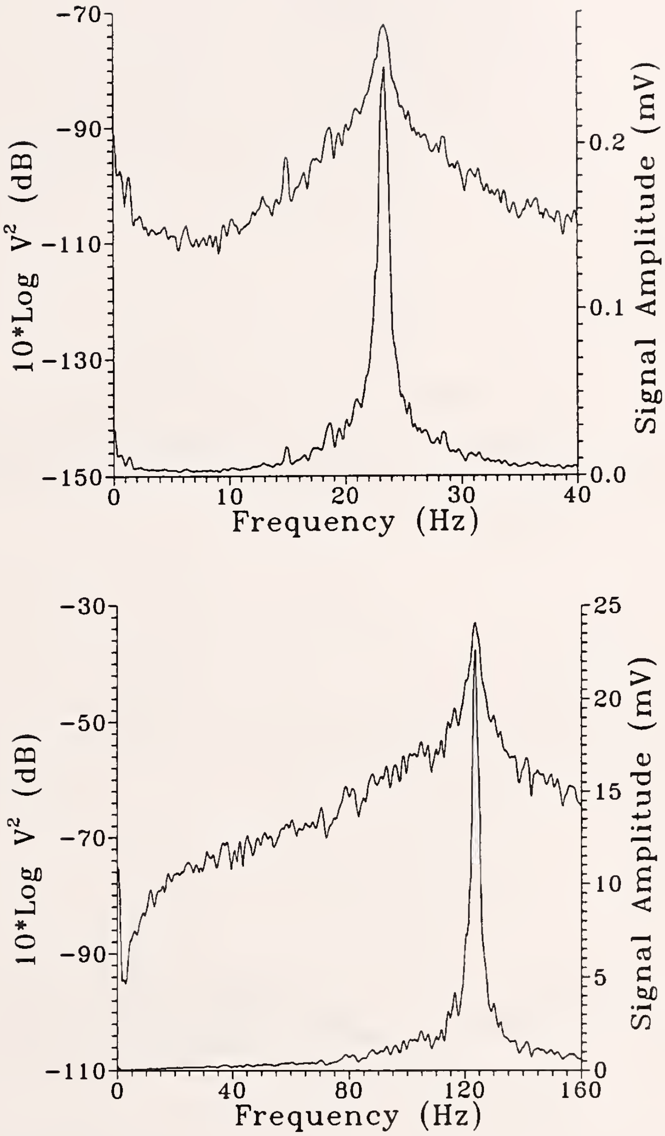

Figure 12. Spectra of 93-4-1 in the straight test duct for LN_2 flow.
Top: 1.05 m/s average flow.
Bottom: 5.77 m/s average flow.

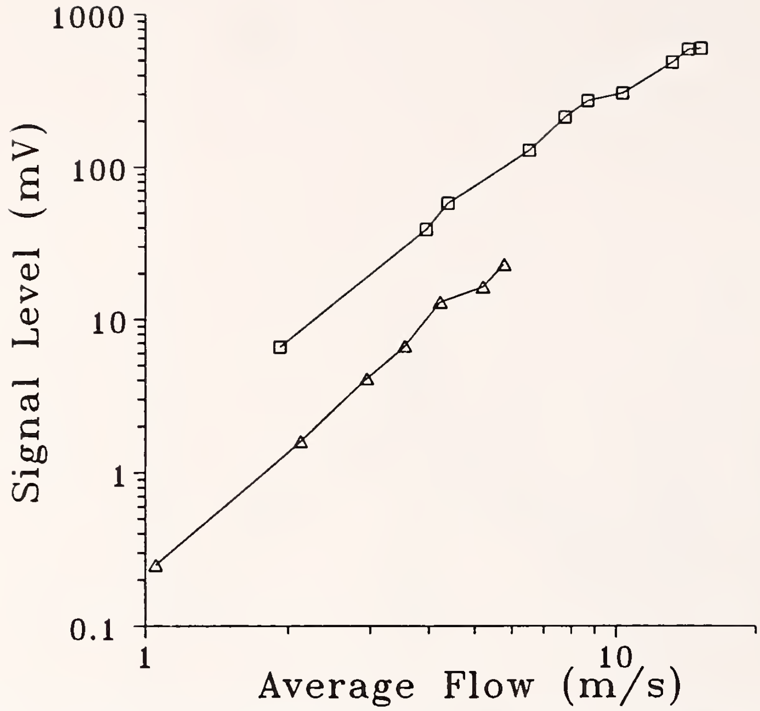

Figure 13. The output signal voltage from 93-4-1 as a function of flow for water in the reversed straight test duct with preceding elbow, squares, and LN_2 at 77 K in the straight test duct, triangles.

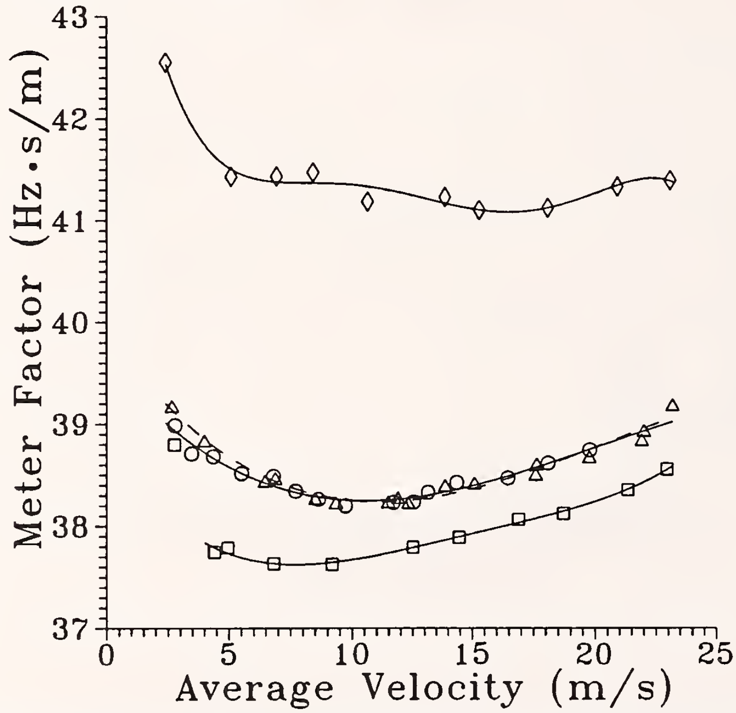

Figure 14. The meter factors with polynomial fits for water of three circular cross sectioned shedder bars with cross slits. In the 28 mm bore 7032 duct side branch. Circles and triangles, 92-9-1 on different days, third order. Squares, 93-10-2, fourth order. Diamonds, 93-9-1, fifth order.

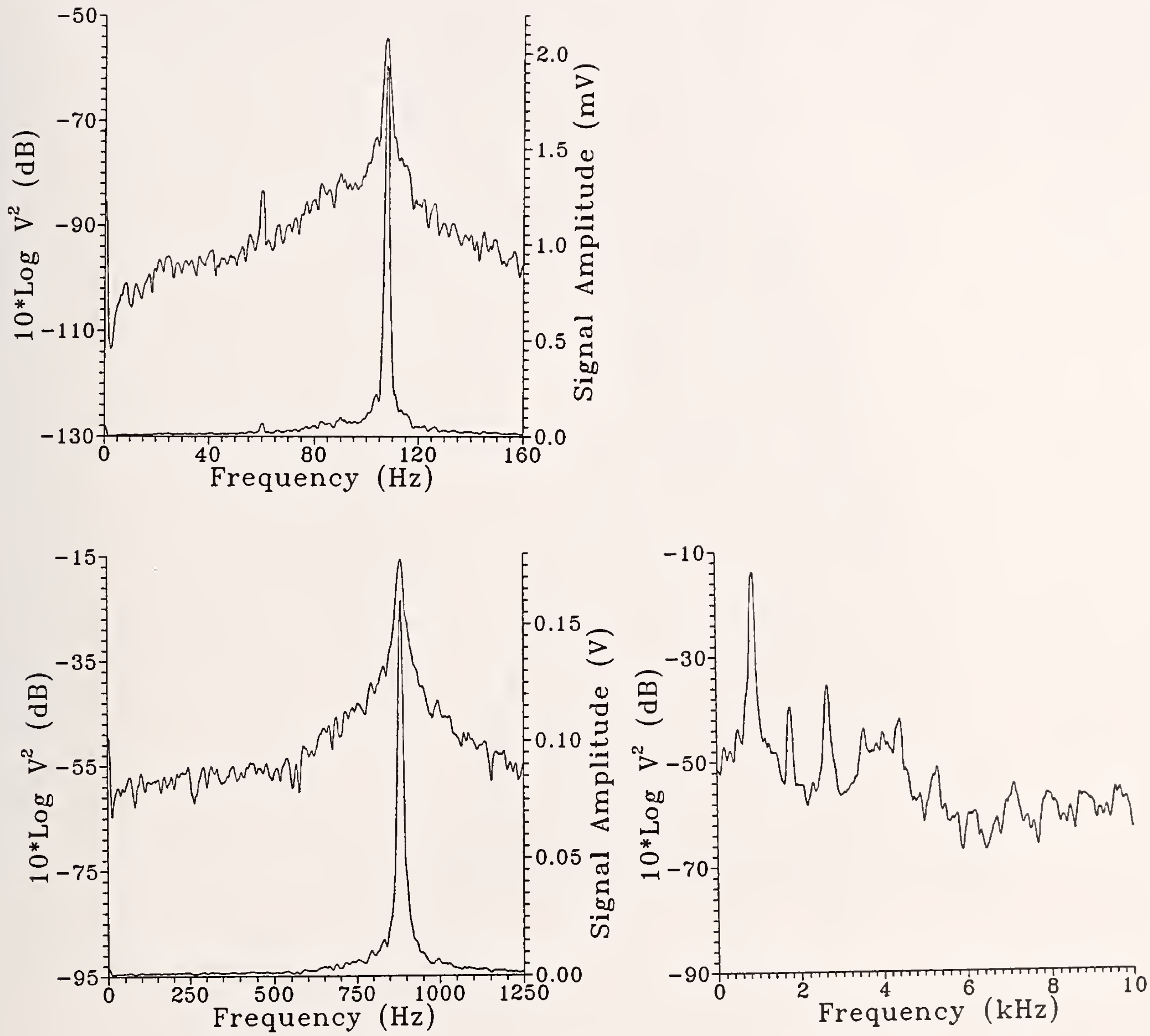

Figure 15. Spectra of 93-10-2 in the 28 mm side branch of the 7032 duct. The shedder bars have a circular cross section with a cross slit on the diameter.
Top: 2.77 m/s average flow.
Bottom left: 22.9 m/s average flow.
Bottom right: 22.9 m/s broad band spectrum.

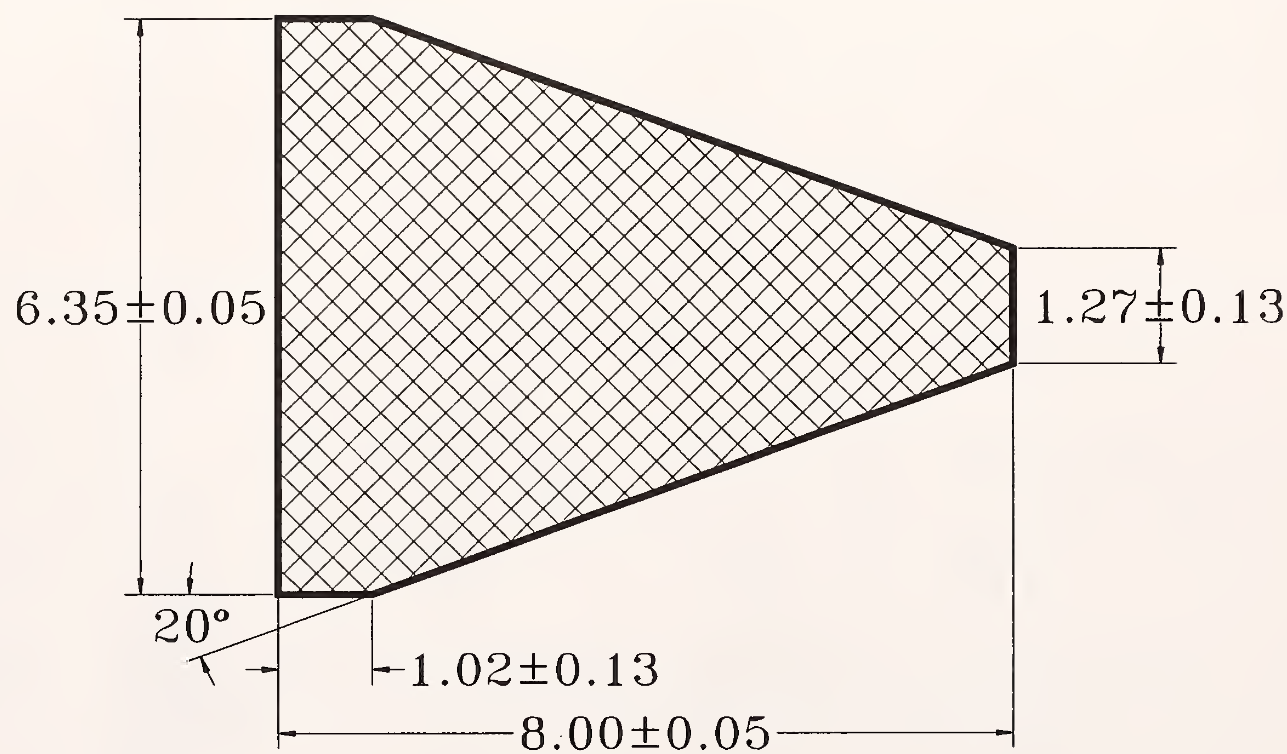

Figure 16. The cross section of the shedder bar of 89-5-1, dimensions in millimeters.

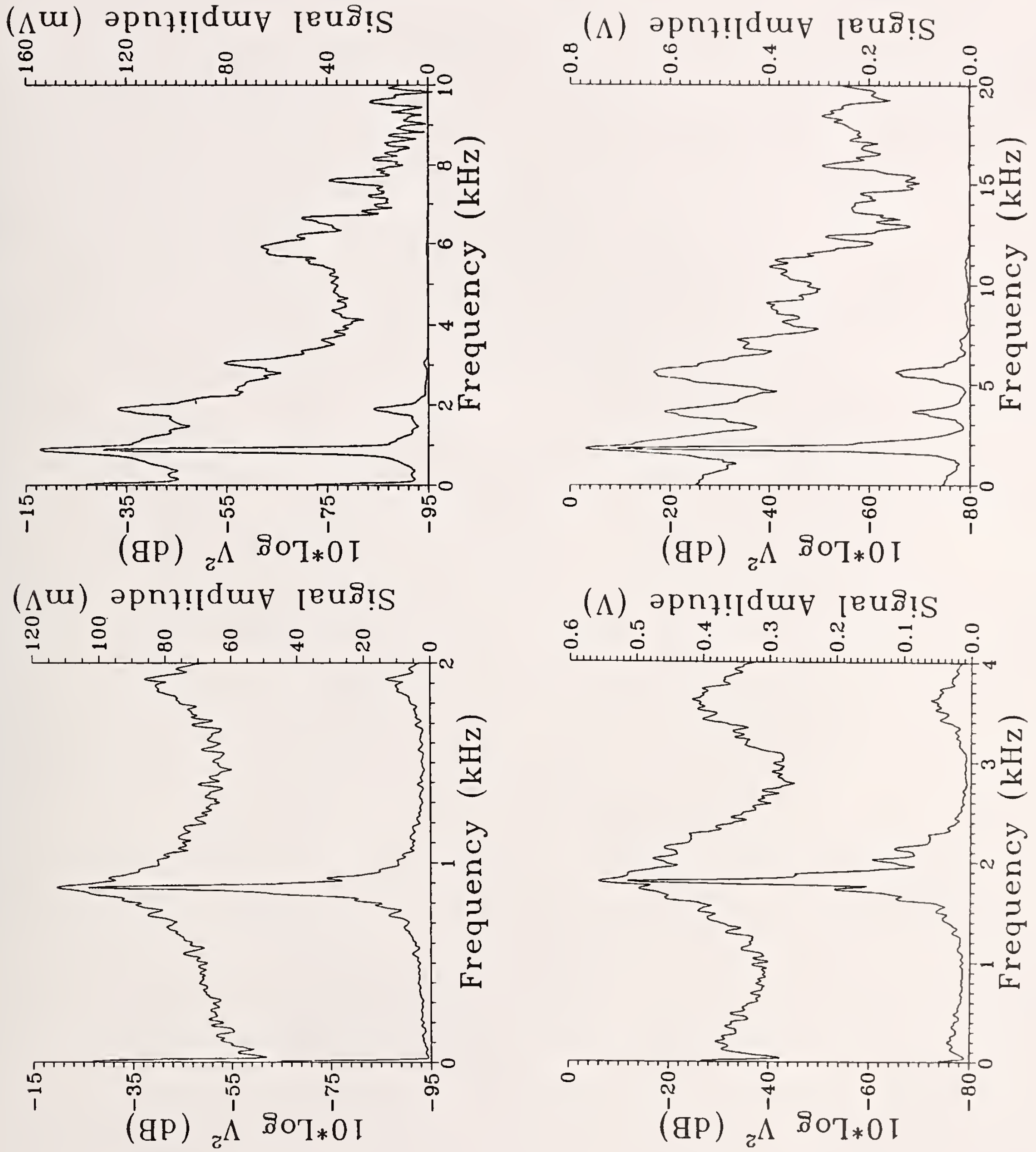

Figure 17. Narrow and wide band spectra from 89-5-1, a hydrogen gas flowmeter tested with compressed air at the density of the hydrogen gas:
Top pair: 38.5 m/s average flow velocity.
Bottom pair: 79 m/s average flow velocity.

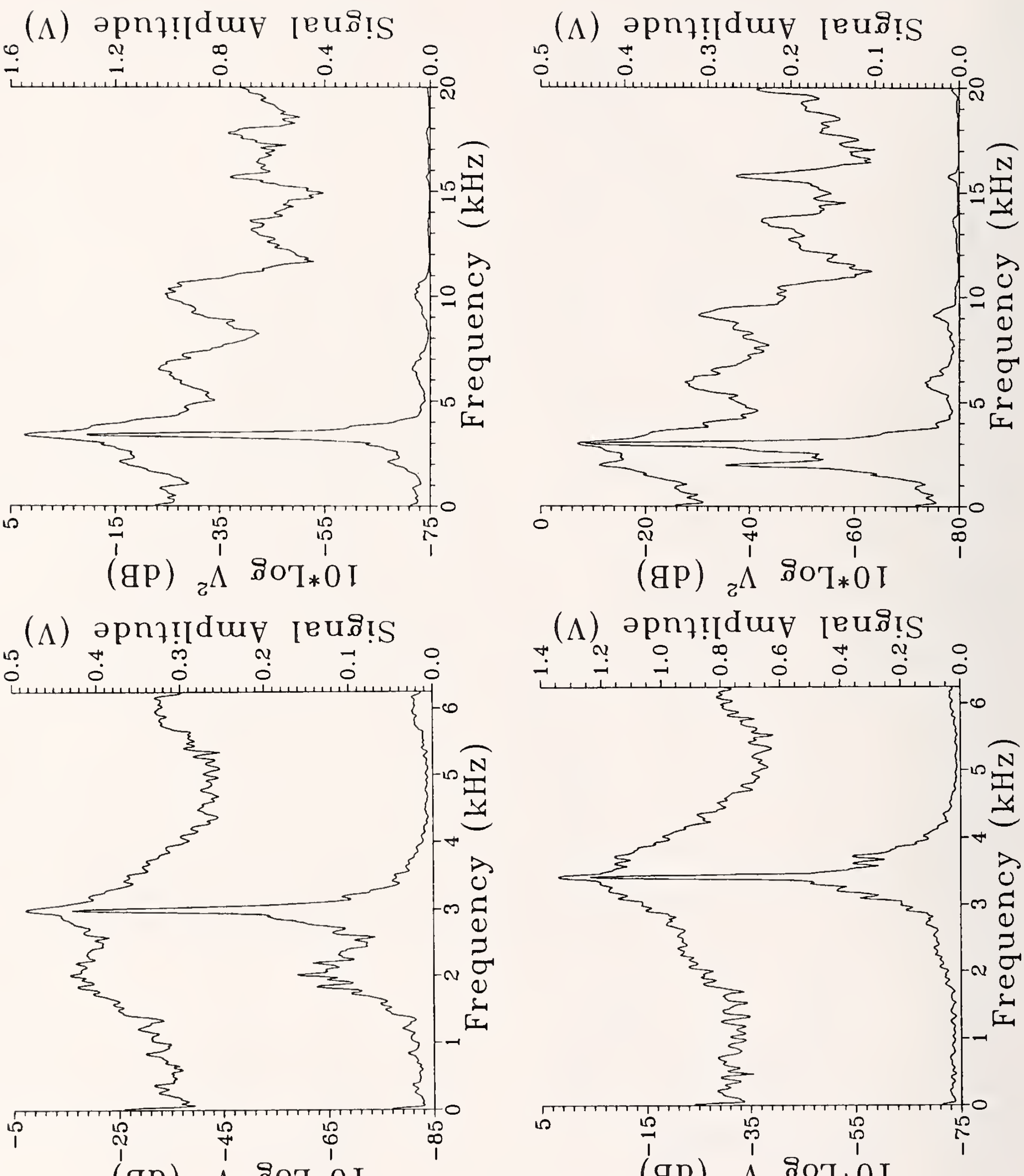

Figure 17. (Continued.)
Top pair: 128 m/s average flow velocity.
Bottom pair: 150 m/s average flow velocity.

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