VORTEX SHEDDING FLOWMETERS FOR LIQUIDS AT HIGH FLOW VELOCITIES

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Abstract

A number of vortex shedding flowmeter designs for flow measurements in liquid oxygen ducts on the space shuttle main engines have been tested in a high head water flow test facility. The results have shown that a vortex shedding element or vane spanning the duct can give a linear response to an average flow velocity of 46 m/s (150 ft/s) in a 1½ inch nominal (41 mm actual) diameter duct while a vane partially spanning the duct can give a linear response to velocities exceeding 55 m/s (180 ft/s). The maximum pressure drops across the flow sensing elements extrapolate to less than 0.7 MPa (100 psi) at 56 m/s (184 ft/s) for liquid oxygen. The test results indicate that the vanes probably cannot be scaled up with pipe size, at least not linearly. The present successful designs of cantilevered vanes can be installed through the 11.2 mm (0.44 in) diameter pressure ports in the shuttle propellant ducts. The full vane shows some sensitivity to swirl and the cantilevered vane shows more.

Introduction

The National Bureau of Standards (NBS) has been requested by NASA to determine whether vortex shedding flowmeters are suitable for measuring liquid oxygen (LOX) flow in ducts on the space shuttle main engine (SSME). The flowmeter will be subject to high levels of vibration, some swirl, and cryogenic temperatures. Also, in the main LOX duct, the maximum flow velocity is 50 m/s (164 ft/s) which is ten times higher than the maximum for which liquid flowmeters are commercially available.

The vortex shedding flowmeter consists of a vortex-shedding vane or strut spanning the pipe on a diameter[1-4] (see figures 4 and 6). The upstream face is generally flat with sharp corners along each edge. Vortices are alternately shed from these corners. The shed rate of these vortices is given by the Struhal equation

$$f = SV/d$$

where V is the velocity, d is the vane width and S is the Struhal number which is a constant nearly independent of any other fluid property for a properly designed meter. Thus, the flow rate is measured by counting vortices for a fixed time interval and multiplying by a conversion factor. The alternate shedding of vortices introduces a time varying pressure difference across the vane. This varying pressure can be measured with a pressure sensing device or can provide a time varying flow sensed by a thermal detector. This pressure provides a lift force that can be measured with a strain gauge. The vortices can also be counted downstream using ultrasonic techniques.

Whether the vortex shedding flowmeter could measure liquid flow at such high velocities can be determined at a much lower cost using water rather than LOX. Unfortunately, conventional water flow facilities are not capable of the high pressures required. The twenty-five diameter long section of straight pipe, recommended for proper meter installation, alone introduces an estimated 0.7 MPa (100 psi) pressure drop. The commercial flowmeter loaned to NBS as a starting point for the tests is estimated to introduce a 3.7 MPa (540 psi) pressure drop at 56 m/s flow.

Public Service Company of Colorado gave NBS permission to connect the test facility illustrated in Figure 1 to the penstocks at their Boulder Hydroelectric plant. The penstocks provide a 557 m (1828 ft) head and a maximum flow of 1.4 m^3/s (22,000 gal/min). The 1½ in nominal diameter (41 mm actual) test section permitted testing of commercial meters of the smallest size without using large quantities of water and introducing large pressure drops in the upstream portion of the flow test piping. The 4 in flowmeter served as a reference meter and was calibrated to 4.5 m/s flow velocity. It is assumed linear on up to 9 m/s.

Flow Meter Test Results

The pressure drop across the only commercial meter tested varied as the velocity squared and extrapolated close to the manufacturers estimated 3.7 MPa at 56 m/s as shown in Figure 2. The vortex detector consisted of a magnetic disc oscillated near a pick up coil by the pressure fluctuations across the vane. The disc was demolished at high flow velocities and replaced by a 7 MPa (1000 psi) variable reluctance pressure transducer. As Figure 3 illustrates, the commercial meter was linear to about 30 m/s (100 ft/s).

The design specifications for a meter in the 4 in main LOX duct call for a maximum pressure drop not to exceed 0.7 MPa (100 psi) at 50 m/s flow. The next meter tested had a vane whose cross section was similar to the commercial meter vane but half the size. The vane was now 6.35 mm wide instead of 12.7 mm. As shown in Figure 2, the maximum pressure drop was now below 0.7 MPa. This vane was linear to about 45 m/s (150 ft/s) as shown in Figure 3. The shedding frequency of the narrower vane was slightly lower. This appears to contradict the Struhal equation. The 12.7 mm wide vane apparently blocked the pipe such that the velocity by the body is more than twice the velocity of the liquid past the 6.4 mm vane. The frequency does increase with decreasing width for vane widths below 6.4 mm.

The vortex detectors on these first vanes were pressure transducers referenced to ambient pressure and sensing the pipe pressure at a port in the side of the vane. The signal spectrum obtained with these vanes displayed on a spectrum analyzer had a high noise background and stray lines independent of flow.

The extra lines were probably resonances in the port and connecting line to the transducer.

The lift sensing vane shown in Figure 4 gave a greatly improved signal-to-noise ratio. Figure 5 shows some test data from models of this vane consisting of a 6.2 mm square vane section and a 6.4 mm wide triangular cross section.

The vane design shown in Figure 6 gave an even better signal-to-noise ratio. The vane portion of this meter was a beryllium copper link with a 5.1 mm wide by 4.2 mm deep rectangular cross section. The ferroelectric strain sensor (PZT) measured the strain in the mounting post. This link design eliminated vane failures from fatigue. The signal-to-noise ratio was 30 dB according to the spectrum analyzer. The filter band width in the signal-processing electronics could be set wide enough to include the flow range of interest without changing the count rate. Test results for this meter are shown in Figure 7 for swirl at various angles. This vane performed the best of any tested. A 3.8 mm wide trapezoidal cross-sectioned link vane tested had a vibration amplitude so extreme it was audible some distance from the pipe. The vane showed considerable wear after a very short period of testing and the sensitivity was not constant.

Since NASA would like to install a flow sensing device through a 11.2 mm pressure transducer port, partial vanes cantilevered from one wall of the pipe were tested. A preliminary test with the Figure 4 squarevane cut off to 18 mm showed a vortex generated signal could be obtained. Similar vanes using the meter body and PZT sensor of Figure 6 with square, triangular and "T" shaped cross sections and spring sections of varying stiffness were tried. Many produced a vortex line in the signal spectrum but in general the signal-to-noise ratio was poor at best.

The spring mounted cantilevered vane evolved after testing a number of alternatives to the design shown in Figure 8. Vanes with widths in the range of about 6 to 4.8 mm with depths around 80% of the width and sides at angles between 90° and 93° with the front face gave the best vortex signals and signal-to-noise ratios. The narrower vanes were better. Vanes 7.6 mm in width could use most of the 11.2 mm port diameter available but gave very poor results with the exception of one vane with a pressure sensor for vortices. The narrower vanes of Figure 8 design were giving sufficiently good signals to try a design that fit through a 11.2 mm port. Adding a 13 mm long by 11 mm cylindrical section between the vane and the mounting resulted in a poor signal-to-noise ratio again. A modification that placed the spring section in this cylindrical section with only a single PZT strain sensor produced a cantilevered vane with a signal-to-noise ratio exceeding 20 dB. This was the best cantilevered vane performance. Results of a flow test with this vane are shown in Figure 7 along with some swirl tests of the same width vane, with the Figure 6 mount. As Figure 7 shows, cantilevered vanes with the same widths as the link vane have a lower sensitivity. This probably results from some of the flow shifting to the side of the pipe opposite the vane.

Early swirl tests of a full vane showed a low sensitivity to swirl. Later tests of the link vane, Figure 7, showed that over 15° of swirl could be added 17 diameters upstream before the signal-to-noise ratio became poor. The sensitivity decreases somewhat, possibly from lost counts. The one cantilevered vane tested in swirl was more sensitive.

Tentative Conclusions

Some conclusions can be drawn from the tests thus far. Many of these are conditional in that other detector designs may give quite different results with the same vane. For instance, any cylinder with a cross section parallel to the flow and a flat up-stream face with sharp corners must shed vortices. However, in these tests only vanes with a nearly rectangular cross section and with the width at least equal to or greater than the depth gave strong signal spectrum lines. A trapezoidal cross sectioned vane with the wider side behind seems to be slightly better. The most successful vanes have had a flat back at least as wide as the front face. Probably, the above observations are the result of using the strain detection method. If an ultrasonic detection method were used, another vane shape may well be superior.

The mechanical design of the vane mounting and detection system seems to be important, judging from the results of tests of cantilevered vanes. As an example, the vane design shown in Figure 8 with a 5.1 mm wide vane gives a strong signal. When the 13 mm long cylindrical section was added between the base of the vane and the vane without any other change, a very poor signal was obtained. This result suggests that the vortex detection method works best when the spring section is close to the vane.

By reducing the width of a full vane to about 0.4 of the width of the commercial size vanes, a pressure drop less than 0.7 MPa (100 psi) at maximum flow is possible. The meter factor of such vanes are constant to about 46 m/s (150 ft/s) and repeatable to about 50 m/s (164 ft/s). The limit may be cavitation down stream of the vane. The tests of the link vane, however, show the break in the linearity occurs at nearly the same flow rate even when the pressure at the meter varies by more than 0.7 MPa (100 psi). This result suggests that the ΔP may limit linearity more than the downstream pressure. This interpretation is not contradicted by the partial wave test results, which show a constant meter factor to much higher flow velocities for the same width vanes, since the pressure drop is lower.

Some commercial vanes above the 2 in nominal size are designed simply by scaling up all the dimensions. These 1½ in meter tests were done assuming that the same thing might be done with a 1½ in meter designed for high velocity. The cantilevered vane tests show that the vortex signal improved as the vane was narrowed from 7.6 mm width to 5 mm.

Larger vanes may not work any better in larger meters if flow separation from the vane sides is responsible for this result. This is ideal for the shuttle applications since this vane size fits easily through the 11.2 mm diameter pressure transducer ports. Tests of larger size meters should better define effects of vane width.

The 20% lower sensitivity of the cantilevered vane relative to a full vane of the same width probably results from the flow shifting away from the vane. This shifting of the flow to the opposite side of the pipe away from the vane probably contributes to the higher sensitivity of the cantilevered vane to swirl. Swirl generates higher transverse flow velocities at the cantilevered vane than at a full vane.

Some of the earlier testing suggested that reproducibility of a vane from one test to the next might be poor. Reproducibility was good from run to run and from vane to vane for vanes in the same body and with the same width and length if the depth and cross section are similar. Using orientation marks so a vane can be placed with the front face perpendicular to the flow direction is an important factor in reproducibility. The meters tested fit between pipe flanges. Gaskets protruding into the flow stream slightly can have a large effect on the meter factor, increasing it as much as 10 to 15%. Gasket intrusions very likely caused at least some of the variations in meter factor noted in the earlier tests.

The vortex generated signal varies considerably in amplitude for all these vanes. The amplified signal amplitude goes from a few volts down to almost nothing for a cycle or two for almost every vane tested. This results in some amplifier gain sensitivity. The link vane signal, however, is sufficiently good that the gain of the first amplifier can be driven to saturation and output a signal of almost uniform amplitude. No instrumentation has yet been specifically designed for these flowmeters.

Testing to date suggests that the vortex shedding flowmeter can measure flow under the conditions prevailing in the space shuttle ducts. The testing is continuing in 51 mm (2 in) and 59 mm (2.3 in) diameter ducts.

Acknowledgements

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Figure 1. The flowmeter test facility.

Figure 2. These curves show the pressure drop ΔP across the meter as a function of flow with the pressure drop in an unobstructed pipe between pressure taps subtracted. The x data show ΔP of the 12.7 mm wide commercial vane. The triangle data show ΔP of a 6.2 mm square vane and the plus data that of a 6.35 mm wide vane with similar cross section to the commercial vane. The 5.1 mm wide link vane is shown by the circle data. This vane would be expected to have an even lower ΔP. Different ΔP instruments were used to measure the link vane ΔP and the pipe correction which may account for the higher measured ΔP. The curves show ΔP as a function of velocity squared which the data should follow.

Figure 3. The counting rate of the 12.7 mm wide vane (circles) and the 6.35 mm wide vane (triangles) as a function of the average flow velocity in m/s.

Figure 4. Flowmeter with a lift-type sensor. The detector is a strain gauge on the upper end of the thin spring section. The lift forces caused by vortex shedding deflect this vane and generate the strain. The narrow annular gap allows, but limits, transverse movement of the upper end of the vane.

Figure 5. The triangles show the meter factor for a 6.2 mm vane of the Figure 4 design. This vane is more linear than a triangular cross sectioned vane with the same mount (circles). The pluses show data from a triangular vane of the same cross section with a pressure sensor which is more linear.

Figure 6. This approximately to scale drawing shows the link vane. A clamping ring and bolts for the plate to which the mounting post attaches has been excluded.

Figure 7. This figure shows the meter factors for the 5.1 mm wide link vane (upper data) and two 5.1 mm wide by 17.8 mm long partial vanes (lower data). The horizontal lines are drawn to demonstrate linearity and scatter. The circles and the diamonds show the link vane 22 and 5 diameters downstream respectively from a reducing section at zero swirl. The point-up triangles show the swirl generator set at 11.5°, the pluses at 15.3° and the x's at 19.2°. The point-down triangles show the Figure 6 design vane in zero swirl, the cross in square and the x minus points, the swirl generator set at 5.1° and at 8.9°, respectively. Beyond the maximum angles, the signal-to-noise ratio was too poor. The plus in a diamond points show the cantilevered vane inserted through a 11.2 mm diameter port.

Figure 8. Lift type cantilevered vane. The vortex sensing mechanism consists of two drive pins acting on PZT sensors connected so their output adds when the vane is moved transversely.

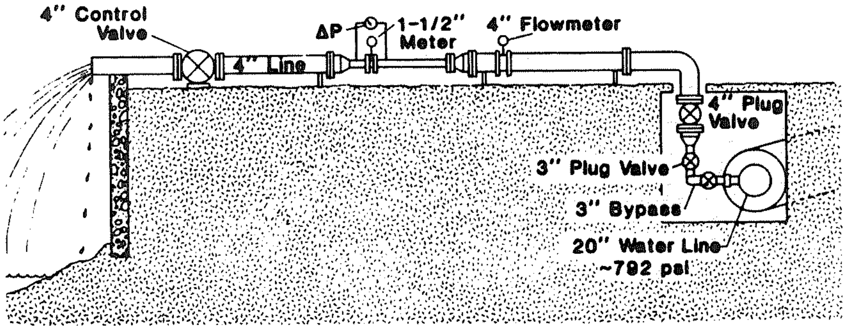

Figure 1.

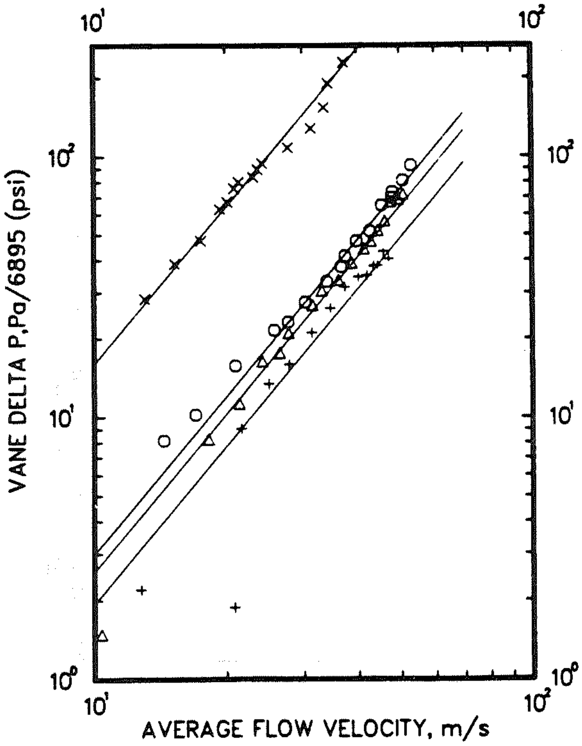

Figure 2.

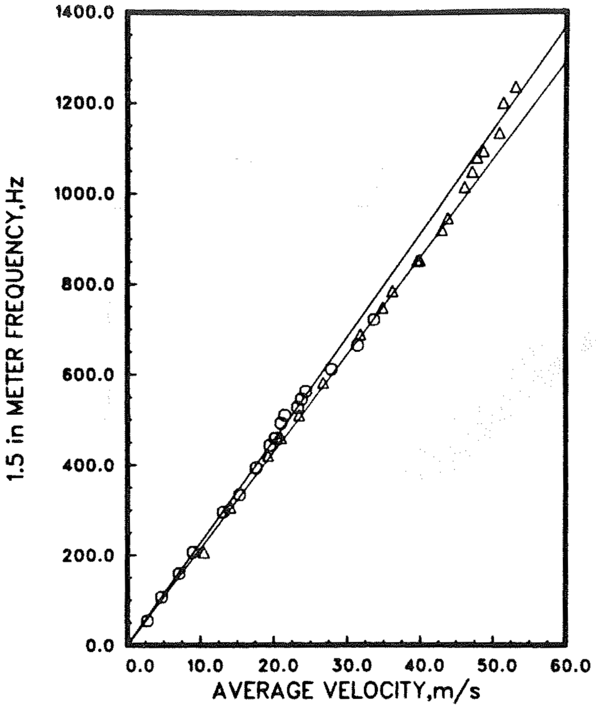

Figure 3.

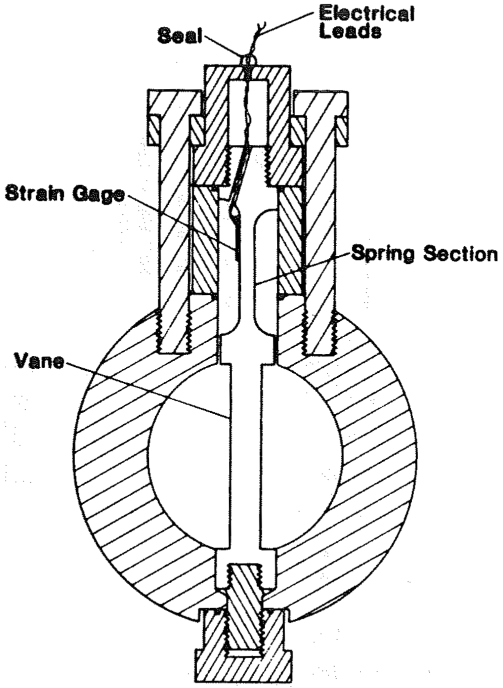

Figure 4.

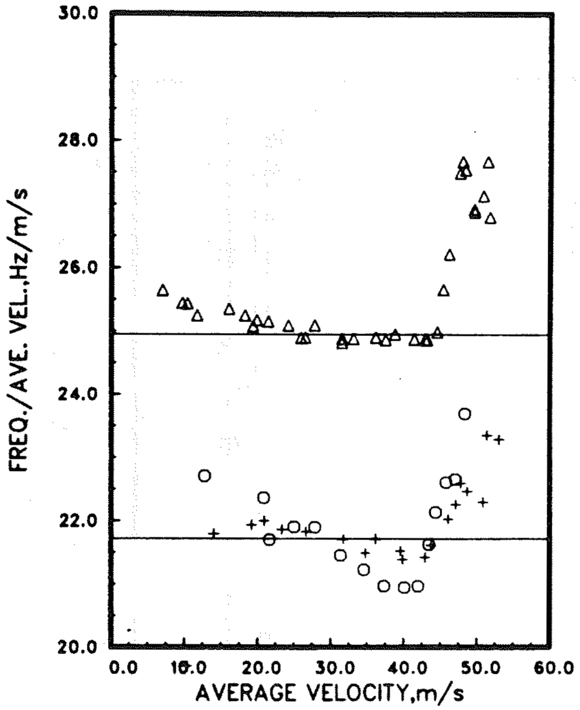

Figure 5.

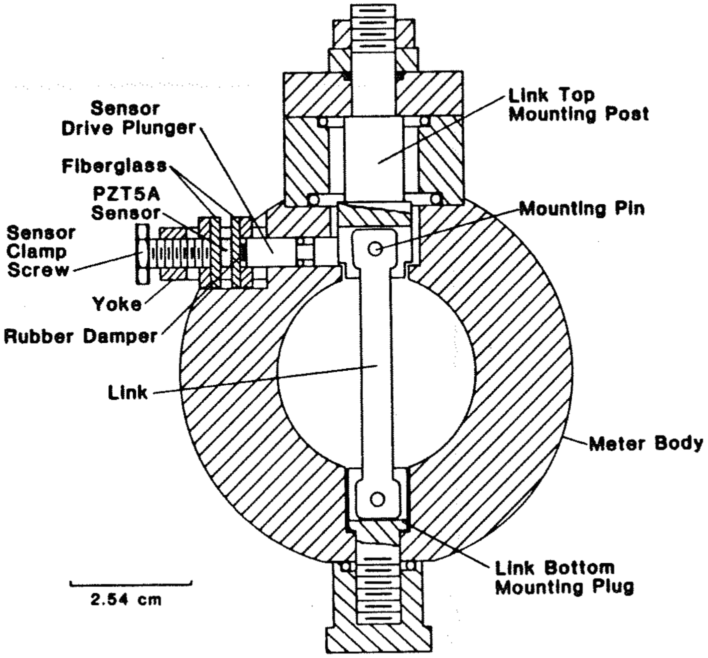

Figure 6.

RESULTS OF 5.1mm WIDTH VANE TESTS

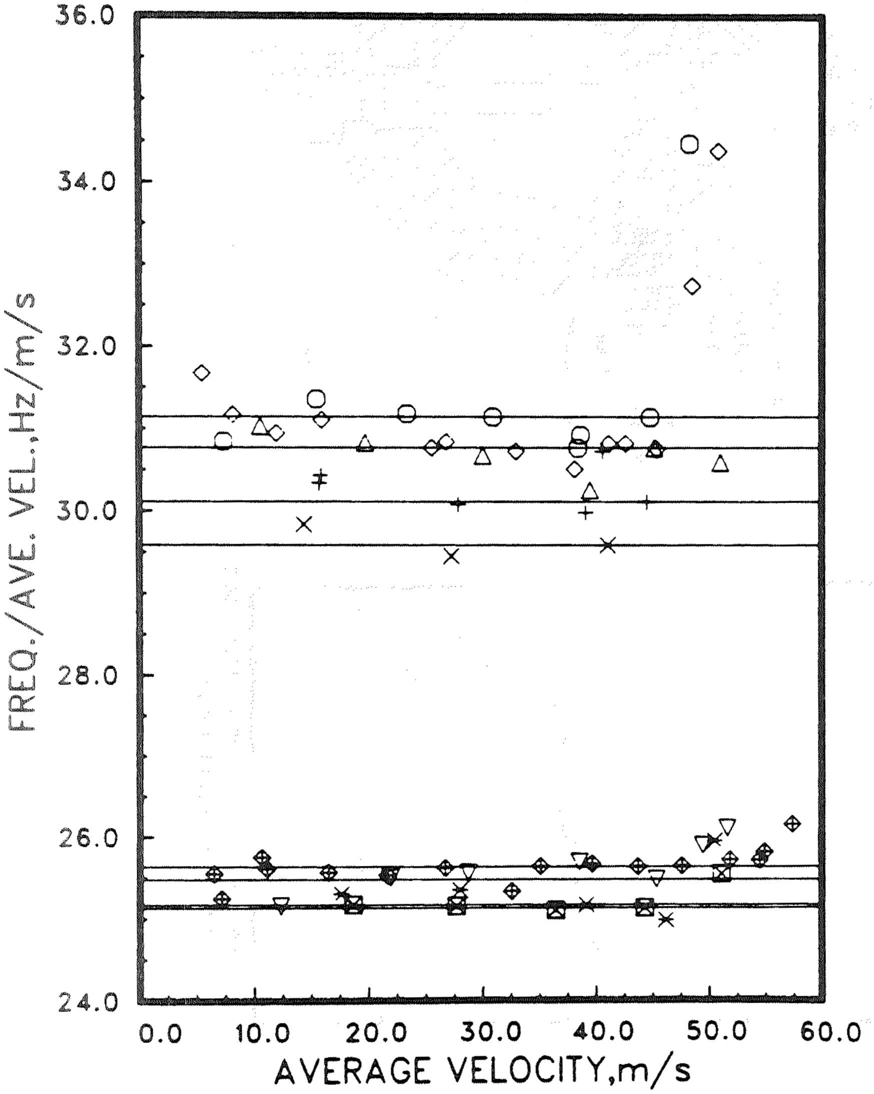

Figure 7.

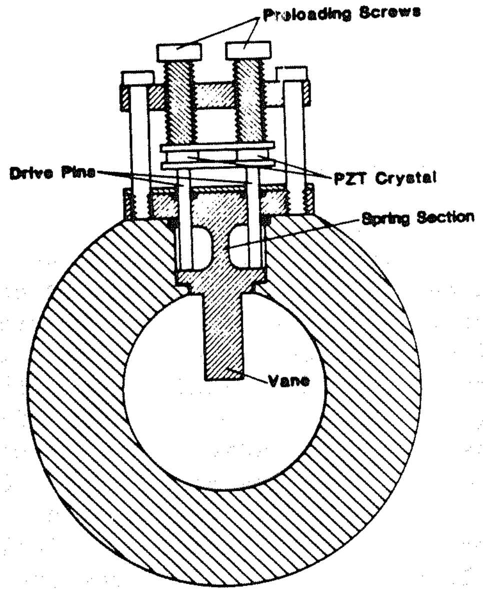
Preloading Screws
Drive Pins
PZT Crystal
Spring Section
Vane

Figure 8.