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THE EFFECT OF DIFFERENT PATH CONFIGURATIONS ON ULTRASONIC FLOW MEASUREMENT

by

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INTRODUCTION

For many years now liquid flow measurement using the Time of Flight of ultrasound has been accepted as an equal partner alongside other flow metering techniques. The advantages of negligible intrusion into the pipe, giving no extra pressure drop and a low chance of transducer fouling and damage, good levels of precision, repeatability, resolution and range make it an attractive method. Further, the direct link of the performance and cost reduction with improvements in electronic technology makes the possibilities for the future performance even more exciting.

Development until recently has been largely on liquid meters, due mainly to the problems of successfully transmitting ultrasound into gases, and detecting the signal. This is particularly acute for low pressure applications. The first successful application for the gas ultrasonic flow meter was the measurement of Flare gas. An application where the good range, ease of installation and low pressure drop is a major requirement. These meters are generally single path, with a modest level of uncertainty, due mainly to the lack of ability to determine the exact pipe size. Meters were then developed for such applications as gas blending, compressor measurement etc., all however being generally single path meters with an uncertainty in the region of 1-2%.

The advantages of multi-path ultrasonic meters have been clear from very early in their development. In 1971, a five-path meter was described by Westinghouse [1] for fiscal measurement of liquids. Further developments showed that a high level of precision could be obtained, even under adverse installation conditions, if several paths were chosen across the pipe, forming chords, and an appropriate algorithm obtained. It has only, in the last five years, been possible to successfully design a multi-path meter for gas measurement. The resultant meter produces results of a "fiscal" standard, for custody transfer.

The paper describes the design of Stork Servex ultrasonic flow meters, which are both novel and advanced in their approach to the problems of both single and multi-path methods of metering using ultrasonic time of flight.

MEASURING METHOD

The meter works on the Time of Flight principle, an absolute digital travel time method. The basic system is shown in Fig.1. Transducers are placed on opposite sides of the pipe, such that the piezo-crystal faces are opposite each other. Pulses of ultrasound are generated simultaneously by both transducers.

At zero flow the time taken for the sound to travel from A to B (t_{AB}) is the same as for B to A(t_{BA}), thus:-

$$t_{AB} = t_{BA} = \frac{L}{C} \quad ---------- (1)$$

If there is a flow as shown in Fig1, the travel time from A to B (t_{AB}) will decrease and B to A (t_{BA}) will increase as below :-

$$t_{AB} = \frac{L}{C + V_a \cos\theta} \quad ----------- (2)$$

$$t_{BA} = \frac{L}{C - V_a \cos\theta} \quad ----------- (3)$$

The simultaneous transmission of the pulses is essential, as small changes in velocity of sound, due for example to changes in gas content, temperature or pressure, will cause errors in the calculation of the fluid velocity. The velocity of sound is thus eliminated by combining equations 2 and 3 in the following way :-

$$V_a = \frac{L}{2\cos\theta}\left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}}\right) \quad --------- (4)$$

This method is essentially therefore based on the primary measurements of distance and time. The ultrasonic pulses can be considered as a gating mechanism for timing of the measurement of time of flight. Due to the digitalisation of the received signal this method is able to check the quality of the transmission of every single pulse individually against built pre-set standards. Thus each set of measurements can be assessed and either accepted or rejected, the record being a good indicator of the meters overall performance.

GAS MEASUREMENT

Signal Detection

The measurement of gas flow using ultrasonics presents some particular problems. There is a large mismatch in acoustic impedance between gas and the transducer resulting in very low levels of signal transmission. This problem increases as the gas pressure reduces. The result is, that the received signal is very low, particularly compared to ultrasound transmitted through other paths, such as the pipe walls. It is conventional wisdom to increase the signal transmission and transducer sensitivity by using high "Q" resonant transducers. Unfortunately, the performance of such transducers is very dependent on the surrounding fluid, and the received signal can become distorted, with excessive ring times. The solution is to use wide band transducers. While such transducers require more power to drive them they retain a very well defined signal with a wide variety of surrounding fluid. At manufacture the signal they produce is checked against a digital signal signature (or footprint). If they are within defined parameters they are acceptable. As the signal shape remains constant it can be compared in the meter processing electronics with the standard digital footprint signal. This enables the detection of very low level signals in high noise conditions. The signals received from sources other than directly through the fluid can be removed by using a time window to catch the actual signal. As the "ringing" of the signals is short this does not extend into the time window to add noise to the received signal.

Solid and Liquid Particles

Under working conditions gas generally contains quantities of solids and liquids when being transported. Offshore gas, in particular, contains large quantities of liquid, and as those who deal with orifice plates will testify, onshore gas contains quantities of solids that erode orifice plate edges. By using digital pulse recognition techniques, the ultrasonic meter can be made relatively immune to solid and liquid deposits. While ultimately too much solid and liquid content will attenuate the signal beyond the point of measurement, until the point of lack of signal the digital processing system ensures the continued accuracy of the meter.

Acoustic Interference

As with all types of gas ultrasonic meters, this system is not immune to the effect of "low noise" valves. Such valves achieve this performance by pushing the audible noise up into the ultrasonic region particularly when they are nearly closed. The use of digital signal processing techniques helps to alleviate this problem although it is still adviseable to place the meter as far a way as possible and preferably upstream of the meter.

Mass Flow Measurement

From the proceeding equations it is quite clear that the meter measures **actual velocity** and thus in the majority of gas applications needs to be corrected, obviously for area, but also for density changes due to gas content, pressure and temperature. There are a number of ways in which this can be done.

Velocity of Sound

The simplest method is to use the knowledge of the velocity of sound obtained from the meter to determine the density. This is done at the same instant as the flow velocity is measured, and in the same plane as the metering. Also, with this technique, the molar mass can also be calculated. The speed of sound is related to the fluid density with the following equations :-

$$\rho = \frac{k.P}{C^2} \text{-----------} (5)$$

and

$$M = \frac{k.z.R.T}{C^2} \text{--------} (6)$$

ρ = Density, M = Molar Mass, T = Temperature, P = Pressure,
R = Universal Gas constant, k = Poissons ratio,
C = Sound Speed, z = Compressibility

The overall uncertainty of mass flow measurement thus depends on the uncertainty of the volume flow measurement, pressure measurement and Poisson ratio. The uncertainty of measuring Poisson ratio is dependent on the gas composition. With Flare gas, for example if a mean range of C_1 to C_8 is taken then a maximum error of approximately 4% could be expected.

Mass Flow Computation

A more precise method for correcting the output is to use pressure and temperature inputs and flow computation to produce a compensated or mass flow output. The meter can thus be treated in the same way as a standard orifice plate or turbine meter within the measuring system. Higher precision compressibility can be taken into account using one of the many "standard" methods such as NX-19, AGA8 etc. It is usual to use this method for Custody Transfer Applications.

Density Meter

Again for more precise compensation, the meter can be used in conjunction with a density meter, feeding into a flow computer. The combination of the actual volume flow and the density output will give either a mass or compensated flow output.

SINGLE PATH METERS

At present, the most common configuration for the transducers is single path, cutting a chord across the pipe cross-section, usually across the centre, Fig.2. The path cuts across the velocity gradient of the pipe with each component of velocity modifying the flight time. The result is a line integral of velocity across the line of transmission. As can be seen however the flow through a pipe with a fully a developed flow profile is axi-symmetric about the centre line, and a line integral does not give full weighting to the velocities towards the outside of the pipe. Thus, the velocity output is always high relative to the mean. At high Reynolds numbers the ratio of recorded velocity to mean velocity remains relatively constant as the changes in profile are small. At lower Reynolds numbers the curve begins to increase as the profile becomes more "peaky". Under conditions of fully developed symmetrical profiles therefore the curve is determined largely by the pipe Reynolds number. The curve obtained is shown in Fig.3. To linearise the curve the velocity obtained has to be modified by a calculated K-factor such that mean velocity $V_m = V_a/K$.

The value of K is a function of chordal position and duct velocity profile. As can be seen in Fig.3, a large number of meter factors were tried to obtain the best fit for the experimental results. The curves K1 to K3 were obtained using theoretical Prandtl type velocity profiles. These curves converge well at high Reynolds numbers but as the number reduces show increasing deviations from the experimental results. The K4 curve developed by Rothfus and Monrad[4] incorporates the influence of the laminar sub-layer, unlike the previous three. The result is a close fit over the Reynolds number range tested.

Acoustic Path Configurations

The configuration of the acoustic path is essential to the effect of installation on the measurement of an ultrasonic meter. The conventional path configuration is shown in Fig.4a. The sound is fired directly at the receiver across the pipe, either at the centreline or along a predetermined chord. Such a configuration is subject to error due to both velocity profile and swirl. A variation is to reflect the signal from the opposite wall, Fig. 4b. This configuration is still sensitive to profile variations but effectively cancels out the rotational velocity induced by swirl. The introduction of swirl adds a component along the flight path, either speeding up or retarding the sound speed dependent on the direction of swirl. Providing that the reflected path is **in a plane parallel to the direction of the pipe axis and the other path**, the effect on each path will be equal and opposite. Thus, cancelling out the swirl component. The same effect can be achieved with two sets of transducers, but the **same rules with regard to the plane of flight apply.** This rule is particularly applicable in the case where swirl breaks into two contra-rotating cores Fig.5. There are further configurations applicable, Fig. 4c and 4d. These involve multiple reflections, 4c has two and 4d has four. The benefit of these configurations are a better averaging of distorted flow but are subject to a swirl component error. Configuration 4d is also very impractical as an installation, however 4c is acceptable within the concept of a "spoolpiece" meter, but is not practical for "insertion" type installation. With the use of contra-rotating double reflection paths it is possible to determine the swirl component itself, as will be described in the multi-path Q.sonic meter.

Practical Design

The practical design is a function of both pressure and pipe size. Where possible, hot tap single path Stork installations use the single reflection method. This has the following advantages:-

- This configuration alleviates the effect of the swirl component of velocity.
- The transducers are installed from one side, making the installation easier particularly for buried pipes.
- A longer path length. giving greater timing resolution.

Such a configuration is possible for most pipe sizes at high pressures, but for low pressure applications such as Flare metering the maximum pipe size for such a configuration is 15", above which the configuration should revert to the conventional direct transmission.

The meters, the Gassonic 400 and the Flaresonic, are installed into the existing line using either a high or low pressure insertion mechanism, Fig. 6, usually by hot tapping the meter offtakes. A spoolpiece single path meter, the P.Sonic is also available.

Performance

A large number of tests have been carried out at the high pressure test facility of the Dutch Gasunie at Westerbork and Groningen and by Oval Engineering Inc. in Yokohama. These tests are detailed in reference 2.

The performance of a single path meter with a variety of straight pipe (SP) configurations and flow straightener (FS) positions is shown in Fig. 7. Over most of the range the linearity is within 1%. There are small shifts with installation of a flow straightener, but all data is continued within a 1% band.

A summary of the effect of bends in different planes is shown. Fig. 8 shows a schematic of the variations of installation tested and Fig. 9, the results achieved. The results are plotted as the difference between the achieved results and a preferred installation.

Effect of Different Bend Configurations at 20 Pipe Diameters

The effect of different bend configurations, 20 pipe diameters upstream of the meter, are shown in Fig.9a. It should be noted that the effect is to generally retain the Reynolds number curve, that is the linearity, but to push the calibration negative. The data for the cross plane configuration with a single bend does show an increase in linearity at the lower flows. The general shift in calibration at higher Reynolds numbers is between is approximately 2% .

Effect of Change in Upsteam Pipe Length.

As shown in Fig 9b, the effect of moving the bend to within 10 diameters of the meter is to depress the calibration further, but still retain the calibration shape. The curve is still retained within 3% at higher Reynolds numbers.

Pulsating Flow

Due to the linear nature of the principle, the absence of moving parts and high repetition, rate the ultrasonic time of flight meter is ideally suited to measure pulsating flows. Aliasing effects, between the pulsating frequency and the sampling rate, can be eliminated by using an asynchronous sampling technique. An example of the measurement of pulsating flow is shown in Fig.10. The results are from two single path Gassonic 400 meters installed in the inlet and outlet ducts of a compressor, about 3 metres from the compressor itself. The inlet flow is relatively stable, while the outlet shows the oscillations of the flow produced by the compressor.

MULTI-PATH METERS

As can be seen the performance of the single path meter is subject to profile variations due both to Reynolds number and installation. While the repeatability, range and the resolution are better than most meters, the overall measurement uncertainty is not within the limits required for Fiscal (Custody Transfer) applications. The solution is readily evident, the use of more than one path across the fluid will improve the data available about the flow profile.

Conventional Multi-Path Configuration

In general, conventional meters use between four and five paths, forming chords across the pipe cross-section, Fig.11. In some cases the transducers fire as X-paths but only to save room on transducer installation. As they are not in the same plane they cannot be used to give detail of the swirl in the pipe. The positioning of the pipe and the weightings of the various paths is done by a numerical Gaussian quadrature method. The advantages of this method are :-

- No additional information about flow profile is required.
- The weighting factors are fixed, relieving the processor of a large volume of computational work.

The drawbacks are :-

- The flow velocity is assumed to be axially symmetrical.
- The additional information with respect to Reynolds Number is lost.
- As the weightings are optimised for a symmetrical profile errors occur when the profile deviates from this optimum.

Because of these drawbacks Stork Servex B.V. have developed a novel design based on a matrix of reflected paths.

Double Reflection Configuration

As discussed previously, a double reflection gives benefits in regard to variation of the performance with velocity profile. It is not, however, a feasible installation for a low cost single path "insertion" meter. For a fiscal meter in which the transducers can be installed permanently into a Spoolpiece it gives valuable extra data. In particular the double reflection meter produces an output that gives data on the degree of swirl being produced in a pipe line. Fig. 12 shows variation in output with angle of flow of swirl flow disturber. Over much of the range the relationship is almost linear. The experiment was set up with two pairs of transducers, transmitting in clockwise and anti-clockwise directions. The reaction to the swirl is opposite and symmetrical. This is clearly shown in Fig.13, comparing the velocity output from the two, changing the swirl from a clockwise angle of 5° to an anticlockwise swirl of 10°. The intermediate region results from the two step procedure of adjusting the flow disturber. The swirl strength and direction can be obtained from the difference between the two paths.

The Five Path Matrics Method

As stated the flow path is likely to compose a number of distortions, asymmetry, swirl and pulsations. The five path matrics meter three single reflection paths and two double reflection paths. From these it is possible to detect the type of velocity profile and measure the strength of any distortions. As can be seen, the double reflection paths give detail of the swirl strength, independent of the profile. The use of three single refection paths placed symmetrically around the pipe circumference shows detail of the profile, Fig.14, independent of any swirl. The deviations from both path types are taken into account in the computation of bulk mean flow.

The calculation **matrix** has been developed to use information from;-

- The flow Reynolds Number.
- The individual velocities along different paths.
- The measured swirl strength.
- Pulsation strength along certain paths.
- The flow asymmetry.

The development of the matrix method is based on experimental measurements and a number of sets of data that classify the different flow profiles encountered in actual installations.

The setup of the five paths are shown in Fig. 15. The advantages of this method are :-

- The close spacing of the acoustic path network, giving a high coverage of the cross-section.
- The measurement is insensitive to the orientation of the meter with respect to the piping.
- The path lengths are much longer, resulting in a more accurate measurement of flow velocity.

Implementation

The meter developed by Stork Servex BV is the Q.sonic. It consists of a spoolpiece with the three single reflection paths at 120^{o} intervals around the tube and two double reflection paths. The Q.sonic is placed in the hazardous area with the basic data processing electronics. The meter can then either talk to a remote unit in the safe area which provides the power supply to the meter and additional computation, or the meter can be supplied separately with a power supply, +/- 15V, 12Vdc or 24Vdc, and the data taken to a flow or control computer. In both cases data can be transferred using a serial RS485 link, up to 700m or an optical fibre, 3Km.

From the Remote unit the data available is via a 4-20mA output, a 0-10Khz frequency, both of which are freely configurable, an RS232 output with all necessary information, flow direction, relay output, and data validity, relay output. Pressure and Temperature can be connected to the **remote unit**, galvanically separated, or to the **local unit**, not galvanically separated.

The same outputs are available direct from the meter, except that the flow direction and validity outputs are opto-isolated open collector outputs. In this form the meter is configured and serviced via the RS485 connections. A P.C. is used to configure the meter. As with the remote unit the P&T corrections can be made locally or into the electronics in the safe area, such as a flow computer.

Performance

Some of the results using the, **preliminary** theoretical computations, of the calibration of a 20" five path Q.sonic meter, tested at the Bernoulli station of Gasunie with different pipe configurations, are shown in Fig. 16. For a straight pipe, Fig.16a, the accuracy of the meter was found to be within 0.3% for most of the range. Each of the points shown is composed of three independent measurements, too close to show as separate values on the scale chosen. The effect of a single and double bend 5.5 pipe diameters upstream are shown in Figs 16b and 16c. The maximum deviation over most of the range is less than 0.3%. As a result of this data improved computations have been developed that significantly improve on these results. An orifice plate to retain the discharge coefficient within the specified uncertainty would require between 15 and 30 diameters of straight pipe after such disturbances, dependant on the area ratio. Data indicates an error of as much as 1% if placed as close as 5 pipe diameters downstream of a single bend, again dependent on the area ratio.

ACCURACY

From equation 4, it can be seen that the errors in flow measurement are due to the uncertainty of the measuring path length, the timing and the angle of transmission. In converting the acoustic velocity into a a volumetric flow the "K" factor is required and the area of the pipe both of which carry uncertainties. The errors can be divided into two parts:-

- Transit time measurement errors.
- Errors due to installation parameters.

Transit Time Measurement

Any timing error in the instrument will cause an error in the velocity measurement. This results from two sources, the timing resolution and the precision with which the signal can gate the timer. With the use of wide band piezo-ceramics and high speed digital processing a timing error of less than 10ns can be achieved. The relation between the timing error and the velocity error is linear. assuming the velocity of sound and transmission angle remain constant the error as a function of pipe diameter due to the timing is :-

As can be expected, the error decreases as the pipe size increases.

Installation Parameters

The installation errors are largely independant, and so the total error will be the RMS. of the individual errors. The total volumetric error E_Q is given by:-

$$E_Q = \sqrt{E_{Vm}^2 + E_A^2 + E_K^2}$$

where E_A is error in measurement of area, E_K is K factor error and

$$E_{Vm} = \sqrt{E_D^2 + E_\theta^2}$$

E_D is the diameter error and E_θ is the error in measuring the transmission angle.

The magnitude of these errors is quite clearly a function of the meter type. A "hot-tap" insertion meter will obviously carry larger errors than a spoolpiece where the dimensions are under the control of the meter manufacturer.

Practical values for these errors for insertion type meters are;-

$$E_A < 0.5\%$$

$$E_D < 0.5\%$$

$$E_\theta < 0.2\%$$

$$E_K < 2.0\%$$

This gives a worst case error of Volumetric flow measurement of 2.1%.

Generally it has been found that the results are better than this. As good as 1% with a flowstraightener and 10 pipe diameters upstream and 5 downstream. Without a straightener these pipe lengths must be doubled.

With a carefully manufactured spoolpiece these are reduced significantly to less than 0.5% as shown with Q.sonic.

APPLICATIONS

With the wide range of variations available from the basic concept from low cost, low pressure insertion type meters to sophisticated multi-path meters the range of applications is extensive. These include for the single path meters Flare and Flue gas monitoring, underground natural gas storage, vapour return metering, leakage detection, compressor efficiency, custody transfer checkmetering and general process control. The multi-path meters are obviously aimed at providing a Fiscal standard of metering for Custody transfer both onshore and offshore, consumption metering for gas fired power stations, bulk gas supply to heavy industrial users etc. It is worth considering a few of these applications in detail.

Flare Gas Metering

Flare metering is an application strewn with failed techniques. This is partly due to the lack of desire to carry out such measurements and the consequent use of the cheapest possible instruments. However, it is clear now that there are tangible benefits to measuring flare gas, not only due to environmental concerns but as a process control mechanism and an indicator of plant efficiency. With the reducing cost of ultrasonic meters and ease of installation it is becoming very viable not only to place them in the main Flare line but also the feeders from the various processes, giving a much clearer idea of where the flare gas is being generated. The good performance at medium and low velocities makes the meter very attractive for flare metering. Also, as was shown in equation 5, the density can be obtained from the velocity of sound, pressure and the Poissons ratio. Further, knowing the temperature it is possible to measure the Molar mass, and indication of the gas quality. Poissons ratio varies with gas content but by taking a mean default mixture it is possible for most applications to obtain an answer within 5%.

Compressor Stations

Because of the ability of the ultrasonic meter to measure unsteady flows, it is ideal for metering flow from compressors. As the pipework is usually very tight the fact that the meter can be installed by "hot tapping" and can be close to the compressor and still give good answers make it ideal. The results shown in Fig. 10 are from a Tenneco station in Texas.

Gas Mixing

In many countries a variety of gas qualities are used to make up the final mix. Often the pipe line is underground. The ability to insert both transducers from the same side combined with installation under pressure and a good level of precision, make the meter very suitable for these applications.

Level Detection

Again the "hot-tapping" installation combined with the lack of added pressure drop make this type of meter useful for leak detection on gas transport systems. When installed large distances apart, 50km, a long term comparison of the results gives a good indication of the presence of small leaks.

CONCLUSIONS

New flow meter concepts, such as ultrasonic time of flight meters, have had their problems in the early days of development and application. However, technology has caught up with these problems very quickly and solved the majority of them. The result is a meter that is becoming well proven as a technology, particularly in the medium precision range of metering. Custody transfer metering is now also becoming feasible with the development of multi-path methods to enhance the accuracy. The major advantages of the technique are the wide dynamic range, negligible pressure drop, lack of sensitivity to liquid droplets and solid particles in the flow, high repeatability, good precision and a variation in design to suit different applications. A major feature for the future is the strong relationship between the meter performance and advances in electronic and computer technology. This ensures that the meters will continue to improve their performance and economic viability.

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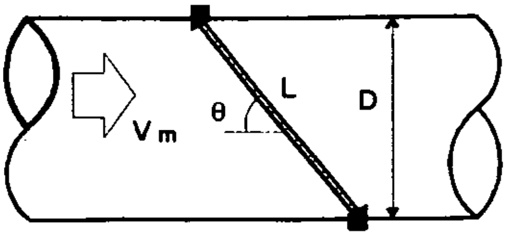


Fig. 1 BASIC SYSTEM

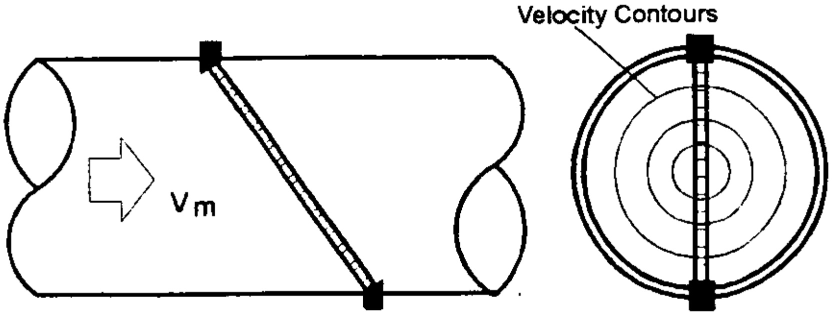


Fig. 2 SINGLE PATH TRANSMISSION

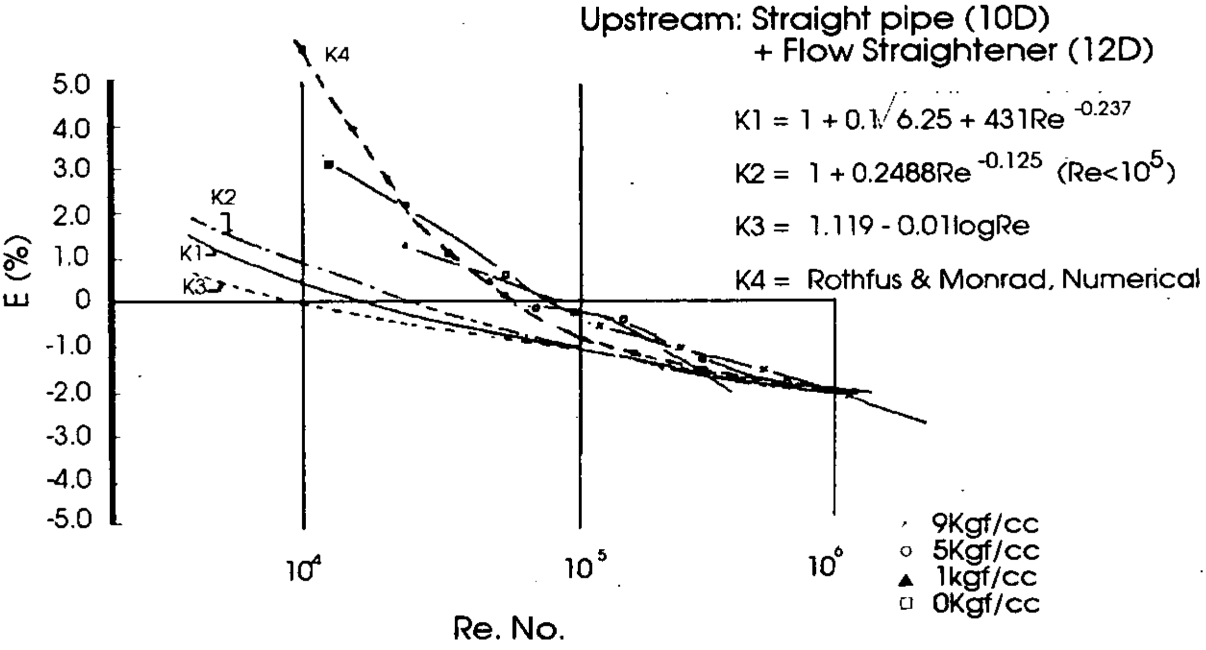
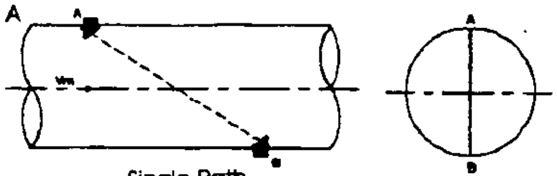
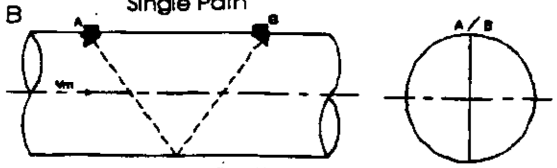


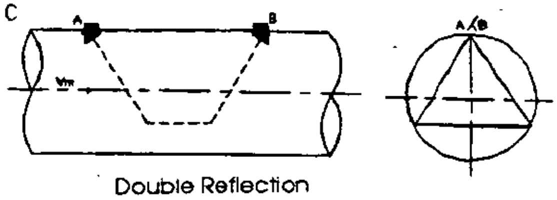
Fig. 3 CHARACTERISIC OF REYNOLDS NUMBER



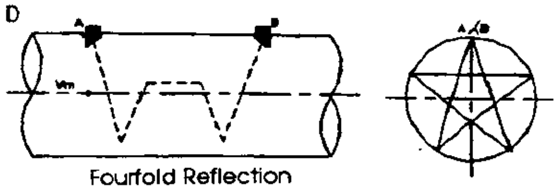
Single Path



Single Reflection



Double Reflection



Fourfold Reflection

Fig. 4 PATH VARIATIONS

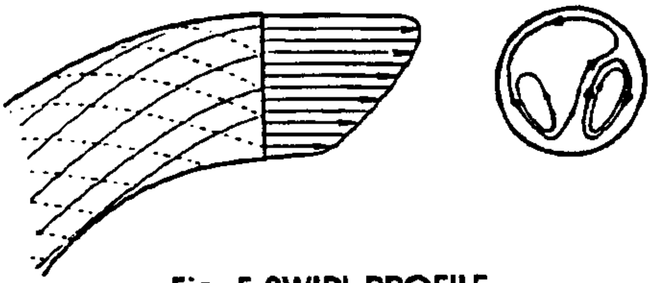


Fig. 5 SWIRL PROFILE

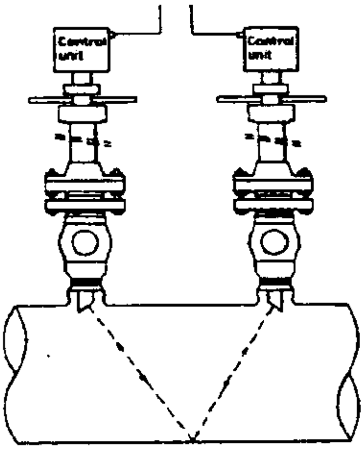


Fig. 6 GASSONIC 400 INSTALLATION

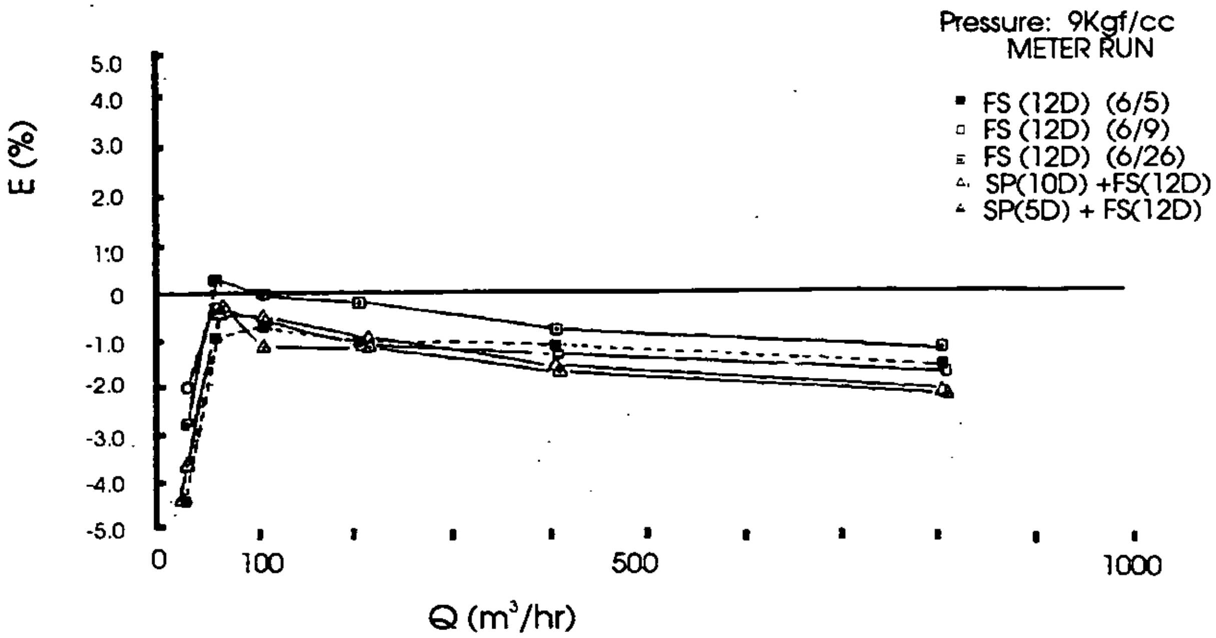
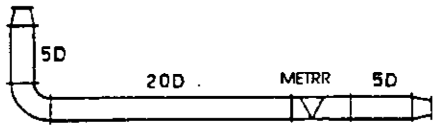
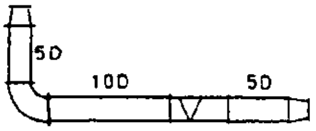


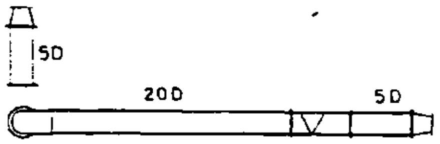
Fig. 7 CALIBRATION WITH VARIOUS PIPE ARRANGEMENTS



Same Plane Elbow SP20D

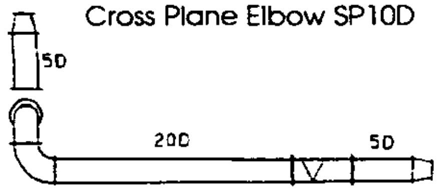


Same Plane Elbow SP10D



Cross Plane Elbow SP20D

Cross Plane Elbow SP10D



Complex Planes Elbow 20D

Fig. 8 PIPE ARRANGEMENTS

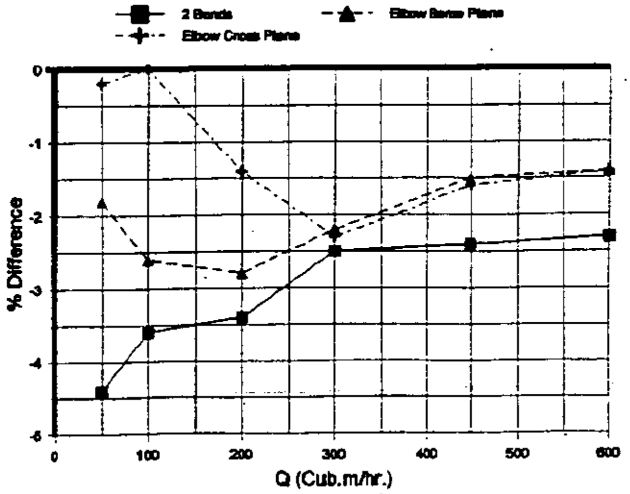


Fig.9a CHANGE IN CALIBRATION WITH VARIOUS BEND CONFIGURATIONS AT 20D

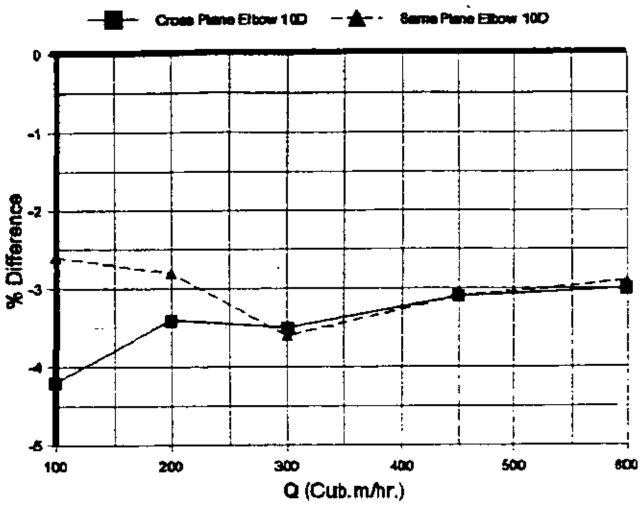


Fig. 9b CALIBRATION CHANGE WITH ELBOWS AT 10D

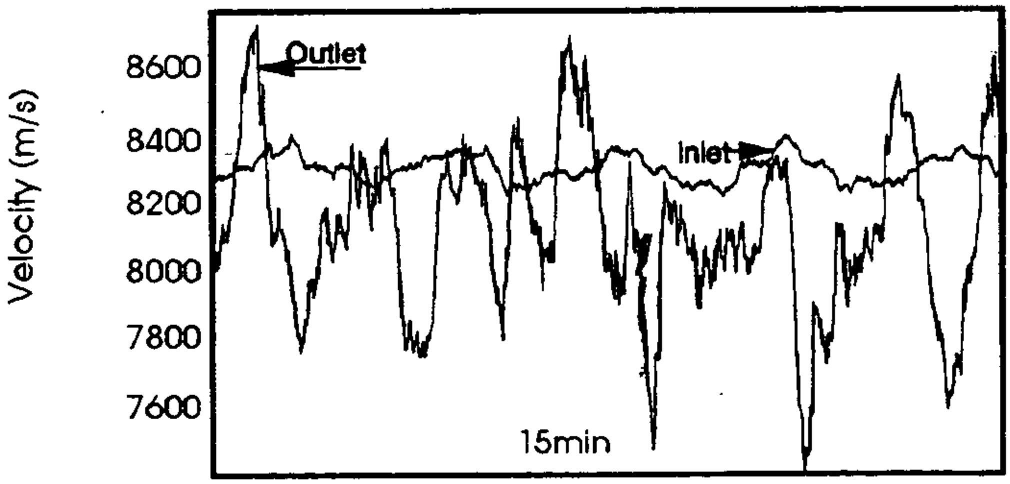


Fig. 10 PULSATING FLOW

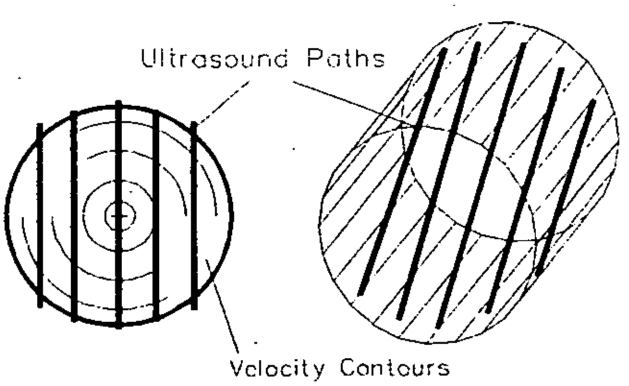


Fig. 11 CONVENTIONAL MULTI-PATH CONFIGURATION

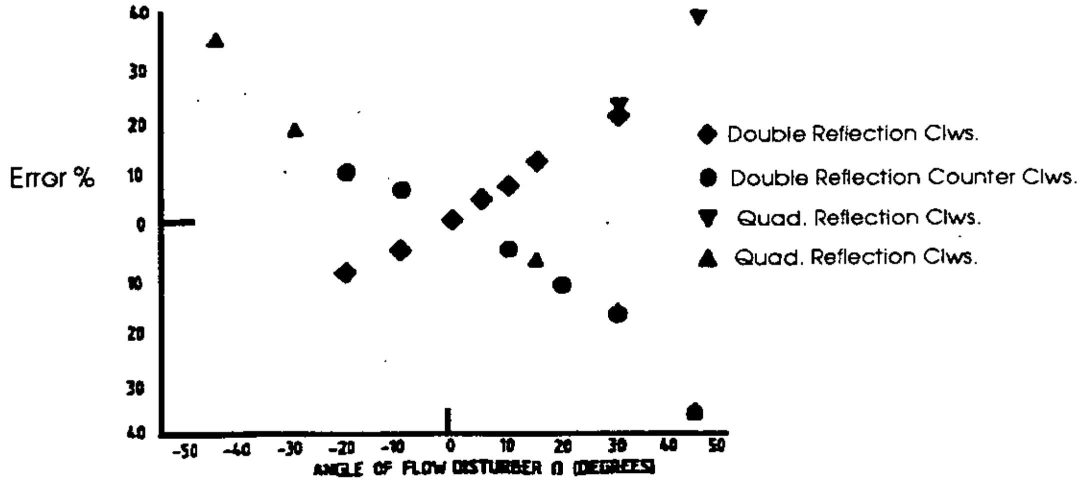


Fig. 12 OUTPUT ERROR WITH SWIRL ANGLE MULTI-REFLECTORS

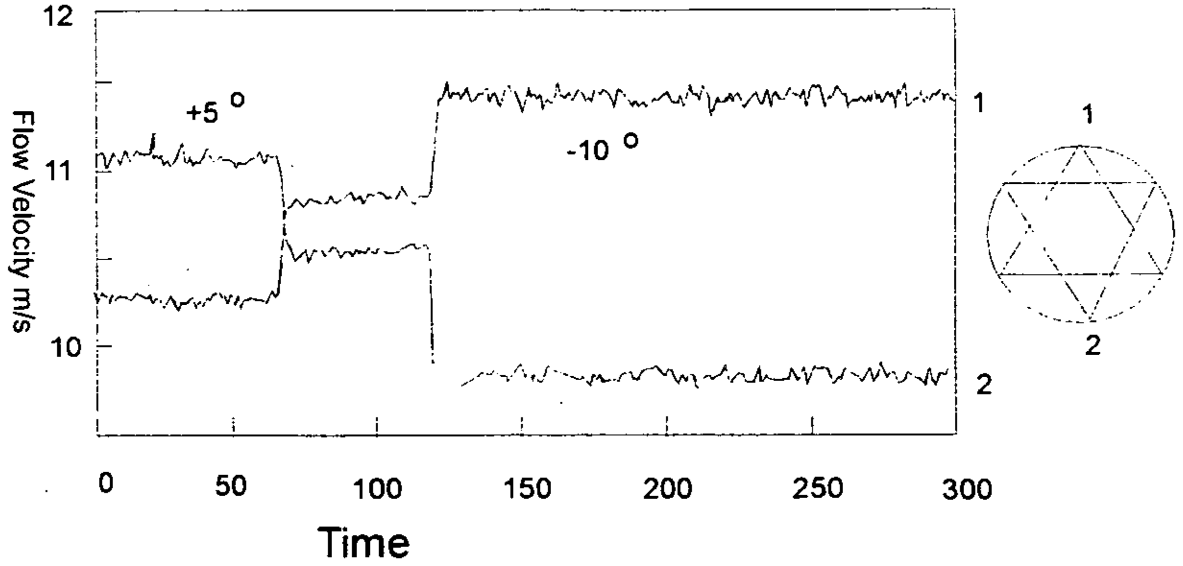


Fig. 13 SWIRL EFFECT ON DOUBLE REFLECTION PATHS

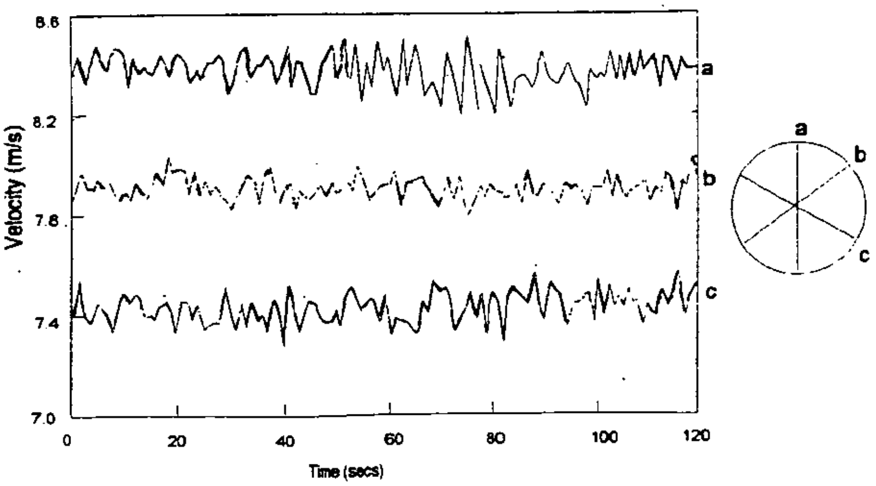


Fig. 14 PROFILE EFFECT ON SINGLE REFLECTIONS

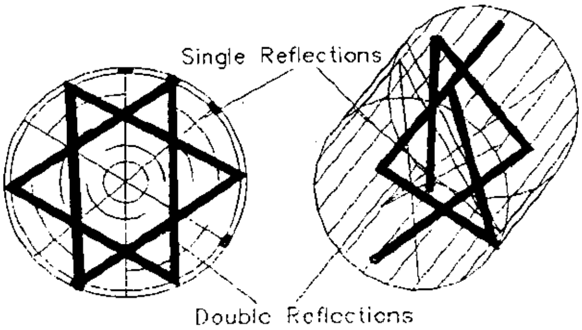


Fig. 15 Q.SONIC PATH CONFIGURATION

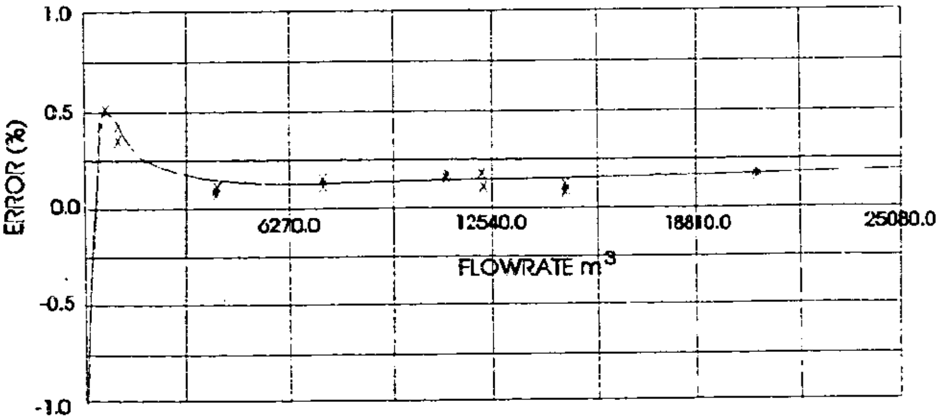


Fig. 16a CALIBRATION OF Q.SONIC METER

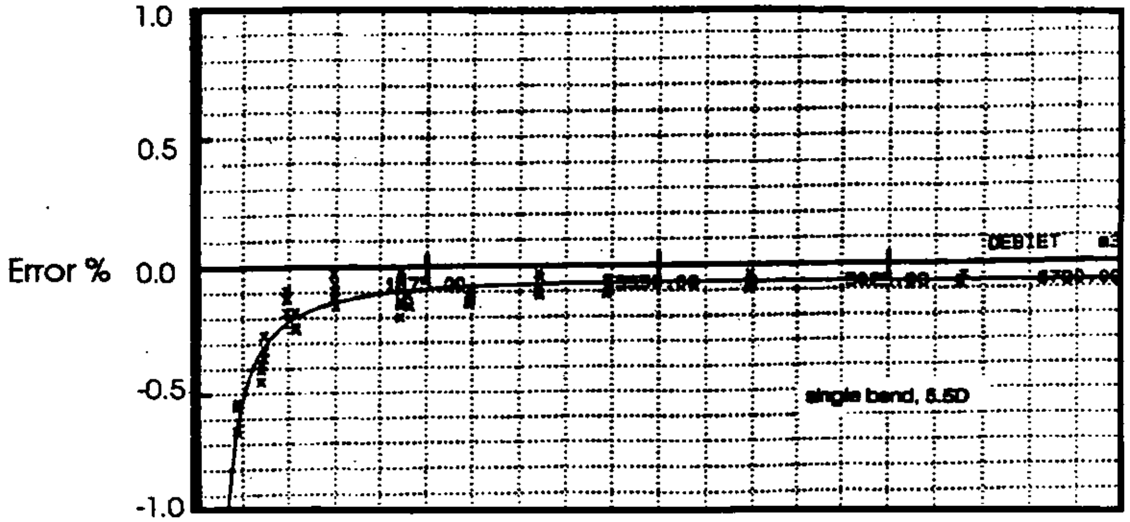


Fig 16b SINGLE BEND (PRELIMINARY RESULTS)

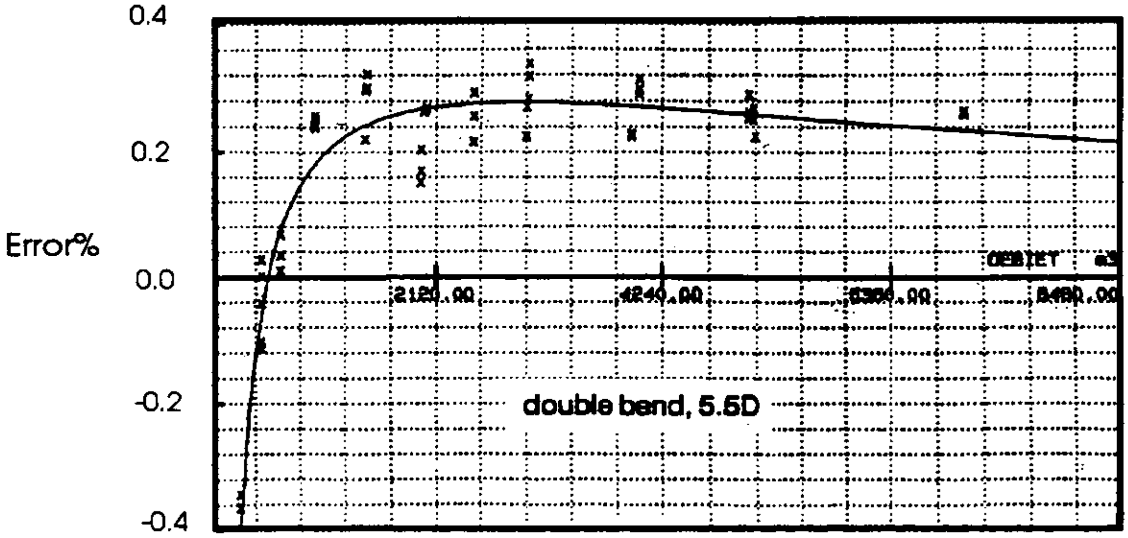


Fig. 16c DOUBLE BEND (PRELIMINARY RESULTS)