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IS LINEARISATION SAFE FOR CUSTODY TRANSFER METERS?

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1 INTRODUCTION

There are a number of end goals for a flow meters used for different applications. For control meters it may be a combination of repeatability, stability and quick response time, for batch applications it may be that repeatability is the main criteria and for leak detection it is the repeatability and stability. For hydrocarbon custody transfer meters, without a doubt, the major criterion is the installed **uncertainty** of the meter.

Many manufacturers, engineers and technicians lose sight of this criterion, and it becomes hidden in a forest of concepts and terms that disguises the end result or is only a small part of the complete picture. The concept of repeatability, or spread, in proving, for example, is often seen as an end goal in the quest for uncertainty by engineers and technicians, but as we know, is but a part of the overall picture that is the final uncertainty of a given installation. Specifications often ignore calibration uncertainties when defining the meter performance, linearity is often completely confused with uncertainty, and last but not least the term accuracy is thrown into the melting pot to add total confusion to the uncertainty picture.

This paper looks at a small part of the picture, flow linearization of meters, a hidden uncertainty that can come up and severely bite the user, unless they have some understanding of the implications and possible effects. Unfortunately in many cases now the methods and corrections are hidden in a "black box" such that the users and regulators are often blissfully ignorant of the potential errors waiting to appear in their metering. The design uncertainties for the system are thus often of little relevance in practice.

2.0 CUSTODY TRANSFER

Before looking at the issue of linearization and its relationship with Custody Transfer it is important that we understand the concept and its implications.Custody transfer in flow measurement can be defined as a metering point (location) where the fluid is being measured for sale from one party to another. During Custody Transfer the measurement uncertainty is of paramount importance to both the seller and the buyer. The term "fiscal metering" also falls into the same category. Fiscal metering, is often interchanged with custody transfer, and refers to metering at a point of a commercial transaction such as when a change in ownership takes place, and may now involve governmental or state regulation in the form of taxation. Custody transfer takes place any time fluids are passed from the ownership of one party to another.

The definition of the uncertainty attributed to a custody transfer system will vary considerably, as it depends on the contract, the regulation, flow conditions, water content, sampling, meter type etc. Generally, however, for liquids this should be in the order of 0.2-0.25% and for gases in the order of 1% or better.

With liquids, in particular, to achieve the proposed uncertainty all aspects of the measurement need to be analyzed. To put it in perspective 0.1% uncertainty of the annual entire sector North Sea oil production in 2012 is equivalent to nominally $90,000,000/year of revenue unaccounted for. These are the numbers we are chasing with flow measurement.

3.0 UNCERTAINTY (PRACTICAL ASPECTS)

The following is not an attempt at detailing the uncertainty components for custody transfer measurement of oil and gas, but to show the practical components to be considered.

3.1 Non-Proved Systems

The total uncertainty will include the following elements:

$$U_{total} = (AU_{temp}^2 + BU_{press}^2 + DU_{rep}^2 + CU_{lin}^2 + EU_{stab}^2 + FU_{cal}^2 + GU_{inst}^2 + HU_{fluid}^2)^{1/2}$$

Where:

A…..H are sensitivity coefficients
U_{total} is the total uncertainty
U_{temp} is the uncertainty due to temperature measurement (Fluid expansion, body expansion)
U_{press} is the uncertainty due to pressure measurement (Fluid expansion, body expansion)
U_{rep} is the uncertainty due to repeatability
U_{lin} is the uncertainty due to linearity (Flow Range)
U_{stab} is the uncertainty due to meter stability with time
U_{cal} is the uncertainty of the calibration facility
U_{inst} is the Installation uncertainty
U_{Fluid} Is the effect of the fluid properties on the calibration

The shaded sections will all come into play when a meter is linearized. Obviously the linearization, will affect the meter flow rate prediction depending on the strength, quality, of the linearization and the range of operation. Similarly, without a strong basis for the process, the meter stability with changing conditions will affect the performance. The calibration facility uncertainty is now an even more important part of the uncertainty, because this must now reflect the appropriate linearization characteristics for the meter at the operational conditions. Installation effects may now become more critical because it can affect the linearization if, for example, the flow profile is related to the process, further more, meter errors due to installation now become entangled in the linearization process, making resolution a more difficult task. Finally, there is the possibility of an uncertainty due to the process fluid. Many meters are Reynolds number dependent, this function relies on knowledge of the density and viscosity. If the method of determining these is flawed, then changes in the fluid properties will change the linearization, and consequently the overall uncertainty of the metering.

3.2 Proved Systems

The big question now is, does proving remove all or any of these factors? At face value yes, but as we shall see, proving may point out the issue, but then correcting the differences due to, for example, viscosity changes is difficult. Producing the correct linearization for the operation, stability and installation, becomes can be formidable task, particularly if the manufacturer is not fully on board to support those changes. A particular attempt, with the help of the supplier, at on site "linearization" is discussed in detail by Oyvind Nesse [1], where USMs were corrected operationally, showing the time and effort required to obtain a sensible conclusion. In practice therefore the uncertainty retains the components for the non-proved installation along with the prover uncertainty. The value of the non-proved components will depend on any correction from proving, how much the calibration changes with time, how quickly it changes and whether a satisfactory linearization can be carried out to correct for the changes. The new uncertainty becomes:

$$U_{total} = (AU_{temp}^2 + BU_{press}^2 + DU_{rep}^2 + \boxed{CU_{lin}^2 + EU_{stab}^2 + FU_{cal}^2 + GU_{inst}^2 + HU_{fluid}^2 + IU_{prove}^2})^{1/2}$$

Where:

IU_{prove} is the proving component.

The effect on proving reproducibility, long term stability, on a USM for example, due to operation in the low Reynolds number region is shown well in reference [1]. The data for a USM calibrated over time with temperature and flowrate can be seen to be varying. The meter was "characterised" to correct for linearity, but as can be seen the long term stability is well outside of an acceptable limit. Stability is basically determined by the meter linearity in this case, and this was not working for low Reynolds numbers for this meter. The correction method was later changed, based on the local proving data, to give a better performance.

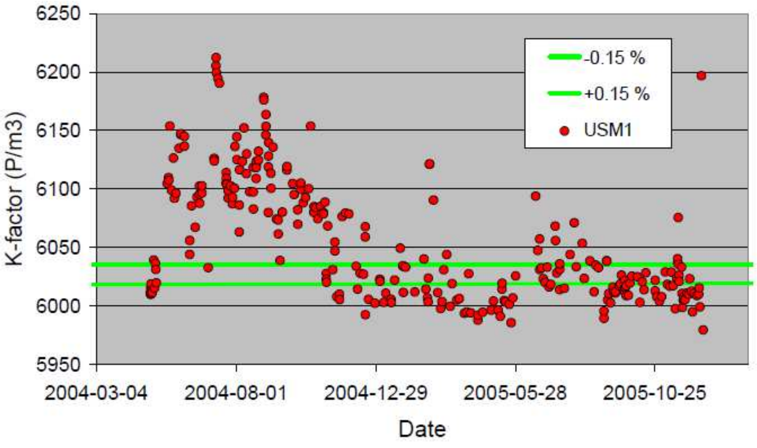

Figure 1 Long Term Calibration of a USM with Varying Conditions[1]

4.0 LINEARITY

The perfect flowmeter should have a basic output, with no calibration, data fir or linearization, that is directly proportional to the flowrate, from zero flow to the maximum required, with no differences or errors. Thus at a flowrate of 3001.234m^3/h the meter should also read 3001.234m^3/h, and at 30.01234m^3/h the meter should also read 30.01234m^3/h. Much as we would all desire such a meter, they do not exist, except in the imagination of astute marketing executives. All meters have some variation, whether this is an offset because of calibration issues, drift, lack of repeatability or the meter not being exactly proportional to the flowrate. They have, essentially, a calibration curve, and the meter is said not to be perfectly linear. There are a number of definitions of linearity, but the most appropriate in our case would be: "Linearity may be used for instruments that give a reading approximately proportional to the true flow rate over their specified range. It is a special case of conformity to a curve ……. linearity refers to the closeness within which the meter achieves a truly linear or proportional response. It is usually defined by stating the maximum deviation (or nonconformity, e.g., ±1 % of flow rate) within which the response lies over a stated range. **With modern signal processing, linearity is probably less important than conformity to a general curve**. Linearity is most commonly used with such meters as the turbine meter."[2]

The comment with regard to modern signal processing should be noted. It is further noted that "One note of caution! Clever electronics can take any signal, however nonlinear, and straighten the characteristic before the signal is output ….. (Referring to the steep part of a turbine meter curve) The characteristic is probably very sensitive to minor variations in this region, and any attempt to use the characteristic could lead to disguised, but serious, errors." [2]

Good design practice for an instrument should be to produce the basic mechanism with the best possible linear relationship between the physical property being used to infer the measurement, and the property being measured, for example flow, temperature or pressure. Signal processing can then be used to make that inferred quantity more accessible or possibly make the relationship more precise. **Good design will get the basic characteristics of the meter as good as possible; signal processing will then be the "icing on the cake" not the cake itself.**

The use of signal processing methods to linearize meters has now become common practice. It is only feasible if the meter is intrinsically stable and repeatable under all conditions. Without this it becomes difficult to both diagnose site problems and determine the potential performance of the meter. Unraveling the effects of linearization to determine the errors and potential solutions is very difficult.

5.0 LINEARIZATION (CHARACTERISATION)

Linearization is a term used to describe the process of making a meter that has a variation in the calibration curve with flow range more linear. It is sometimes referred to as characterization. A typical method is to take the calibration curve for a turbine meter, shown in Figure 2, and linearize it to "improve" the meter performance.

The curve is shown as a function of K factor. This is essentially the ratio of the meter reading to the calibration reading. This method amplifies the shape, and clarifies the linear performance. The curve is achieved by calibrating the meter at a number of flowrates across its range. In this case the meter calibration has been repeated 5 times at each flowrate to achieve a mean value to define the calibration curve. The curve shape is defined by the bearing friction at the very low flows, viscosity at the hump and a rising characteristic at the top flows. To obtain the linearity a range has to be associated with the curve. In this hypothetical curve it was chosen at the point where the linearity achieved is +/- 0.25%.

It is common practice to linearize the meter on site by obtaining the curve as shown, with a linearity of +/- 0.25%, and using a flow computer to "pull" the data closer to a straight line by using either a lookup table or some other form of curve fit. In practice, as indicated, it never truly makes it a straight line, and so the curve is shown just as closer to the straight line, and now has a linearity of +/- 0.1%.

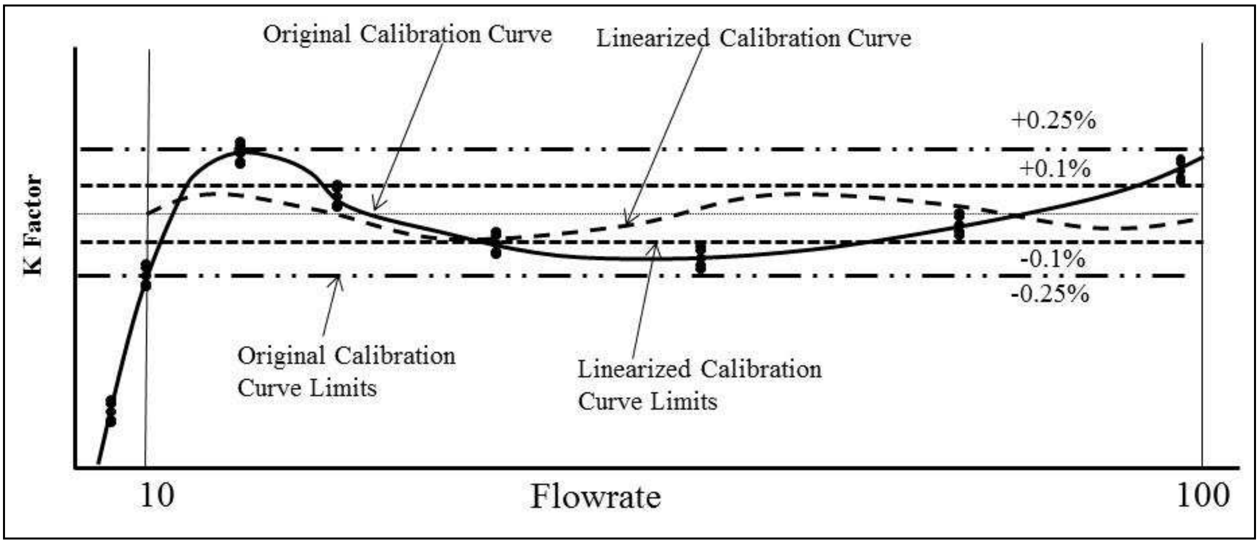

Figure 2 Hypothetical Linearization of Turbine Meter

It should be noted, that the perfect "zero" linearity curve, is not achieved, and as will be described later this new curve probably is only of value at an instant in time because of the inherent stability of the meter, and therefore probably does not have a real value in improving the uncertainty.

5.1 Why is Linearization Required?

The first, and probably most pertinent reason, is that the meter has a fundamental physical relationship that is not a direct linear relationship. The best example would be a differential pressure meter, such as an orifice plate. Here the fundamental physical law relationship between flow and the output, differential pressure, is a square law. Linearization ensures that the output is square rooted. This form of processing is required by the fundamental theory of the device, and is fully understood in terms of physics and is not a result of a calibration. This paper is not discussing this type of linearization. The paper is concerned with that used to correct the meter after the fundamental relationship has been implemented. So, for example, in the case of an orifice plate the linearization discussed in this paper is not the theoretical conversion type as seen with taking the square root of the primary signal. It is the type concerned with the implementation of the non-theoretical data fit of the meters primary signal to the flowrate output, i.e. in this case the discharge coefficient Vs Reynolds number relationship. Linearization discussed here therefore is primarily required to keep the meter primary signal to flowrate relationship within the specified uncertainty over a range of flow conditions.

There are other reasons for linearization, there is the prospect of improving the overall uncertainty of the meter, which may be adequate within the specification, but linearization may be perceived as reducing it further, or at least giving some head room to the meter uncertainty. Perhaps the final reason, and more specious

is that it allows specifications to be pushed to the limit and become more competitive.

5.2 Linearization Correlation Parameter

Linearization relies on there being a base variable, a physical correlation parameter, to linearize against. This parameter must have a strong relationship with the linearizing function, preferably with the minimum of correction. Further the parameter must be easily and accurately calculable, as the whole basis of the linearization relies on this base. If the base cannot be determined within acceptable limits and is not stable, then the linearization will be incorrect, leading to unexpected and often unexplained errors. The most common correlation parameter for meters that rely on fluid mechanics as their basis of operation is Reynolds number, a parameter that is difficult to measure and control. In the case of Coriolis meters temperature and pressure also represent linearization correlation parameters as they are required to correct for the linearity's due to stiffness changes. Both of these parameters are much easier than Reynolds number to measure, and consequently are much more stable corrections. For gas meters, at the high flows the correlation parameter may be Mach number, which is essentially a velocity based parameter.

The linearity curve must be stable, repeatable and with the minimum of scatter compared to the correlation parameter. If there are several parameters at work, that cannot all be well characterized, then they can lead to errors in linearization. One such example would be trying to linearize a turbine meter at low flows where the bearing friction is becoming a major factor. The curve will now be influenced over time by the wear on the bearings, changing the shape of the calibration curve, figure 3. This would require a new curve to be placed in the flow computer as the calibration changed. This part of the curve also exhibits a further issue, the steepness of the curve means that a small change in flowrate results in a large change in calibration. Thus the linearity is also contributing to the repeatability, stability, of the curve. Trying to correct for this inevitably leads to an increased uncertainty. This is also demonstrated in figure 3. The lowest uncertainty correction is achieved when the relationship between the calibration and the correlation parameter is minimized.

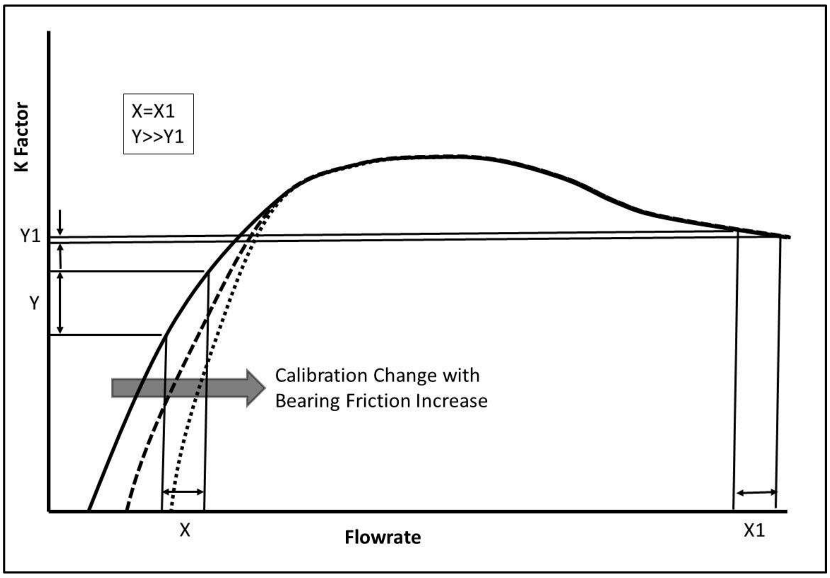

Figure 3 Effect Bearing Friction & Steepness of Curve on Linearization

5.3 Does Linearization Have a Real Value?

For almost any meter there is some potential value in linearization. It can improve the uncertainty of the overall performance of the meter, particularly over a significant range. For some meter designs it is essential to achieve an acceptable performance. Some USMs and Coriolis meters are non-linear beyond the levels discussed in the section on Custody Transfer, particularly at low and sometimes medium Reynolds numbers, and so to meet these requirements over such a range they **must be** linearized.

There is an argument that increasing the low uncertainty range of a meter is economically useful. For example, in loading of large tankers it is common practice to have a bank of turbine meters, possibly up to 5 meters. The meters are sized to be run at their single "sweet spot", the point where they are most linear and least effected by such issues as viscosity. The loading rates of the tanker are determined and then a sufficient number of meters brought on line to ensure this condition. Equally when starting up and shutting down, meters will be brought on line to ensure their operation at the sweet spot. Proving of the meter is also only at a single flowrate, the loading flowrate, or over a much reduced range. The problem with this is that it becomes a large bulky expensive system, with a complex control system. In theory, to have a single meter, with an acceptable performance that can operate over the full required range would be less bulky, have a reduced cost of installation and less complex control function. This is in many respects the economic driving force for linear meters, and hence linearization.

The issue, however, is clear; linearization should only be carried out if the correlation parameter is strong and solid. If not, errors will appear, and without on-site calibration they will not be easily caught or determined.
One of the major downsides is that it hides the causes of errors, by virtue of complicating the operation of the meter, and the effect that external parameters, such as installation errors, are having on the meter output. Resolving errors with a linearized meter is akin to peeling away layers of an onion to get to the answer. It can make the potential errors higher or lower than for the non-linearized case; the problem is that, without a lot of extra testing, it is difficult to determine.

6.0 LINEARIZATION APPLIED TO ACTUAL METERS

Historically we have been linearizing meters for many years. Differential pressure meters have always been corrected at low Reynolds numbers. Early on an attempt was made to solve the problem by developing alternative designs from the familiar square edge orifice plate, using quarter circle and conical entrance plates to achieve a linear performance at low Reynolds numbers. Unfortunately like all engineering solutions "you win some and you lose some", and the improvement at the low end of the Reynolds number scale was offset by a step in the discharge calibration curve at high Reynolds numbers. A case again of engineering solving one problem by creating another!
The early BS 1042-1964[3] shows clearly the non-linearity of the square edge orifice plate. At the time of BS 10420 (1964) the correction calculations were carried out by hand, and there was no shame in a meter having a Reynolds number characteristic, it was clearly stated in BS1042 along with the method of calculation. Nowadays, in ISO 5167 and AGA3, for orifices, of course there is an equation, the Reader Harris/Gallagher equation, and the flow computer does the correction. **As with most meters this is an empirical linearization based on knowledge of the Reynolds number, and as a consequence requires an associated extra uncertainty based on the knowledge of the flowing Reynolds number, and confidence in the shape of the curve.**

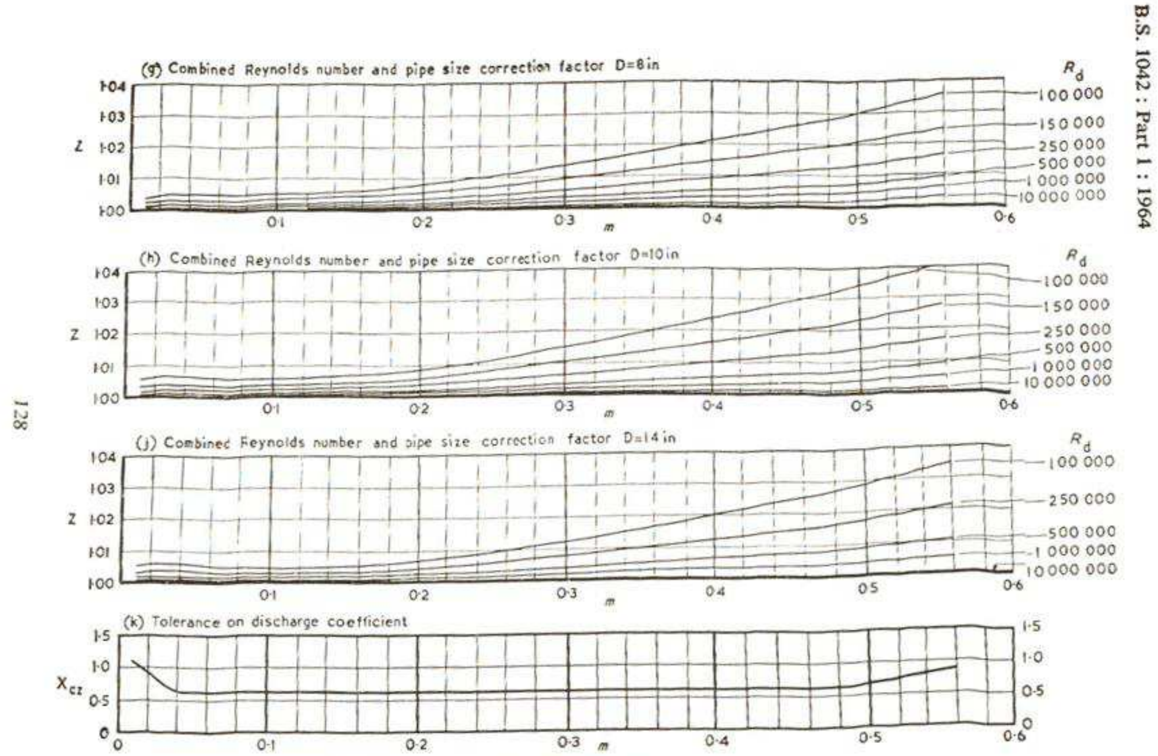

Fig. 41. Data for orifice plate with flange tappings—*continued*

Figure 4 Combined Pipe Size & Reynolds Number Corrections for Flange Taps, BS 1042:1964[3]

6.1 Turbine Meters

Turbine meters have already been discussed briefly in a previous section as an example of one method used to linearize a meter. For a flat bladed turbine meter the main correlating parameter is assumed to be the flowrate, although fluid product in the form of viscosity may be brought in as an extra parameter. Increasingly users are employing a multi-point linearization, up to a 12-point meter factor linearization curves for multiple crude oil grades and products, figure 5. The meter factor curve for each flowmeter and product combination is determined by proving when the flowmeter is first installed. Minor shifts in flowmeter performance are corrected in the flow computer which lifts or lowers the meter factor curve, based on the meter factor obtained at the latest official flowmeter proving. During operation, the meter factor is continuously adjusted for flowrate. The reported meter factor is the 'flow weighted' average meter factor. The linearization is often called by the euphemism, "normalized to the base Meter factor". In other words the points away from the base meter factor are brought into line with that factor. When the meter is re-proved the complete curve is often assumed to stay the same and may be shifted in line with the new prove value. In many cases only if the meter factor moves beyond a certain limits, usually of the order of +/-0.2-0.25 is a change made. This limit is the assumed long term stability of a turbine meter. If the prove is within this limit the meter is often left with the original meter factor.

This implies that there is in the calculation uncertainty of a given meter of at least a 0.2% allowance, either by policy or contract, for linearity/ stability. Over the usable flow range of a turbine meter they are normally better than +/- 0.1-0.15%. When linearized the implication is that they will be far better, probably 0.05% or less. The linearization is only changed when a new product is sent through the line or there is a significant viscosity or temperature change. The linearization is therefore based on a knowledge of Reynolds number, and as a consequence, requires an associated extra uncertainty based on the Reynolds number and the shape of the curve.

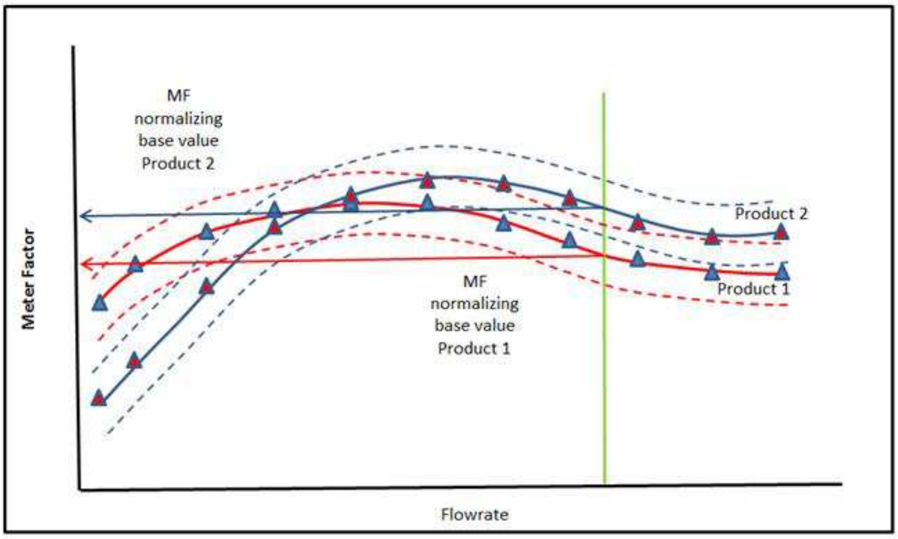

Figure 5 Linearization of a Turbine Meter

The points to be made about this methodology are:

- The uncertainty for a **given viscosity** will be heavily influenced by the stability of the meter, 0.2-0.25%!
- This is only applicable to one viscosity, when the viscosity changes, the stability remains the same but is now shifted in line with the calibration shift.
- If the change in viscosity is due to temperature, as for example a system I audited in 1994 measured oil supplied from tanks. The temperature changed from winter to summer of -15 to 40°C, resulting in a continuous annual viscosity change of 5 to 30cS. The meter factor shifted but also the linearity changed, figure 6. This was a continuous change and so the issues to be addressed are:
    - The linearization requires to be carried out over the complete range of viscosity changes.
    - If this is not done then single point proves are not sufficient to determine the new calibration.
    - At what stage should a new prove be carried out?
    - More importantly there is additional uncertainty that must be added to the measurement.
    - How repeatable are the changes with viscosity?

The value of linearizing to 0.05% must be seriously in doubt under these circumstances.

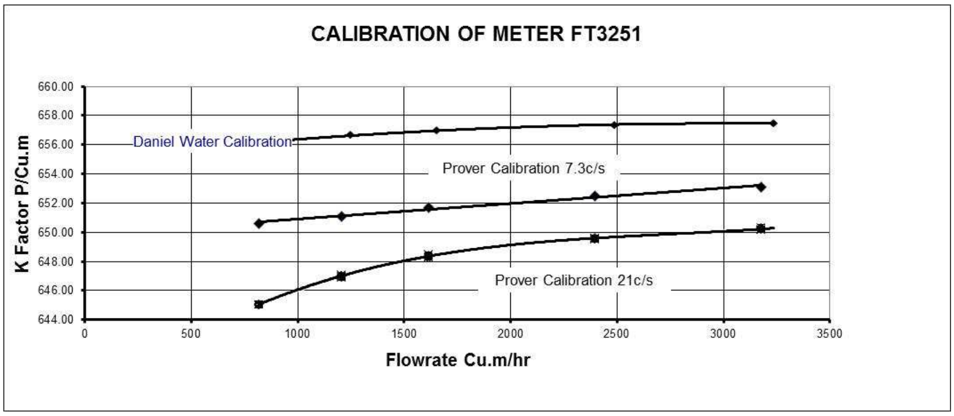

Figure 6 Calibration of 14" Turbines at 7.3 and 21cS

Remembering back to the value of uncertainty for the measurement of oil, it would have been more sensible to ensure that the meter package essentially could be set up to run the meters at single flowrates, thus at least requiring only a single prove, and a policy of when to prove. There would still be extra uncertainty, but this would be controlled and significantly reduced.

With a helical bladed meter it would be hoped that the viscosity movement would be reduced, with a consequent lessening of the effect on the uncertainty, but the principle is still the same, if the stability of the meter is in the order of 0.2-0.25% the value of linearizing the meter to better than 0.05% is probably “fools gold”, because once the proving and linearizing is carried out the meter has possibly changed its calibration.

6.2 Ultrasonic Flow Meters

There are three distinct areas, defined by Reynolds number, to consider when viewing linearization of time of flight based USMs used for Custody Transfer. This paper does not include the issues with single path and “clamp-on” meters, as they are not currently considered a standard for Custody Transfer, but concentrates on multi-path type meters.

The three areas where linearization is used with different effect are:

- High Reynolds number, nominally above 10^6: This will include Gases, LNG and fluids such as Butanes etc.
- Medium Reynolds number, nominally between 10^4 and 10^6: This will include the majority of hydrocarbon liquids, including many types of crude.
- Low Reynolds number, nominally below 10^4: This will include the heavy oils now being produced.

There are many variations of paths to produce a multipath meter, chordal, bouncing, four paths, eight paths, 5 paths, 6 paths etc. They all have a different basic linearity, depending on design, path configuration, effects of transducer ports and profile. The amount of effect is usually governed by Reynolds number. A typical example is seen in figure 7. The calibration curves of two meters, one using the Legendre solution and the other the Jacobian solution to the four path Gaussian quadrature path positioning..

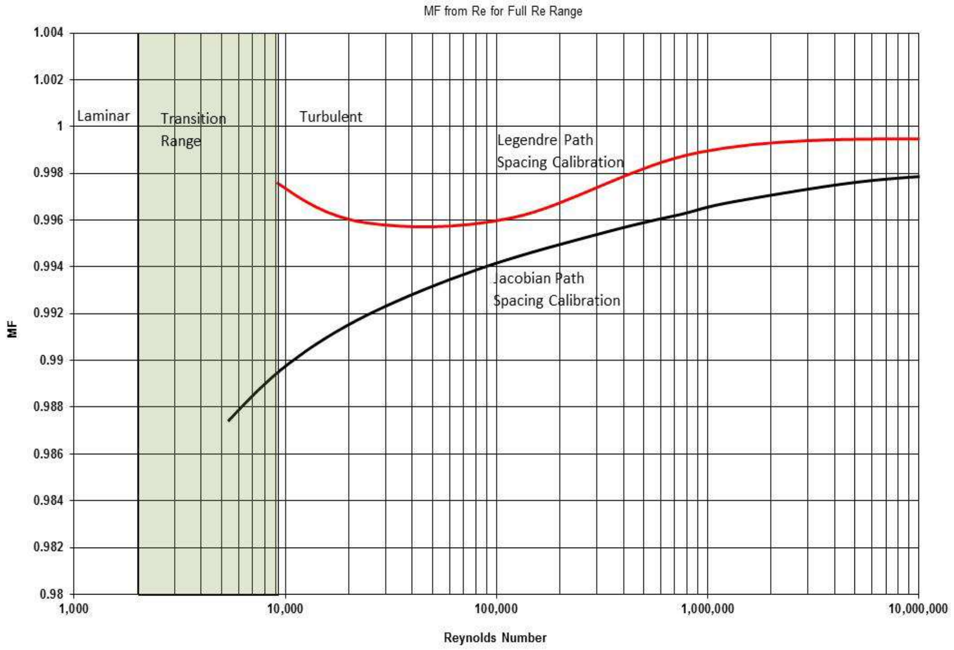

Figure 7 Different Shaped Curves for Legendre and Jacobian Solutions for Four Path Gaussian Meters

Two features are immediately apparent, the Jacobian basic curve is more non-linear than the Legendre over the range of 10^4 to 10^6 and would thus require more linearization, and also as the Reynolds number increases towards 10^6 both curves are becoming more linear. What is not so clear, however, is that the Jacobian solution is more stable when the Reynolds number goes below 10^4. There will be many more variations to these curves depending on the path configurations, but the majority will require linearization to meet the current linearity specifications, of between +/- 0.12 and 0.15%. It should be noted that these are calibration shapes with a fully developed flow profile.

6.21 High Reynolds Number

As stated, in general along with most fluid machines, as the Reynolds number increases the effects become more stable, in this case meters become more linear. Calibrations of 10 eight path meters [4] without any correction on water, calibrated above a Reynolds number of 5×10^5 to 3×10^6 show a linearity of +/- 0.08% across the range, figure 10.

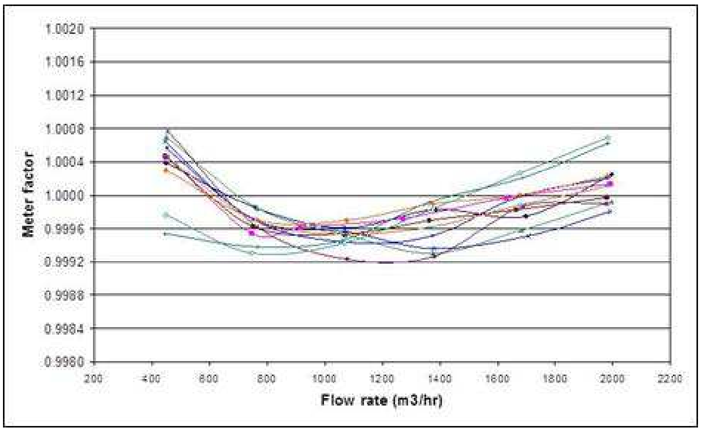

Figure 8 Calibration of 10 Liquid Meters at High Reynolds Number [4]

Gas meters operate at higher Reynolds numbers, up to 10^7 and are generally linear "out of the box" to within acceptable specification for gas meters on Custody transfer application, +/- 0.3%. Even though they are often within specification, they are almost inevitably linearized to improve the performance.

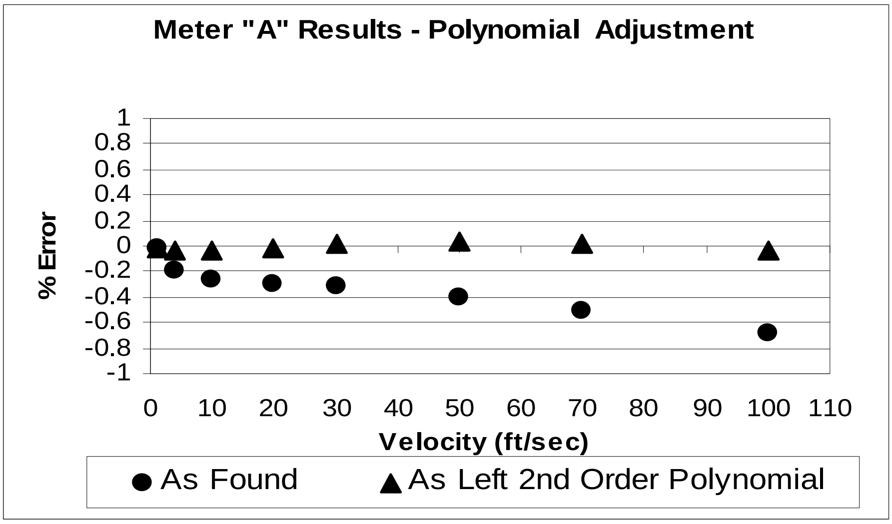

Figure 9 Linearization of a Gas USM [5]

There are several issues relating to the linearization of gas meters to consider. The first is that the meter in figure 9, for example, has been reduced to a notional linearity of around +/- 0.05% from +/- 0.3%. Should this now become the number to include in the uncertainty calculation? The uncertainty of the calibration facility that has produced this "new" linearized curve is in the order of 0.2-0.3%, and so the question should be raised as how reliable is this linearization. The second issue is that many USMs use only a velocity correction. If the non-linearity is due to Mach number, then this may be valid, but most of the non-linearity is Reynolds number related, and so to have any validity the correction must be corrected for Reynolds number, in fact some combination of that plus Mach number. A further issue to note is, how do we determine Reynolds number of an operational gas? Within current Custody Transfer specifications for gas, this issue is probably not of great consequence, but there are pressures to reduce the uncertainty of gas measurement, and then this will become more critical.

6.22 Medium Reynolds Numbers

It is in the medium range that there is most need to understand the implications of linearization. This is where the majority of meters are sold, and it is generally where currently hydrocarbons are at their greatest value. The performance of meters is dependent on the design, number of paths, path configuration and possibly the transducer installation, but the major issue with all of these factors is that the non-linearity induced by them is dependent on Reynolds number. The problem then is to determine how to correct for this.

There are a number of different methods available to correct the linearity of multipath USMs, but all in the end are either a direct or inferred methods to determine Reynolds number, discussed in more detail in section 6.24.

6.23 Low Reynolds Number - Transition and Laminar Flow

At transition the issues are non-linearity combined with poor repeatability. Poor repeatability is due to the large variation in turbulence and profile changes due to the flow switching from laminar to turbulent with time. The issues can be mitigated by moving the outer paths away from the walls towards the centre, which is why, for example, the Jacobian spaced meters have less problems going through transition than the Legendre, for which the outer paths are closer to the pipe walls, where the turbulence levels are higher. The meter, like most meters, is still very non-linear during this phase, and difficult to linearize.

A better solution is to design out the problem. This can be done by reducing the bore of the meter section [7].
Laminar flow, not only has a rapid variation in profile with Reynolds number [8] , but has practical problems with temperature gradients. Depending on the path configuration the linearity will change during these large and quick changes in profile with Reynolds number, shown in figure 10 as the ratio of the mean to the centerline velocity. Reynolds number correction becomes more critical in this region.

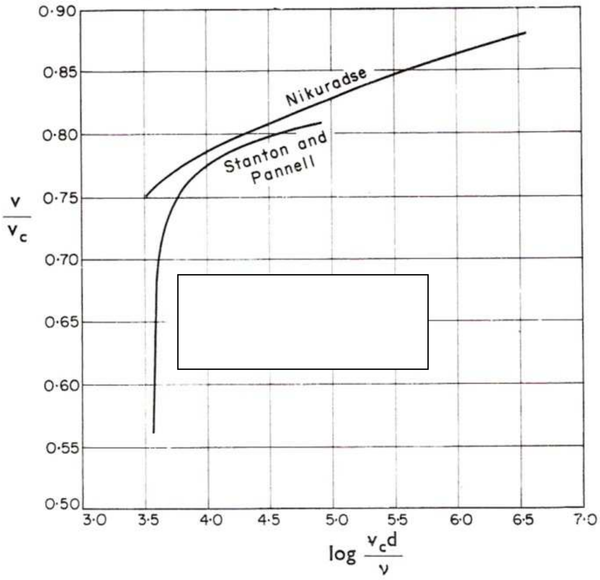

Figure 10 Change in Profile with Reynolds Number [8]

6.24 Methods of Linearizing USMs

There are a number of methods available for determining the Reynolds number of the meter at flowing conditions.

6.241 Direct Reynolds Number Correction

There are several methods available for this:

- **Fixed kinematic viscosity inputs**: It is possible to put in a fixed value and compensate for temperature. This obviously requires an initial value, either by theory or sampling, and then to be sure of the relationship with temperature. If the fluid changes then the base viscosity will change resulting in errors in compensation.
- **Measuring viscosity using an on-line viscomete**r: It is another possible method, but good inline viscometers are few and far between.
- **Ultrasound and Viscosity**: There is an empirical relationship between viscosity and velocity of sound (VOS). There is also a relationship between acoustic attenuation and VOS. Using VOS is attractive as it is a direct output form the meter, but the data, particularly for crude oils is sparse, and can again lead to errors. The other method is attenuation of the signal. This method is difficult to implement without calibration.

If not used correctly, these methods can lead to significant mis-calculation of Reynolds number, with a consequent error in the linearization.

6.242 Flow Profile

The second, and probably most common method, is to use the change in flow profile. This is calculated by using the ratio of the outer chords to the inner chords, and called flatness ratio. (For gas meters it is usually calculated as the inverse). A typical curve for flatness ratio against Reynolds number is shown in figure 11. As can be seen its shape varies with Reynolds number, in the same way as the actual profile variation.

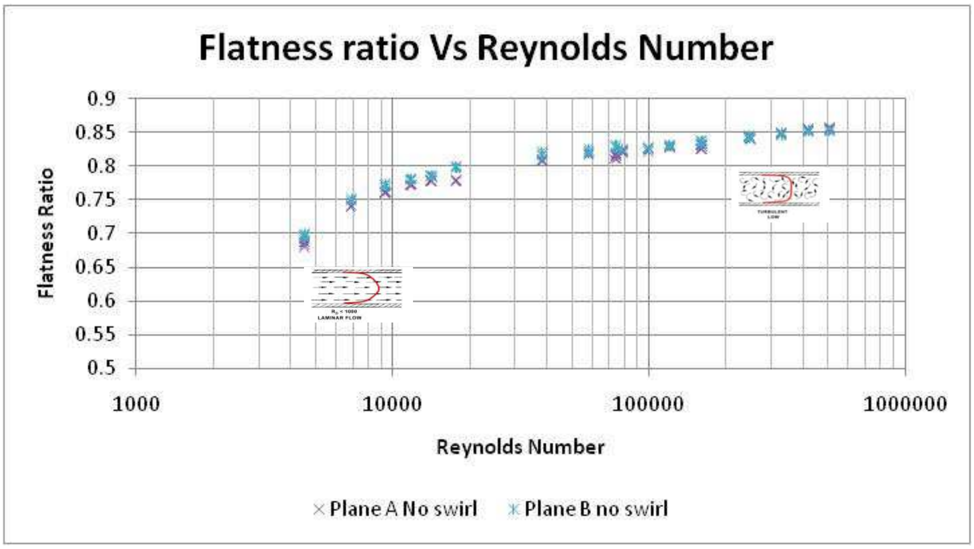

Figure 11 Flatness Ratio Vs Reynolds Number for a Straight Pipe [6]

The corrections are then carried out by either plotting the meter factor against flatness ratio, or calculating the actual Reynolds number from the flatness.

The problem with using flatness ratio as the correlation parameter, is the effect of changes in profile due to installation conditions on some meters. As can be seen from figure 12, the flatness ratio changes on a chordal meter with the introduction of swirl, such that it is now potentially different corrections at the same Reynolds number. The flatness, as expected increases, the profile becomes more flat, and there is less variation across the Reynolds number range, making it more difficult to form a relationship with Reynolds number.

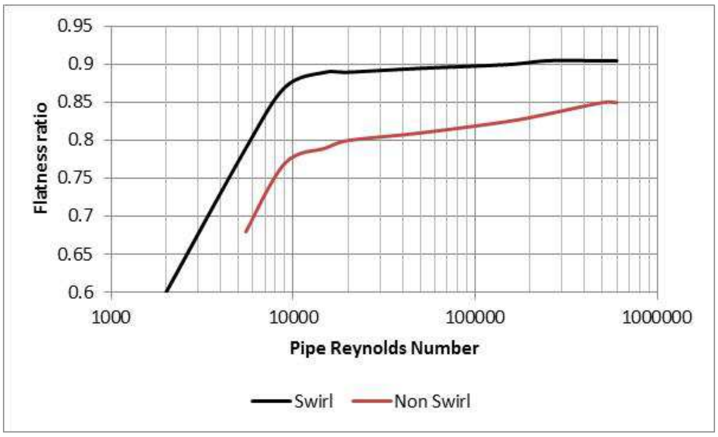

Figure 12 Flatness of the Profile with and without Swirl

The introduction of 8 path meters has helped by removing the asymmetry and reducing the flatness change detected by the meter. There may also be an argument here for the use of flow conditioners to ensure the stability of profile correction factor. The traditional flow conditioner is designed to try and produce under all conditions of upstream installation conditions a flow that simulates a fully developed profile. The conditioner in itself does not follow the Reynolds number profile changes, but if the conditioner is now considered with a section of pipe downstream, a plenum chamber the final profile will change in line with the expected Reynolds number changes [9]. This would produce a more stable correlation factor for meter correction. The other method is to have a reduced bore at the meter section, this will control the incoming flow profile to a degree, but not as well as a flow conditioner.

6.243 Weighting Factors

There are other less commonly used methods, such as varying the weighting function of the paths. This is described in some detail in reference [1]. In this method essentially access is required to the very basis of the calculations for the flowmeter, and can only be carried out with the help and consent of the manufacturer. The operation, described [1], was at low Reynolds numbers and it required that the original linearization, based on flow profile, be turned off and then a set of weighting factors were derived from the prover data for the meters to essentially linearize the meter. Changing weighting factors can be controversial, as the method changes the basis of operation of the meter, and may lead to unexpected consequences, particularly out of the Reynolds number range of the linearization.

6.3 Coriolis Meters

With Coriolis meters we have several linearizations, temperature and pressure corrections for changes in tube stiffness that have been used almost since the inception of Coriolis meters. As this paper is about flow related changes, the concentration in this section will be on Reynolds number variations.

6.31 Reynolds Number Effect on Coriolis Meters

For many years it was considered that the Coriolis meter, because it is a "mass meter" is not affected by Reynolds number. It is a fluid machine and therefore must inevitably have some Reynolds number influence on its performance. This really came to light after tests by NEL [10], although it was at first adjudged to be a viscosity effect. A typical set of data is shown in figures 13 & 14, which look eerily like the performance of USMs at low Reynolds number.

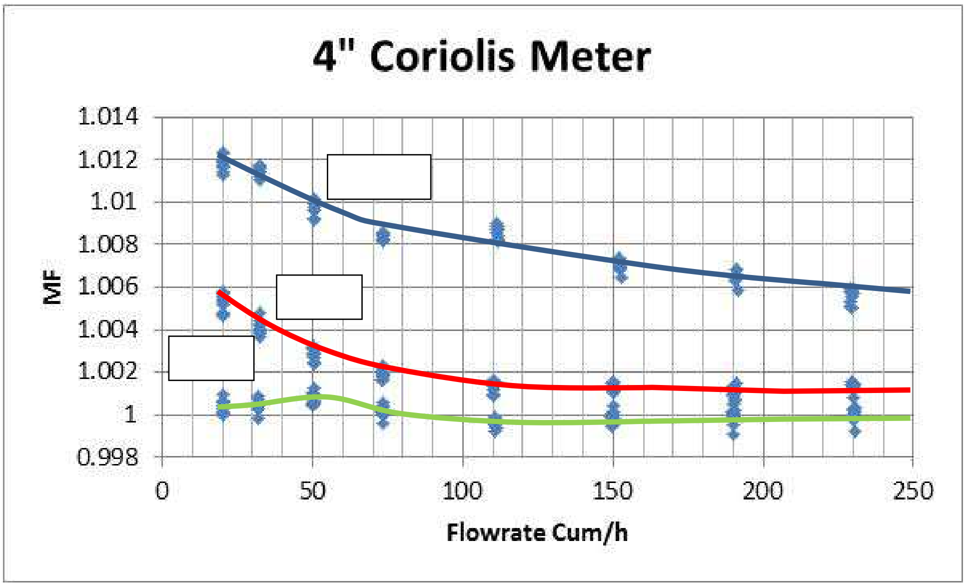

Figure 13 Calibration of a 4' Coriolis Meter Vs Flowrate

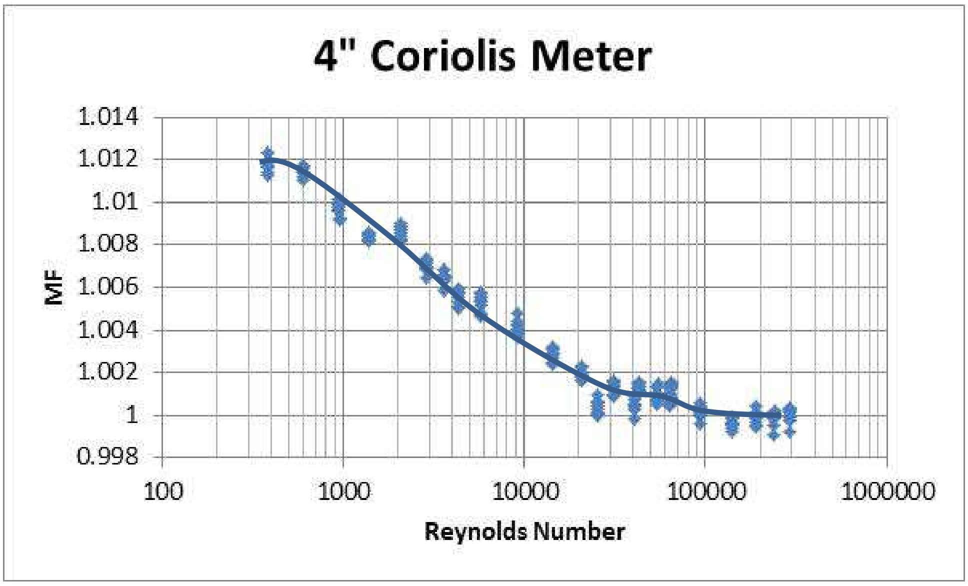

Figure 14 Calibration of a 4" Coriolis Meter Vs Reynolds Number

It is quite clear from the preceding data that the Coriolis meter has to be linearized for operation below 10,000 Reynolds number. By a Reynolds number of 10^3, the meter shown is non-linear by the order of 1.01%, far beyond the 0.1% mark already discussed for custody transfer of hydrocarbons. The reason appears to be related to an out of phase operation when the flow becomes laminar [11]. The amount of deviation appears to be related to the design, and so there is no universal correction. There are only two real ways of correcting for the non-linearity, using the inherent ability of a Coriolis meter to determine viscosity, which along with the knowledge of the density allows for the calculation of Reynolds number, and hence a correction. The other method is the use of an external measurement of viscosity, either by estimation or another device.

There is very little data at present showing how the different manufacturers deal with this. However, what should be clear is that there will be an extra uncertainty added to the calibration, based on the quality of the linearization. It has been stated that the meter does not need to be calibrated in this region, because the curve is so repeatable. The question is how repeatable is repeatable? Only independent data can decide this. It should be noted that it has taken over 20 years to find a basic property in this meter, and we still do not know the full extent of the problem.

7.0 CALIBRATION & PROVING

Calibration becomes a critical issue when a meter is linearized. It is still claimed that for liquid USMs and Coriolis meters in particular, a water calibration is sufficient even though the chances of going into the low Reynolds number area with water are small. This then pre-supposes that the non-linearity of the meters remains the same within the required uncertainty. Again remembering that we are looking for 0.1% or better can this really be true on liquid? Even with gas meters it may be necessary to re-think calibration when the uncertainty requirements become tighter. Obviously not calibrating the meters over the range of operation must carry with it an inherent risk that the correction is wrong. **The meter should only be used with a water calibration when the manufacturers can show that their production is sufficiently robust to**

make the assumption that their meters will meet the uncertainty criteria without calibration at operational conditions.

A reference has already been made to the influence of proving on the situation. In theory if the meter is linearized correctly, the only issue of proving is to demonstrate the meter performance under operational conditions. This is a problem if the linearization is not robust or correct. An example is of a USM where the Reynolds number was not correct because the calculation of viscosity was incorrect. The Meter Factor variation through the year can be seen in figure 15.

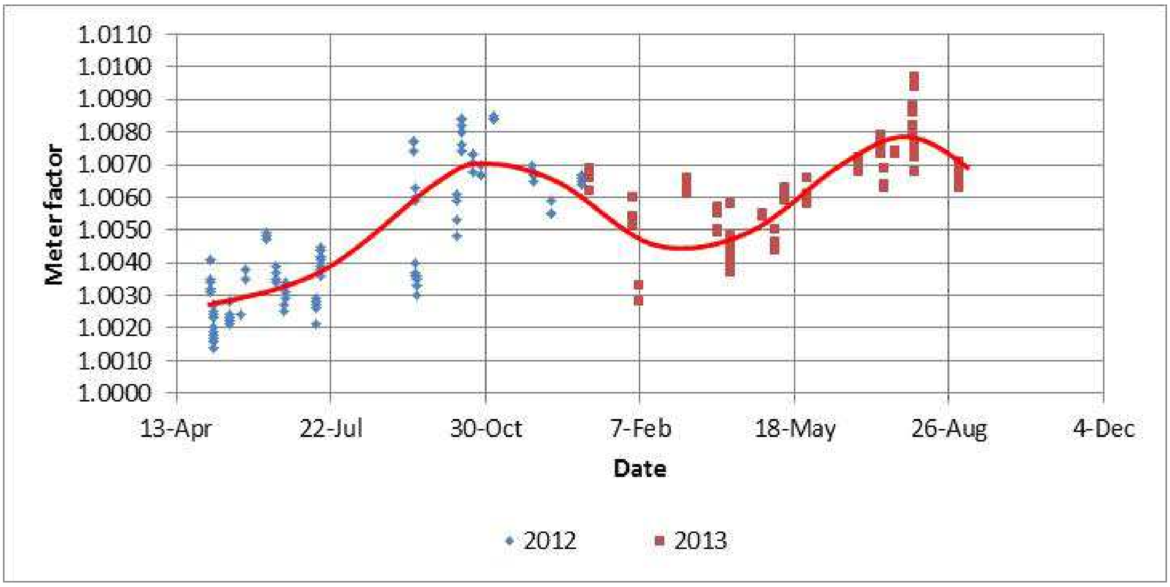

Figure 15 MF Provings through Year

The cause of the problem was an incorrect reading of the viscosity. The shape of the calibration curve of the meter, figure 16, shows the meter over reads as the Reynolds number reduces through the actual operating Reynolds number, but

flattens as the Reynolds number increases. The viscosity put the meter Reynolds number in the region of the flatter curve, resulting in an annual oscillating shape through the year. The viscosity change though the year was nominally 2.4:1, obviously giving the same change in Reynolds number, which as can be seen from the curve below should result in a maximum correction in the order of 0.3%, but as the Reynolds number was incorrect, the resultant change was only 0.03%. This is very similar to the situation in reference 1.

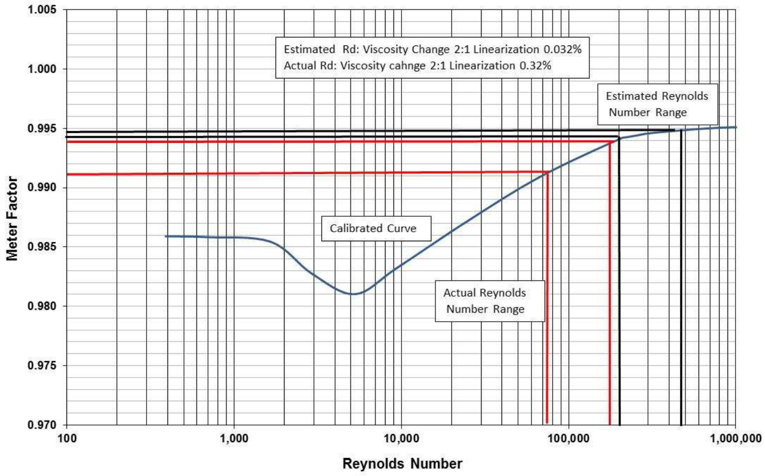

Figure 16 Actual Corrections Compared to Estimated

Unlike reference 1 the solution was to correct the correlation factor based on the data, rather than use new weighting factors. After correction, as can be seen in figure 17, there is still a small average oscillation throughout the year, but the overall change is flattened out across the temperature/viscosity changes. The major issue is that t**he correction had to be made in the meter firmware and could not have been corrected by the user.**

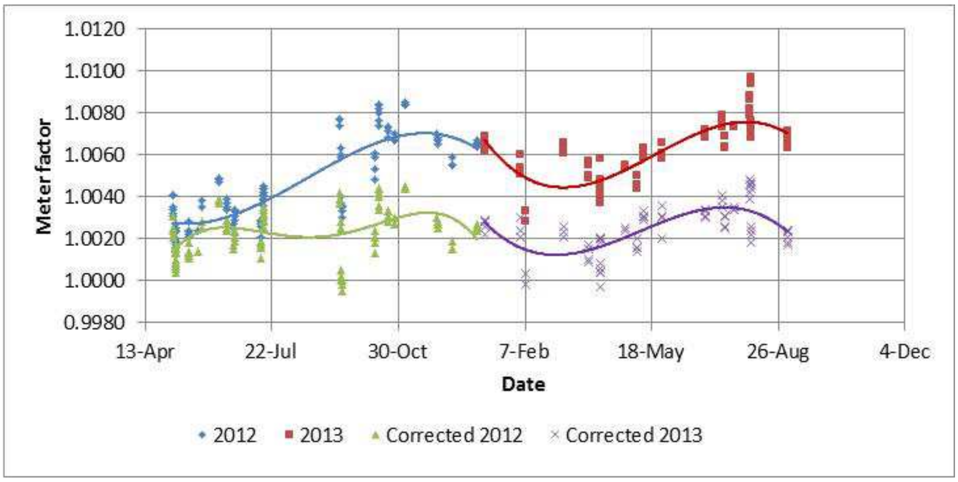

Figure 17 Corrected Provings for Reynolds Number

The lesson to be learnt from this example is that a curve fit, linearization, is only as good as the uncertainty of the required inputs, "garbage in garbage out".

8.0 IS LINEARIZATION SAFE FOR CUSTODY TRANSFER METERS?

This is the crux of the matter and the title of the paper, but to get here we have had to review the methods used for different meters. The following points need to be made:

- At what level of uncertainty do we need to be achieving to meet the contract or regulatory responsibilities for the metering? If this is a system uncertainty of 0.3% or better then great care must be taken with the metering, and this will include the methodology of correcting the meter.
- The physics and methodology for the corrections should be made available for the users so that they can make a value judgment as the validity of the corrections. (This is generally done for temperature and pressure corrections, why not flow related?)
- When linearizing meters, the true value of the linearization should be assessed, for example does linearization of turbine meters really add any value to the end uncertainty in practical terms?
- Liquid USMs have now a better history of manufacturers demonstrating the method of corrections, but Coriolis meters are only just beginning to get to this point, and more data needs to be available to assess the performance of meters at lower Reynolds numbers.
- For low uncertainty installations meters cannot be treated as black boxes, regulators and users need to know how the final answer is to be achieved, to ensure that they are confident in the final operation of the meter.
- Calibration on fluid close to operational conditions is, in my view, absolutely necessary for low uncertainty installations. Only if it can be rigorously demonstrated that the linearity can be "extrapolated" to other conditions, within the required uncertainty, would it be acceptable to, for example, calibrate on water and then assume the performance at lower Reynolds numbers.
- Proving may not solve the problem without a good deal of effort if the correlation factor, curve shape or calibration is not robust. It will certainly show the problem clearly, but correction will currently need help from the vendor, as the changes to be made are intimately tied to the meter operation, and usually held in the firmware of the meter.

9.0 FINAL COMMENTS

Meter linearization is a necessary evil. It has been made more accessible with the improvements in electronics, processing and software. In some respects it has made us lazy in terms of basic design of instruments using the processing power to cut development corners, but also for end users who do not want to spend the time finding out about the possible pitfalls of meters. They become convenient black boxes to purchase and install and the assumed uncertainty is then accepted. Yet those uncertainties are still there, and they consume money. Linearization masks fundamental flaws and makes investigation of errors in measurement more difficult, as it covers the problem with layers of corrections.

If linearization needs to be carried out the correlation factor must be solid. It must have:

- A good relationship with the correction.
- It must be readily calculable.
- It must be repeatable.
- It is preferable that it is as small a correction as possible.

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