The demands of quality standards throughout the world such as ISO 9000 and BS5750 have led to the major pressure gauge users demanding instruments that stay in calibration longer. Resources are no longer available to recalibrate pressure gauges on a regular basis. Ultimately wear on a gauge movement or plastic deformation of the Bourdon tube can lead to failure of the measuring element.

This report outlines some of the development work being researched at WIKA, in conjunction with the major gauge users, to improve the safety and long-term accuracy of Bourdon tube pressure gauges. Recommendations on the best type of pressure gauge for countering the effects of vibration and pulsation in process plants are also included in this report.

Fig. 1  Components of a Bourdon tube pressure gauge
1.1 Introduction

Bourdon tube pressure gauges represent about 90% of the market for mechanical pressure measurement. But mechanical vibration and pulsating pressure are common causes of failure for this type of gauge.

This report looks into the reasons for the failure of Bourdon tube gauges and covers a number of techniques that can prolong the life of the instruments. A close examination is also made of the implications of using damped movements and liquid-filled cases to prolong the life of a gauge.

All the research data in this report is based on 4” (100 mm) stainless steel Bourdon tube gauges.

1.2 Common frequency ranges

When designing a pressure gauge it is important to take into account some of the common frequencies encountered within the industry, thus preventing these frequencies from matching the resonant frequency of the pressure gauge. Table 1 shows some examples of common frequencies.

<table>
<thead>
<tr>
<th>Application</th>
<th>Frequency Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Alternating Current - Single Pole Motors</td>
<td>50</td>
</tr>
<tr>
<td>USA Alternating Current - Single Pole Motors</td>
<td>60</td>
</tr>
<tr>
<td>Typical Hydraulic Drive Assembly</td>
<td>120</td>
</tr>
<tr>
<td>Five Piston Pump with 50Hz Motor at 1440 RPM</td>
<td>24</td>
</tr>
<tr>
<td>High Pressure Cleaning Machine at 2000 PSI</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 1 Common equipment frequencies found in the process industry. When designing pressure gauges it is important that the resonant frequency of the gauges should be different from the common frequencies found in the process industry.

The following section looks at these areas of high stress and shows how research into new techniques of Bourdon tube production has led to the development of a much stronger and safer tube.

2. Initial examination of Bourdon tube measuring elements

The combined effect of pressure loading and elastic deformation due to mechanical vibration produce areas of high stress within a Bourdon tube. These areas of high stress initially cause the calibration of the instrument to shift and can ultimately lead to the failure of the tube itself.

2.1a Location of the maximum tube stress

Using FEM (finite element method) calculations, the stresses of a Bourdon tube when under pressure (Fig. 2) and when subjected to mechanical vibration (Fig. 3) were determined.

In Fig. 2 the maximum stress caused by steady internal pressure is uniform over the complete length of the tube with the exception of the end sections. The maximum stress where the Bourdon tube is attached to the connection begins at an angle of 30° along the tube from the connection.

![Fig. 2 Stress of a Bourdon Tube under pressure. The maximum load is over the whole length of the tube with the exception of the ends.](image-url)
In Fig. 3 the maximum stress caused by mechanical vibration occurs at an angle of between 30° and 60° along the tube from the connection. It is therefore clear that the area of maximum stress occurs where the effects of the pressure and vibration stresses combine in the area of 30° to 60° along the tube from the connection.

The greatest material stress in both cases is at the narrow edge of the Bourdon tube, see Fig. 4, radius R. Contrary to common beliefs, the joint between the tube and the gauge connection is in an area of reduced stress.

2.1b Techniques to strengthen the area of maximum stress

A - Cold working and annealing the Bourdon tube
By cold working the Bourdon tube during the manufacturing process it is possible to increase the yield point of the tube from 250 N/mm² to 400-600 N/mm². This stronger tube gives an improved performance and service life.

Furthermore it was found that by annealing the stainless steel tube at 950°F for 3 hours, the material stress spikes at the edges of the tube, created from the tube forming process, were significantly reduced.

B - The WIKA Bourdon tube design
The area of maximum stress on the tube between 30° and 60° was found to be at the narrow edge of the tube (see Fig. 4). The development of a WIKA tube design with a more rounded profile was found to reduce these stresses at the narrow edge (see Fig. 5). The key to this development was to maintain the rounder profile and still retain sufficient deflection at the end of the tube to drive the gauge movement.

C - Damping the tube movement by liquid filling the case
Liquid filling the pressure gauge case reduces the effects of mechanical vibration on the Bourdon tube by reducing the amplitude of its vibration. This is covered in greater detail later in the report.
2.2a Stresses at the free end of a Bourdon tube

The simple and cost effective way of closing the end of a Bourdon tube is to pinch the end and seal it with a weld. FEM stress analysis of this technique shows that this creates an area of high stress at the end of the tube (see Fig. 6). Under pressure cycling tests this method of closing the tube lead to a failure after about 300,000 cycles.

![Fig. 6](image)

If a tube is closed by compressing the end, a high area of stress is produced. Typically after 300,000 pressure cycles, failure will occur at the tip.

2.2b Techniques to strengthen the free end of a Bourdon tube

A - Tube end closing technique

By keeping the tube profile unaltered at the end and closing the tube with a weld cap of the same material, the stress was significantly reduced (see Fig. 7).

The same pressure cycling tests were repeated using this technique and after 3 million cycles the tube had not failed.

![Fig. 7](image)

Closing the tube by end capping on a circular profile removes the high area of stress at the end. This tube design will survive over 3 million pressure cycles without failure.

B - The WIKA Bourdon tube design

When developing the new Bourdon tube design (as covered in section 2.1b), it was found that if both ends of the new tube design were finished with a full circular profile, rather than the elliptical profile of the normal tube, any stress that still remained at the end of the tube was reduced even further (see Fig. 7). Although this made the tubes more costly to manufacture, it was decided that the benefits were significant enough to justify recommending the change.
2.3 Calibration stability and safety of WIKA Bourdon tubes

With the development of the WIKA tube design and the techniques to strengthen this tube, the calibration stability, endurance and safety of the tube have been considerably improved (see Fig. 8).

The stronger more consistent tube allows higher standards to be set for its performance. Fig. 8 illustrates the minimum burst pressures for the stronger tube, showing a large safety margin compared to the normal full scale pressure. The actual burst pressures are usually much higher as can be seen from Table 2.

### Table 2 - The special techniques used to produce the WIKA Bourdon tube lead to a much higher degree of calibration, stability and safety.

<table>
<thead>
<tr>
<th>Internal Pressure</th>
<th>% of Range</th>
<th>Endurance</th>
</tr>
</thead>
<tbody>
<tr>
<td>190 PSI</td>
<td>95%</td>
<td>200,000 pressure cycles before calibration error occurs (0 PSI to 190 PSI)</td>
</tr>
<tr>
<td>260 PSI</td>
<td>130%</td>
<td>2 hours continuous overload before calibration error occurs</td>
</tr>
<tr>
<td>1,800 PSI</td>
<td>900%</td>
<td>Minimum burst pressure of the Bourdon tube</td>
</tr>
<tr>
<td>8,600 PSI</td>
<td>4,300%</td>
<td>Typical burst pressure of the Bourdon tube</td>
</tr>
</tbody>
</table>

**Fig. 8**  The improved design produces a stronger and safer tube with high burst pressures throughout the range.
2.4 Resonant frequency of a Bourdon tube

Using an oscillation generator, the resonant frequency of different Bourdon tube pressure ranges was determined (see Fig. 9). These tests were conducted without the movement attached to the tube end. For example, the resonant frequency for a 60 PSI Bourdon tube is about 100Hz and for a 400 PSI tube just under 200Hz.

![Graph showing resonant frequency of different Bourdon Tubes.](image)

The red diamonds in figure 10 show the deflection at the end of the tube caused by the resonant frequency oscillating the tube. The blue triangles show the normal design deflection allowed for the tube. Clearly even at quite low accelerations of only 2.5g the tube will quickly fail.

For higher pressures the greater tube strength and more rounded geometry reduces the deflection at the end of the tube. As can be seen from the graph at 250 PSI and 2.5g acceleration (red diamond) the deflection falls within the design limits of the tube. The green squares show that by increasing the acceleration to 5g the deflection of the tube once again moves outside its design limits.

![Graph showing deflection vs. Bourdon Tube Range.](image)

2.5 Bourdon Tube endurance at resonant frequency

Fig. 11 shows the number of oscillation cycles various Bourdon tube pressure ranges could withstand, before failure, when subjected to their resonant frequency. Failure was defined as when a crack appeared in the tube and the internal pressure dropped.

It can clearly be seen that for the tubes which are oscillating well outside their design limits, the failure occurs quickly. But as the oscillation deflections approach the normal design deflection, the life of the tube increases.

This shows the importance of preventing the Bourdon tube from oscillating outside its design limits, if the life and safety of the Bourdon tube is to be increased.

Tests were performed on four different 250 PSI tube designs to determine which had the best life under its resonant frequency (see Table 3).
Table 3 The number of cycles before rupture of the different Bourdon tube assemblies subjected to their resonant frequency. The WIKA tube design is 3 times better than a flat tube, but liquid filling adds considerable protection against rupture.

<table>
<thead>
<tr>
<th>Design Variant</th>
<th>Bourdon Tube Assembly</th>
<th>Acceleration (g)</th>
<th>Number of Resonant Cycles Before Rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1</td>
<td>Traditional flat tube H/W = 0.30</td>
<td>2.5g</td>
<td>30,000</td>
</tr>
<tr>
<td>Design 2</td>
<td>Traditional flat tube inserted 7 mm into the connection H/W = 0.30</td>
<td>2.5g</td>
<td>30,000</td>
</tr>
<tr>
<td>Design 3</td>
<td>WIKA tube design H/W = 0.52</td>
<td>2.5g</td>
<td>100,000</td>
</tr>
<tr>
<td>Design 4</td>
<td>WIKA tube design, glycerine filled case - 86.5% concentration</td>
<td>2.5g</td>
<td>10 million - no rupture</td>
</tr>
<tr>
<td>Design 4</td>
<td>WIKA tube design, glycerine filled case - 86.5% concentration</td>
<td>10g</td>
<td>10 million - no rupture</td>
</tr>
</tbody>
</table>

Design 1 was a standard Bourdon tube profile, cold worked and annealed, using the cap end tube closing technique.

Design 2 was the same as Design 1, but with the tube inserted into the connection by 7 mm. Both these designs had the same endurance to their resonant frequency. This shows that inserting the tube further into the connection does not increase the endurance of the tube on these welded assemblies.

Design 3 shows that the WIKA tube design with a rounder profile and circular ends increases the endurance of the tube by a factor of three.

Design 4 clearly shows the effect of liquid filling the case of a pressure gauge. The 86.5% glycerine/13.5% water filling prevented the tube from oscillating outside its design limits at its resonant frequency, thus significantly increasing the life of the tube. After 10 million cycles no failure had occurred at 2.5g. The load was then increased to 10g, but still no failure had occurred after 10 million cycles.

3.1 Instruments with damped movements

Damped movements have an extension to the pinion or quadrant running into a small pot filled with a highly viscous liquid which provides the desired damping forces. The pointer on these designs was found to be free of oscillations and also the oscillations of the tube were kept within the design limits.

At first this would seem to be a good solution, but the tests showed the opposite. Because the pinion is damped, all of the damping forces are transmitted to the toothing, quadrant and connecting link to the tube end piece. These parts are thus subjected to strong forces and wear quickly.

The movement with pinion damping was completely inoperable after 100 hours. The toothing was severely damaged and the bearing necks were ground down, whereupon the quadrant came loose and wedged itself in the movement. The tube which was no longer damped by the movement was then free to oscillate, with the increased risk of a resonant rupture of the tube.

The movement with pinion and quadrant damping also suffered similar damage. The two damped components and the PTFE toothing were relatively undamaged, but the problem was shifted further along the movement to the connecting link which became severely worn. After 200 hours the pointer had a zero error of 30% (pointer reading 50 PSI with no pressure on the gauge). This excessive wear on the link is caused by the Bourdon tube trying to oscillate against the damped movement. The relatively rigid linking of the free end of the tube can also lead to harmonics of the tubes natural frequency causing it to oscillate with a full wave or even a double wave form. This puts further additional stresses on the tube.

3. Examination of different instrument variations

The tests examined so far have been with just the gauge connection and Bourdon tube. The following series of tests were conducted to determine the effects of vibration on complete instruments with connection, tube, movement, and pointer all linked.

A testing standard developed by one of the leading petrochemical companies for testing Bourdon tube gauges was used as follows:

- Acceleration : 10g
- Frequency range : 100-500Hz
- Frequency change : 1 octave/minute
- Duration of test : 200 hours
3.2 Undamped pressure gauges

With an unfilled and undamped movement the vibration caused the pointer to oscillate significantly at practically all frequencies.

Although the gauge had no significant internal damping forces, it was found to be unexpectedly durable in the vibration fatigue test. The only fault found after the 200 hours was a zero deviation of 3%. All of the components were operational.

The main concern from these tests was that the tube in the undamped instrument could oscillate with a high amplitude leading to the increased danger of a resonant rupture.

3.3 Liquid-filled instruments

In the liquid-filled gauge the oscillations of the Bourdon tube, the movement and the pointer were strongly damped. The damping of the Bourdon tube (as shown earlier in the report) reduced the amplitude of the tube and significantly reduced the loading on the movement. The damage to the instruments as outlined in sections 3.1 and 3.2 did not occur. The liquid filling also acted as a lubricant and coolant to all the moving parts further reducing their wear.

The gauge was still fully operational after the test and the reading of the gauge was still within its published accuracy of 1.0%.

4. Recommendations

A) A liquid filled case is the best solution to counter the effects of vibration. Liquid filling the case of a gauge dampens the oscillations of the tube at the pressure element itself, preventing the tube from oscillating outside its design limits. Furthermore, the filling acts as a lubricant and coolant to all the moving parts, extending their life (Tables 3 and 4).

B) WIKA does not recommend the use of damped movements. The movement provides a good calming effect to the pointer but accelerates the wear on the movement. With severe vibration this can eventually lead to a resonance rupture of the Bourdon tube (Tables 3 and 4).

C) The cold working and annealing of the Bourdon tube combined with the WIKA tube design and special tube end closing techniques, increases the calibration stability, endurance and safety of the Bourdon tube (Table 2, 3 & Fig. 8).

D) Liquid filling improves the safety of a Bourdon tube by preventing a resonant rupture from occurring should the movement fail (Table 3).

E) WIKA recommends the removal of the zero stop on the gauge dial since this disguises calibration errors. The new tube design is strong enough not to need this. Under and over range stops are already on the movement.

F) Inserting the tube by up to 7 mm into the connection of the gauge before welding does not increase the strength of the tube.

5. Implementation

Most of these recommendations have already been incorporated into the WIKA standard product design. As well as the research covered in this paper there is considerable effort being put into other areas such as diaphragm gauges, chemical seal systems, longer lasting movements, etc.

The benefits of this work have already been seen with gauges that stay in calibration longer, and with a greater degree of safety for their users.

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