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Load Cells and Weigh Modules | Technical Note VPGFS-06

Vessel Weighing

Scope

Load cells may be used to weigh vessels in various installation configurations. The installation of load cells into a practical field application requires following several basic rules as well as careful design attention if the system has to be accurate and provide a long, maintenance free span of operation.

This Technical Note describes the options and external influences, applicable for the design of a weighing vessel, such as type and number of load cells to use, mode of operation, overall accuracy required and piping.

Accuracy

Accuracy requirements for load cells used in scales for trade are clearly defined by Weights and Measures Authorities. For process weighing applications it is more difficult to define accuracy and usually it is requested for a system "to be as accurate as possible".

Calculating true system accuracy is possible by adding the individual errors of the external influences and should be done in the very early stage of design. Determined by the application, weighing systems can be divided into the following categories:

High accuracy	±0.02% to ±0.10%	Scales for trade
Medium accuracy	±0.10% to ±0.50%	General purpose
Low accuracy	±0.50% to ±5.00%	Level detection

The maximum achievable system accuracy equals approximately 5000 divisions, i.e., 1 kg divisions for a weighing system with a capacity of 5 tons. However the accuracy of most process weighing applications is limited to approximately 750 divisions due to external influences.

Mechanical Considerations

It is a common misconception that a load cell can be considered as a solid piece of metal on which vessels, silos or hoppers can be supported. The performance of a load cell depends primarily on its ability to deflect under highly repeatable conditions when load is applied or removed. More importantly, if more than one load cell is used then the deflection and output of each load cell should be equal for equal loading.

The general considerations to design a weighing vessel are:

- Use a rigid foundation for maximum accuracy.
- Avoid force shunts between the foundation and the vessel as much as possible.
- Keep clearance around the vessel and sufficient clearance between the foundation and vessel.
- Try to incorporate a calibration facility on to the vessel.
- Avoid sloshing of liquids, by dividing the vessel into compartments.
- Pay attention to material entry and exit; avoid impact forces due to material flow. Realize the air flow and air pressure due to material flow.
- Pipe connections and other external equipment to the vessel should be as flexible as possible.
- For outdoor installation; realize the wind influence.
- System integrity is virtually important; use safety systems if necessary.
- Realize the influence of temperature differences of the vessel and its connections.

Mode of Operation

Load cells measure force in one of two directions; tension or compression. In the tensile mode the vessel is suspended from one or more load cells. In the compressive mode a vessel is supported by load cells.

The use of a tension or compression system depends upon the mechanical structure around the vessel and the ease of making the system. If a vessel must be placed on an open concrete pad, compression will be a logical way to operate, because a tension system would require an expensive additional overhead supporting structure.

As a general rule, if a suitable structure for a tension application is available, it is usually easier, more acceptable and less costly to suspend the vessel from one or more load cells up to a vessel capacity of 15 tons. When the vessel capacity exceeds this value,

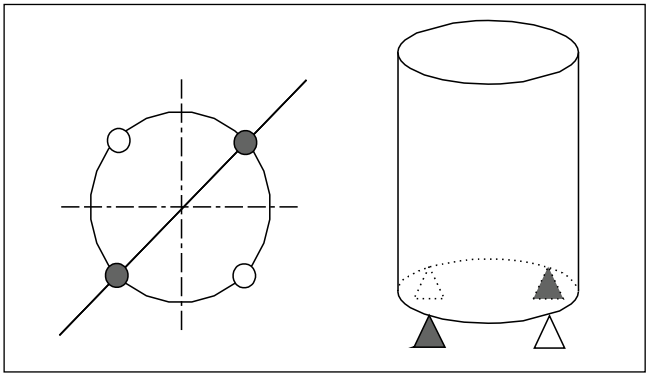
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the physical size of the load cells and the tension rods become large, installation becomes more difficult and there is more cost involved in making the required hardware than providing an adequate base for compression assemblies. Furthermore, a large tension system has a low natural frequency, which might cause the connected indicator to exhibit fluctuations on its reading. Stiff, low deflection supporting members are therefore desirable.

In theory, suspension of a vessel by a single load cell may be the ideal solution, but such tension installations are not usually feasible. Three or four point supports are the most commonly used configurations.

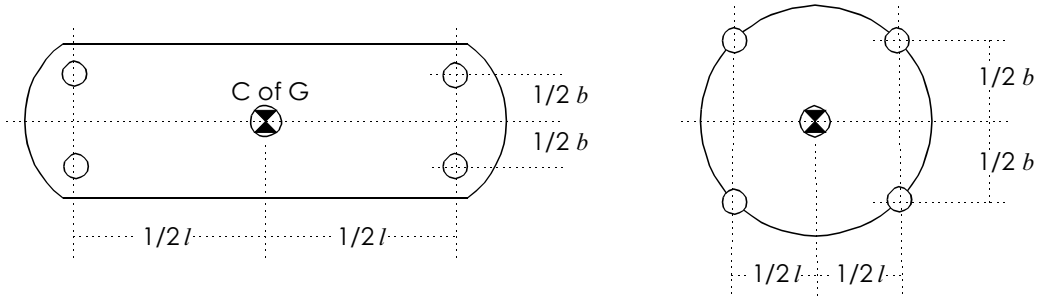
The Number of Load Cells

The number of load cells to support a vessel is usually fixed by the design of the vessel, especially for an existing system. The most ideal situation is to support a vessel by three load cells. If a weighing vessel is supported by four or more load cells and the stiffness of the vessel is to high, the construction might be statically undefined. In this case three or in the worse case only two load cells will bear the total weight. **A high vertical vessel, especially with a closed top is very stiff.**

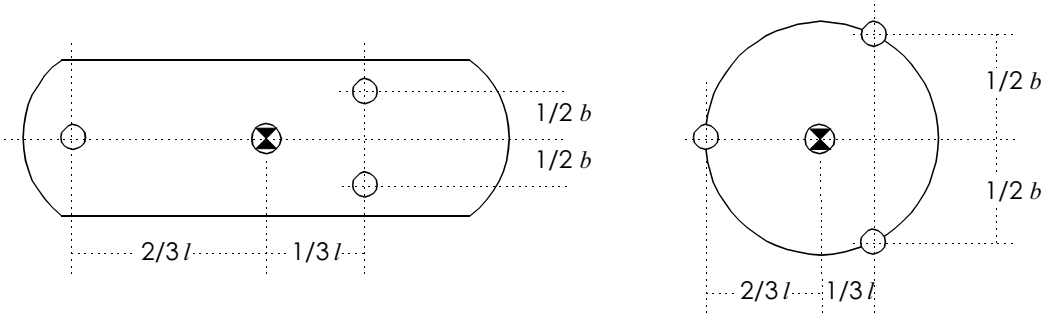


When only two load cells bear the total weight, an overload situation on these cells might occur. By measuring the output of every individual load cell (before filling the vessel), such a situation can be recognized and corrected by placing shim plates underneath the cells with minor output.

The load cells should be positioned in such a way that each load cell will bear the same amount of weight. This can be established by calculating the sum of moments on each side of the Center of Gravity (C of G) which should be equal. The moment of each individual load cell equals the product of the force and the perpendicular distance of that load cell to the center of gravity.



Horizontal and vertical vessel, supported by four load cells



Horizontal and vertical vessel, supported by three load cells

Vessel Weighing

Pivot Weighing

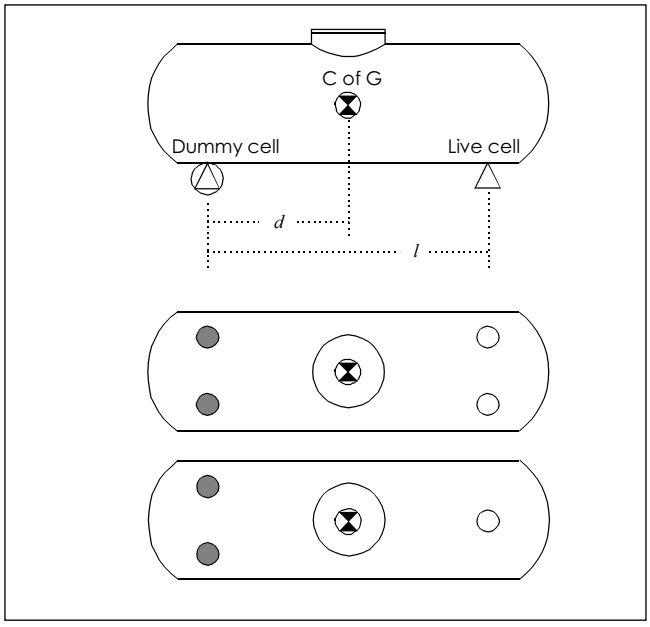
In certain applications it is possible to weigh only half the vessel, the other half is supported on dummy load cells or flexure beams acting as pivots. Such a system can only be used when weighing a symmetrical vessel containing liquids. Solid materials will pile-up on the sides and will cause a shift of the center of gravity. The accuracy that can be obtained with these systems is less than with an entire supported vessel. In practice, accuracies of ±0.5% can be achieved. Pivot weighing provides an excellent, low cost level detection system.

In fact not the weight, but the force is measured by the load cell(s). The force on the load cell(s) can be calculated by:

$$F_{lc} = (d * F_{tot})/l$$

The distance "l" between the live and dummy cells should be as long as possible to achieve maximum accuracy.

Horizontal forces on the vessel out of the plane of the pivots must be avoided (wind forces on vertical outdoor vessel!).

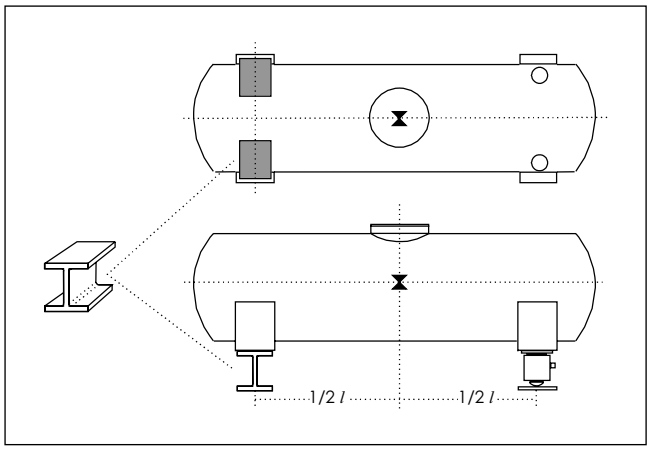


Besides dummy load cells, flexure beams are often used to provide the vessel to pivot with the load cell deflection. It is essential to align the beam webs very carefully for maximum accuracy.

The main advantage of flexure beams is their ability to take up horizontal side forces. Therefore no constrainers are necessary to get a stable construction.

The selection of the flexure beam must be based on the ability of the beam to bear the weight of the vessel without bending of the web (buckling effect).

Excessive bending of the pivoting beams, during installation should be avoided.



Load Cell and Mount Selection

VPG Transducers offers a wide range of industrial load cells and mounts, with a capacity from 6 kg to approximately 200 t. The load cell elements are made of nickel-plated tool steel or (more suitable for the process industry) stainless steel.

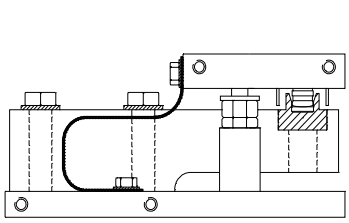
The selection of which capacity to use in a weighing application should be based on the following factors :

- Determine the maximum weight of the applied load, or "Live Load".
- Calculate the weight, "tare", of the construction, or "Dead Load".
- Determine the number of load cells to be used in the structure (N).
- Check the possible presence of unequal loading conditions (factor f_a). This factor is an allowance for low tare estimates and unequal load distribution. Standard: $f_a = 1.3$.
- Check on extra factors as vibration, shock, etc. (factor f_b). This factor is a dynamic load factor; for static weighing $f_b = 1$.
- For outdoor vessels, calculate the windforce F_w (Technical Note VPGT-07).

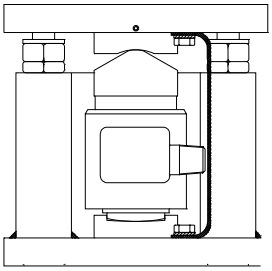
The individual minimum load cell capacity can be calculated by :

$$F_w + (f_a * f_b * (\text{LiveLoad} + \text{DeadLoad})/N)$$

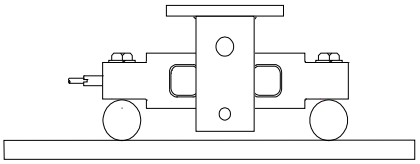
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SSB load cell + mount



CSP load cell + mount



DESB load cell + mount

The manner in which the load is transmitted through a load cell has a major impact on the accuracy and repeatability that can be achieved from the system. As a result, the mounting system around the load cell is of paramount importance.

The load should always be transmitted vertically through the load cell in the way which it was designed and tested to measure force. Load cell supports have to be designed avoiding the following effects to the load cell:

- Lateral forces
- Bending moments
- Torsion moments
- Off center loading to the load cell

These effects may be caused by expansion of the vessel due to temperature decrease or deflection of the vessel's construction due to loading. Further, for high outdoor vessel, an overturn protection has to be incorporated within the mount. **All mounts/load cells must be placed on the same horizontal level.**

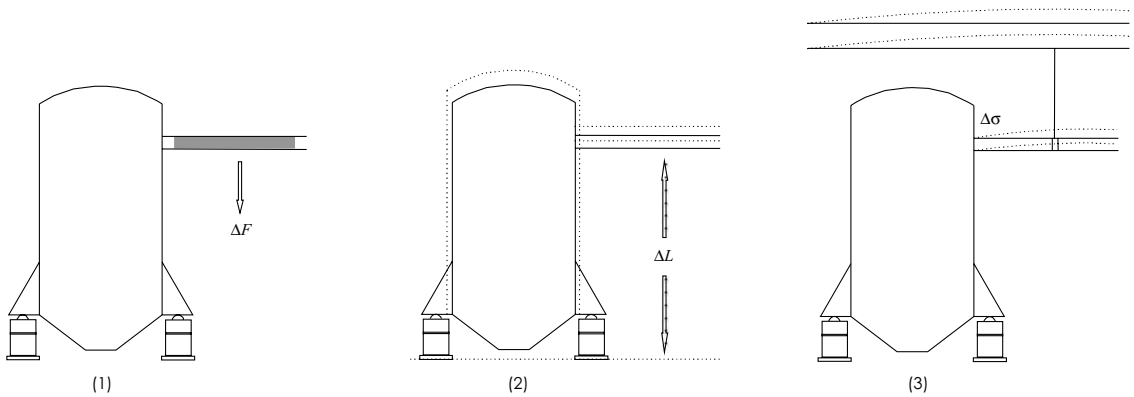
Load cells should be protected against direct sunlight or dripping aggressive liquids by protective screens. Prevent the load cells from being submerged; i.e., in a pit.

Avoid electric welding after installation of the load cells. If welding is necessary and the load cells can not be removed then disconnect each individual load cell cable from the indicator or measuring instrument. Place the clamp earthing electrode of the welding apparatus in the very neighborhood of the weld to avoid a current path through the load cells. Further, connect a flexible copper lead of at least 16 mm^2 cross section between the vessel and foundation over each load cell.

External Connections

From an accuracy point of view, a weighing system should be free from its surroundings. However in most industrial applications a contact between the weighing object and its surroundings is present. Examples are: pipes, tubes, pneumatic/hydraulic hoses, electrical cables, bellows and constrainers.

Usually the weight of pipes or cables can be treated as a part of the dead load of the vessel. If the influence of pipes or cables is not constant, non-repeatability and hysteresis can be introduced, e.g., (1) a pipe with changing contents or stiff pipes, (2) thermal expansion of the vessel, or (3) a friction-effect created in the clamping points.



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When one of these situations is likely to be present, it is recommended first to calculate the error and to relate this to the required system's accuracy, before any (expensive) solutions are considered.

1. The Stiffness of Pipes

The stiffness of the pipes in relation to the stiffness of the weighing system plays an important role in the error development. The stiffness of the weighing system (C_s) can be calculated by:

$$C_s = (n * E_{max} * g) / f$$

n = The number of load cells

E_{max} = The individual load cell capacity

f = The deflection of the load cell

g = Gravitation (approximately 9.8 m/s^2)

The stiffness of the pipes C_t can be calculated by the sum of the stiffness of each individual pipe C_a:

$$C_a = (0.05 * K * E * (D^4 - d^4)) / l^3$$

K = Clamping factor

K = Outer diameter of pipe

d = Inner diameter of pipe

L = Length of pipe

E = Elasticity modulus,

for steel: $E = 210.000\ N/mm^2$
for copper: $E = 110.000\ N/mm^2$
for aluminium: $E = 70.000\ N/mm^2$

The clamping factor K equals K =12 for a pipe clamped rigidly at both ends. The following K-values below are valid for a pipe with constant diameter, with a bend (1) in the vertical plane or (2) in a horizontal plane, and clamped rigidly at both ends.

The influence on span (e) can now be calculated by:

$$e = (C_t / C_s) * 100\%$$

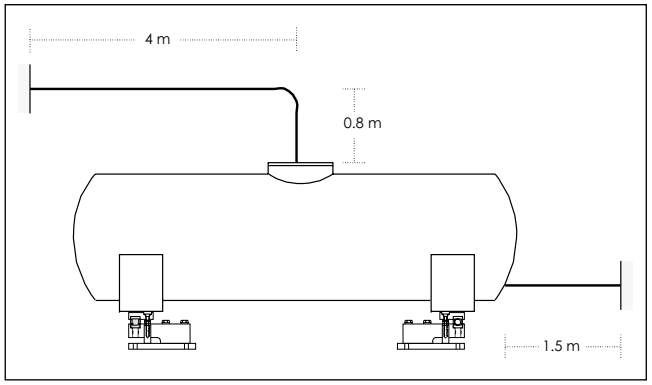
The error which is caused by the stiffness of the pipes is a typical span-error and can be reduced by the calibration procedure. However, stiffness of the pipes are no stable values and can change during operation.

Example:

A vessel is supported by four load cells, with a capacity of 2 t and a deflection of 0.5 mm.

Two pipes are connected to the vessel, one bend in the vertical plane as in the opposite drawing.

The pipes are made of steel with an inner diameter of 30 mm and an outer diameter of 40 mm.

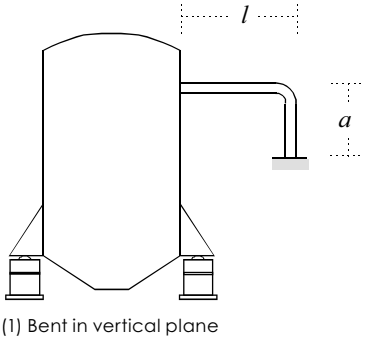


The stiffness C_s of the weighing system equals:

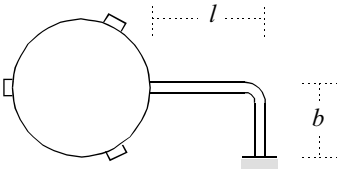
$$C_s = (4 * 2000 * 9.8) / 0.5 = 156800\ N/mm$$

The stiffness C_{a1} of the pipe, bent in the vertical plane equals:

$$C_{a1} = (0.05 * 8 * 210000 * (40^4 - 30^4)) / 4000^3 = 2.30\ N/mm$$



(1) Bent in vertical plane



(2) Bent in horizontal plane

A	B	C
0.21		8.0
0.51		6.0
1.01		4.8
5.01		3.4
	0.21	7.1
	0.51	4.3
	1.01	1.8
	5.01	0.06

Clamping factor K for a pipe with constant diameter and clamped rigidly at both ends.

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The stiffness C_{a2} of the straight pipe equals:

$C_{a2} = (0.05 * 12 * 210000 * (40^4 - 30^4))/1500^3 = 65.33\ N/\text{mm}$

The total stiffness C_t of the pipes equals $C_{a1} + C_{a2}$ = 67.33 N/mm. The influence on span (e) can now be calculated:

$$e = (67.63/156800) * 100\% = 0.043\%$$

2. Thermal Expansion

The height of the clamping point of the pipe can change with any change in ambient temperature by expansion of the vessel. Stiff pipes will try to counteract this movement, causing a zero-shift and non-reproducibility.

$$\Delta L = Lo + \Delta T * \alpha$$

The change in height can be calculated by:

ΔL = Change in length (mm)

Lo = Original length (mm)

ΔT = Change in ambient temperature: T – To (K)

α = Linear expansion (K^{-1}),

for steel	$\alpha = 1.2 * 10^{-5}$
for copper	$\alpha = 1.7 * 10^{-5}$
for aluminium	$\alpha = 2.4 * 10^{-5}$

The reaction force of the pipe can be calculated by:

$$F = \Delta L * C_a$$

F = Reaction force of the pipe

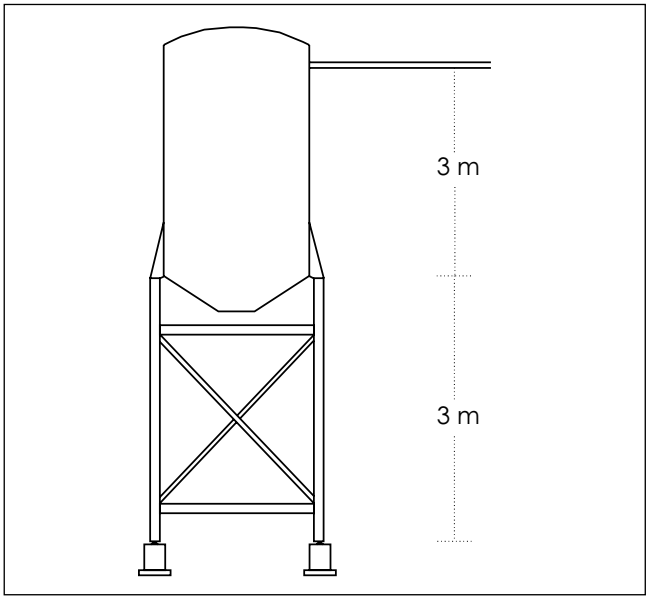
C_a = Stiffness of the pipe

The error to the system can be calculated by:

$$e = (F/\text{scale capacity} * g) * 100\%$$

The error which is caused by thermal expansion is a typical zero-error. Weighing systems without connections to the outer world are not affected by temperature effects, provided that a well designed mounting system is used.

Load cells are manufactured to operate within a certain temperature range, normally from –40 to +80°C. A load cell is compensated for a part of this temperature range to operate within specifications, normally –10 to +40°C. Shields or insulation paths must be established to keep the load cell within the operating range and for high accuracy systems within the compensated temperature range.



Example:

A vessel is supported on four load cells, by a supporting structure made of steel. The scale capacity equals 10 tons. The vessel is made of aluminium. A pipe with a stiffness C_a of 75 N/mm is connected to the vessel. The critical dimensions are indicated in the figure opposite. During the day the ambient temperature decreases from 15 to 25°C.

The height of the supporting structure will decrease with:

$$\Delta L = 3000 * (25 - 15) * 1.2 * 10^{-5} = 0.35\ \text{mm}$$

The height of the vessel will decrease with:

$$\Delta L = 3000 * (25 - 15) * 2.4 * 10^{-5} = 0.72\ \text{mm}$$

The height of the clamping point of the pipe will change with 0.35 + 0.72 = 1.07 mm. This will cause a reaction force of the pipe of:

$$F = 1.07 * 75 = 80.25\ N$$

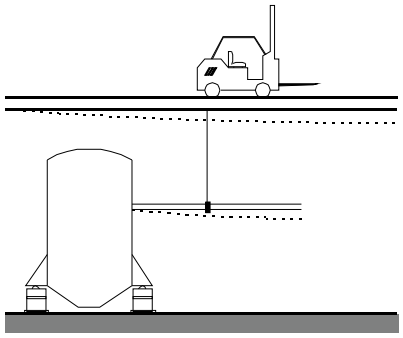
The error to the system, caused by the temperature decrease will be:

$$e = (80.25/10000 * 9.8) * 100\% = 0.08\%$$

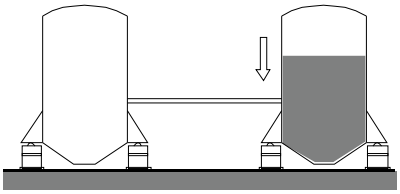
3. Friction-Effects

Friction-effects created in the clamping points are leading to an undefined error, causing non-repeatability and hysteresis. Pipe supports, especially the first supports away from the vessel should be attached to the same structure as to which the vessel is supported.

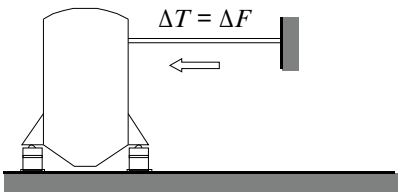
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Care should be paid to less obvious sources of deflection which are often ignored, such as deflection of the floor or roof and...



...two weighing vessels with pipe connections.



Large horizontal side forces may arise by thermal linear expansion of rigidly clamped pipes.

Compensators

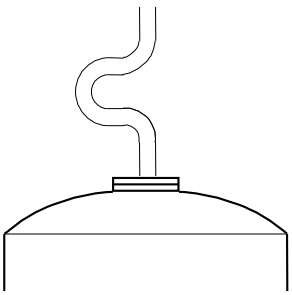
When the influence of pipes exceed the allowed error then the following solutions should be considered:

- Decrease the length of pipe(s).
- Design the clamping to be less rigid.
- Introduce compensators in the pipe.

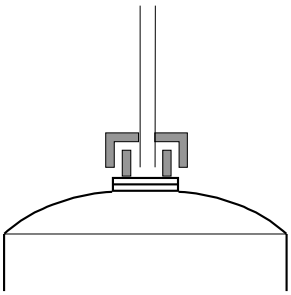
All piping tends to sag from its theoretical design position due to its own dead weight. This effect will decrease with the length of the pipe. It is therefore important to check all piping runs between the vessel and the first pipe support for adequate clearance.

Flexible piping devices or compensators should be selected based on their flexibility and their process chemistry suitability i.e., high or low pressure systems, temperature, aggressive chemicals.

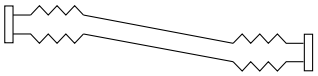
Flexible devices of non-metallic materials offer more flexibility in less space and with less vibration



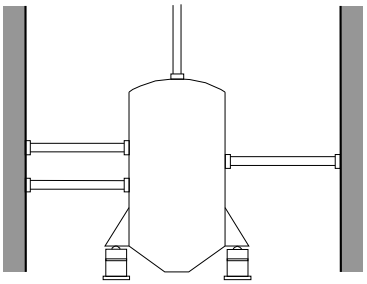
Elbow



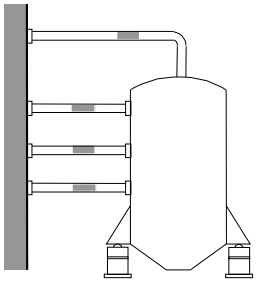
Stub



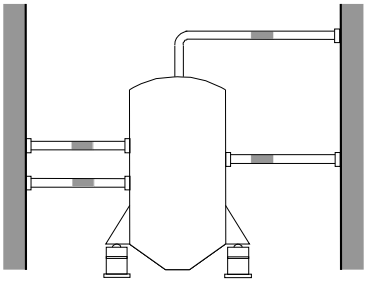
Flexible piping devices



Avoid



Avoid if possible



Correct installation

Vessel Weighing

transmission than the metal counterparts. These benefits plus, variously, increased wear, corrosion and fatigue resistance makes non-metallic materials highly attractive when the process pressure and temperature requirements can be met.

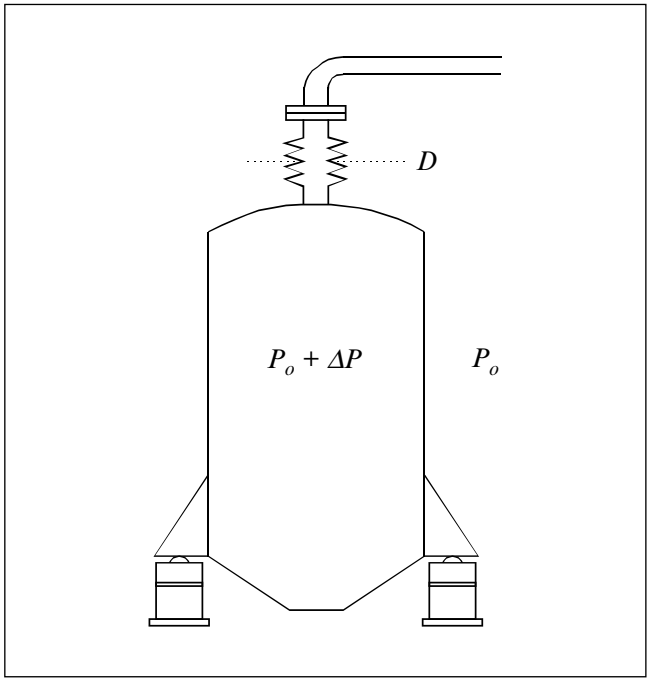
When large displacements must be accommodated with low force, consider using two compensators in series or a bent U-shape flexible hose. This is particularly important for low capacity systems were even small piping forces will disturb weigh system stability.

Do not stretch or compress compensators excessively to compensate for initial piping misalignments at fitup, to prevent their stiffness characteristics from being altered.

When multiple pipes are connected to a weighing vessel, then the connections should be made symmetrical if possible.

Pressurized Vessels

If the content of the vessel is under gas pressure and the pipe connection is made with a vertical compensator (bellow), a vertical disturbance force can arise. The compensators should be located in horizontal piping runs adjacent to the weigh vessel to avoid these vertical thrust forces from varying internal pressures associated with material flow and process chemistry. A temporary over-pressure can also be created by filling a vessel with a dusty material.



The disturbing force can be calculated by:

$$F = (\Delta P * \pi * D^2) / 4$$

ΔP = Over or under-pressure (N/m^2)

D = Effective diameter of the bellow (m)

Example:

A vessel is pressurized with 2 bar over-pressure and the pipe connection is made with a vertical bellow having an effective diameter of 150 mm.

The maximum disturbing force can be calculated by:

$$F = (2 * 10^5 * \pi * (150 * 10^{-3})^2) / 4 = 3534\ N$$

The flexibility of the bellow will cause the indicator to bounce between the actual weight and the actual weight plus the maximum disturbing force.

Gas pressure in a vertical pipe gives minor influence if the pipe is connected to the vessel with a stiff part as indicated in the last drawing of the previous page.

Restraining Devices

Load cells should be protected against side forces by the use of restraining devices. These assemblies are designed to allow ample vertical freedom for weight sensing, while simultaneously eliminating inaccuracies caused by side loading.

Accuracy and reliability of systems not protected in this way would be greatly reduced in the presence of extraneous forces, which might even result in damaged to the load cell in extreme cases.

Two types of restraining devices are used:

- Stay rods
- Limiting stops

Most mounts offered by VPG Transducers are self-aligning with an in-build limiter. These mounts do not require further restraining devices in most applications. Stay rods must be used when a vibrator or mixer is used in the vessel!

Stay rods should not essentially transfer any forces to the container in the vertical direction, but have sufficient strength in the horizontal direction to be able to absorb the maximum horizontal forces arising. The length of the stay rods should be chosen as long as possible, as this has a favorable effect on reducing vertical forces.

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The arrangement of the stay rods depends on the plan view geometry of the structure. In most cases four stay rods give the best results. Figure 3 below represents a basic stay rod arrangement for a vessel under thermal expansion. More information about the arrangement of stay rods for specific applications is available on request.

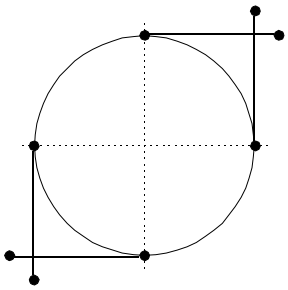


Figure 1

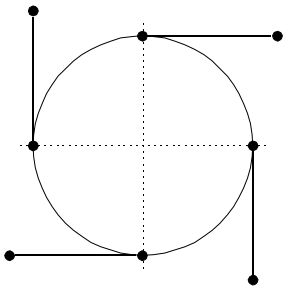


Figure 2

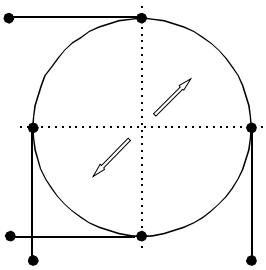


Figure 3

Note: Placing stay rods as represented in figure 1 will cause high stresses in the stay rods and should be avoided. The arrangement in figure 2 will cause a rotation of the vessel. This configuration should be avoided if there are stiff connections to the vessel. Stay rods should be placed in a position that will exert no further stress to the vessel structure, as shown in Figure 3.