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# Accuracy effect of encoder scale mounting methods

## Clips or adhesive?

It is often desirable to mount a high accuracy encoder scale such that it is free to expand independently of the substrate to which it is mounted. This ensures that the behaviour of the scale as temperature changes can be well understood and system accuracy maintained. However, other practical requirements must also be met. The result is that any encoder mounting solution aiming to allow independent expansion of the scale must meet the following three conditions:

- Avoid restricting free expansion of the scale in the measurement direction
- Provide a secured datum point
- Restrict movement of the scale in other directions (to keep the scale straight and flat, and resist machine vibrations, gravity, etc.)

Commonly available mounting methods usually use either: low friction clips at discrete positions along the scale, together with a secure clamp at the datum position; or an adhesive backing tape along the length of the scale, and epoxy to fix the datum position. Track mounting is also available; it behaves in a broadly similar way to clip mounting, and so will not be discussed separately in this article.

As neither clip nor adhesive mounting is able to allow perfectly free expansion of the scale, both have a very small effect on the accuracy of the installed scale. The behaviour of each mounting system can be modelled and its effect on error predicted. In many applications this effect can be ignored but, when the highest accuracy is required, it can be useful to consider which mounting method is best. This article discusses the pros and cons of these two solutions, allowing the system designer to select the most suitable method for their application.

## Clip and clamp mounting

In this method, a clamp firmly secures the scale at one position, providing a reliable datum, and clips are regularly spaced along the rest of the scale length. Clamps are designed to restrict all movement of the scale at the point at which they act. The purpose of a clip is two-fold: it must exert as little frictional force on the scale as possible, to allow free movement in the measuring direction, but it must be difficult to bend away from the substrate, to stop the scale 'panting' under vibration.

The length of scale from the datum to the end of the scale is known as the 'free length' – it is free to expand under its own coefficient of thermal expansion (CTE).

However, small frictional forces between the clip, scale, and substrate, prevent the scale having perfectly free expansion, causing a measurement error.

Let us consider, as an example, a 1000 mm (free length) RSLM stainless steel scale clip mounted to an aluminium substrate subjected to a temperature change of 5 °C.

As the temperature begins to increase and the aluminium expands more than the steel (due to its higher CTE) the frictional force between the clips, scale, and substrate stretches the scale further than its CTE would predict. This continues only until the frictional force is overcome by the tension being created in the scale; thereafter, the scale slips progressively under the clips, ultimately expanding independently. After the full 5 °C temperature change, the 1 m section of aluminium beneath the scale will have expanded 110 µm, whilst the scale will have expanded by 54 µm plus the error caused by the initial 'stick' period before the scale began to slip. This error is brought about within the first fraction of a degree of temperature change, usually no more than 0.5-1 °C. The magnitude of this error can be calculated, as follows:

$$\xi = \frac{\overline{q}l^2}{2Ea}$$

where,

$\xi$ = additional extension or compression of the scale, at its free end, caused by clip friction

$\overline{q}$ = clip drag per unit length, $\overline{q}_{RSLM} \cong 10\ \mathrm{Nm}^{-1}$

$l$ = length from fixed point, in m

$E$ = Young's modulus for the scale, $E_{RSLM} \cong 200\ \mathrm{GNm}^{-2}$

$a$ = cross sectional area of the scale, $a_{RSLM} = 2.25 \times 10^{-5}\ \mathrm{m}^2$

Therefore, in this example:

$$\xi = \frac{10 \times 1^2}{2 \times 200 \times 10^9 \times 2.25 \times 10^{-5}} = 1.1\ \mu\mathrm{m}$$

Hence, the scale has expanded by a total of 55.1 µm, rather than the 54 µm predicted by its CTE alone.

This stick/slip behaviour of clip mounting means that, when the temperature in an application fluctuates within a certain range, the calculated error can be considered as a hysteresis band; the actual error caused by the clips will always fall within this band.

## Adhesive mounting

In this method, a two-part epoxy is usually employed to secure the scale at one position, providing a reliable datum, and self-adhesive backing tape is used along the rest of the scale length. The adhesive must hold the scale down, against vibrations or gravity, but be compliant enough not to restrict expansion of the scale in the measuring direction. The movement of the scale is never truly free, as the adhesive will tend to resist being sheared, so, causing a very small measurement error. The most suitable adhesive tapes for scale mounting, such as that supplied with RSLM, behave as many viscous-damped springs, each holding a point on the scale to an adjacent point on the substrate. Independent expansion requires each point on the scale to move away from its original point of mounting; it is this movement that is hampered by the 'stiffness' of the adhesive. Modelling the adhesive as a multitude of springs, whose number increases with free length, allows us to calculate the error caused by this effect using the approximation.

$$\xi \cong \frac{\bar{k} l^3 \rho}{3Ea}$$

where,

$\xi$ = additional extension of the scale, at its free end, caused by adhesive tape

$\bar{k}$ = elastic stiffness of self-adhesive per unit length, $\bar{k}_{\mathrm{RSLM}} \cong 50\ \mathrm{kNm}^{-2}$

$l$ = length, in m

$\rho = (CTE_{substrate} - CTE_{\mathrm{scale}}) \times \Delta T$ = differential expansion for temperature change $\Delta T$, relative to installation temperature

$CTE_{substrate}$ = $22 \times 10^{-6} \times K^{-1}$,

$CTE_{\mathrm{scale}}$ = $10.8 \times 10^{-6} \times K^{-1}$, $\Delta T$ = 5K in this example

$E$ = Young's modulus for the scale, $E_{\mathrm{RSLM}} \cong 200\ \mathrm{GNm}^{-2}$

$a$ = cross sectional area of the scale, $a_{\mathrm{RSLM}} = 2.25 \times 10^{-5}\ \mathrm{m}^2$

Therefore, in the example system described above,

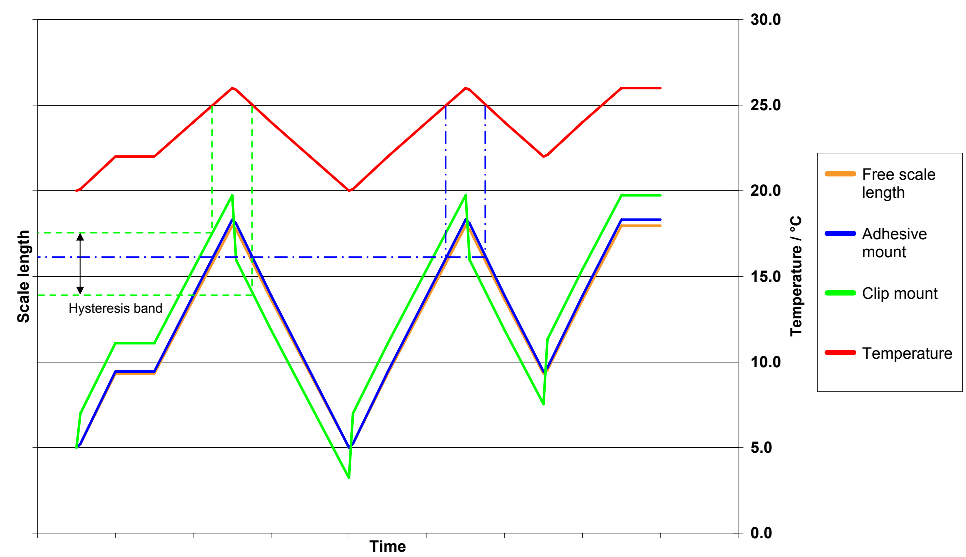
$$\xi = \frac{50 \times 10^3 \times 1^3 \times (22 - 10.8) \times 10^{-6} \times 5}{3 \times 200 \times 10^9 \times 2.25 \times 10^{-5}} = 0.2\ \mu\mathrm{m}$$

Hence, the scale has expanded by a total of 54.2 µm, rather than the 54 µm predicted by its CTE, or 55.5 µm if clip mounted.

In contrast to clip mounting, the error caused by adhesive mounting has neglible hysteresis band; the error at a particular temperature can be predicted, as it is not dependent on whether the temperature has increased or decreased to reach the target temperature.

The linear relationship between error and temperature seen with adhesive mounting means that the error is typically negligible for small $\Delta T$. This is not the case for clip mounting where, provided the temperature change is large enough that the scale is slipping (~0.5 °C), error is not dependent on temperature and the full error is seen even for small temperature excursions.

The graph below illustrates how scale length is affected by the different mounting methods during a series of temperature changes. As temperature increases or decreases, the full error from clip mounting is seen almost immediately, and forms a hysteresis band around the scale length predicted by CTE alone ('free scale length') – the scale length at a particular temperature depends upon whether the measurement is made during a heating or cooling cycle. For adhesive mounting, the scale length is the same however the temperature is changing. This is shown by the pairs of green and blue dotted lines on the graph. However, for adhesive mounting, much lower errors are seen and they change in proportion to the temperature change.



## Which method is best?

One of the major differences between the two mounting methods is the magnitude of the error they cause in thermally controlled (i.e. small $\Delta T$) environments, as seen in the examples above. Perhaps more subtle is that the inaccuracy caused by adhesive mounting is proportional to the differential expansion between the scale and substrate. The effect of this is that whilst clip mounting causes a specific error almost independent of the temperature change experienced (provided it is greater than ~0.5 °C), the error from adhesive mounting under small changes in temperature is almost insignificant.

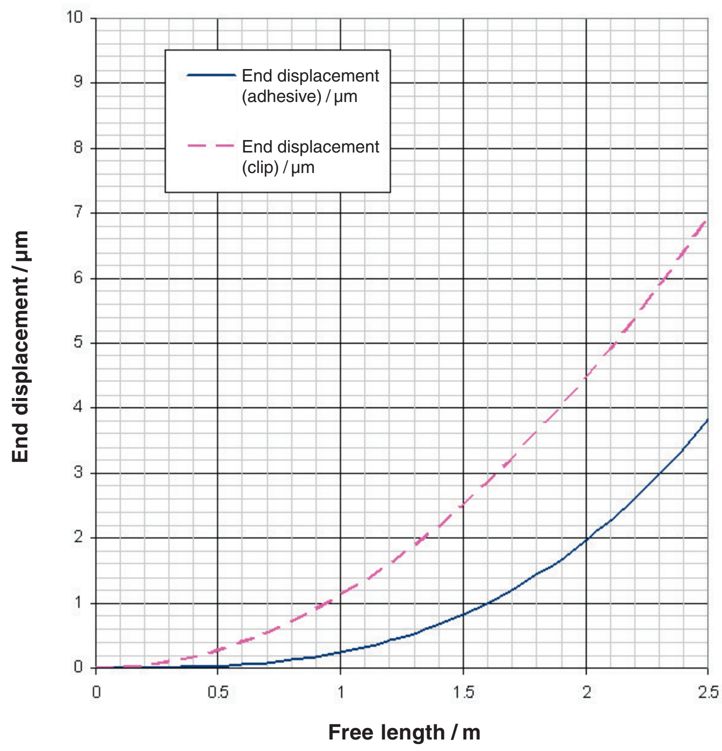
However, adhesive mounting is not always preferable. For instance, if the scale needs to be removed after installation, adhesive mounting adds a significant time and cost where clips would not. This is particularly true for glass scales, where there is the risk of breaking the scale during removal.

Also, for large temperature excursions, the maximum shear displacement the adhesive can tolerate must be considered. Large differential CTEs, large temperature changes, and long free lengths can lead to several millimetres of shear. The limit for most adhesives is around 1 mm, so clip mounting must be used. Shipping temperatures, after scale installation, should considered when calculating maximum shear.

As error is proportional to $l^2$ for clip mounting, but $l^3$ for adhesive mounting, increased length will always close the gap between the accuracy of the two methods until, eventually, clip mounting becomes more accurate. This point is usually at free lengths greater than 2 m, and often much more. The graph below shows how the end displacement of the scale (its position relative to that predicted by CTE alone) changes with free length, for clip and for adhesive mounting. The square (clip) or cubic (adhesive) relationship between length and error also means that it is advisable to place the datum point at the scale midpoint, to achieve the best possible accuracy. ;

Renishaw provides an error prediction application to help system designers with their choice of mounting (contact your local Renishaw office for more information). Temperature of installation, operation, and shipping, as well as substrate material and free length, can all be specified, allowing convenient prediction of mounting errors.

**Behaviour of a stainless steel (RSLM) scale on an aluminium substrate, over a temperature range of 5 °C**



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