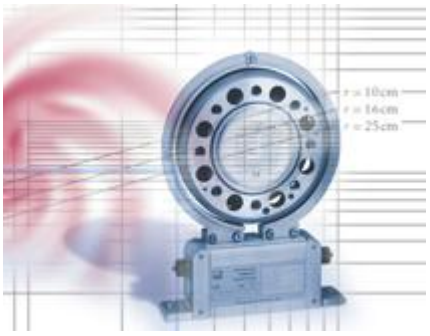
Centrifugal acceleration in torque measurement - often underestimated, however, very effective

What do a roller coaster, a spin dryer and a centrifuge have in common with rotating torque measurement technology? The answer is amazing: centrifugal acceleration. The combination of rotation and dimension results in acceleration. Multiplying acceleration by the existing mass causes high forces that require correspondingly safe structures.



Accelerations in a roller coaster, on the one hand, must not be too high to avoid potential health risks and, on the other hand, should be high enough to cancel out gravity and induce a feeling of weightlessness. Everyone knows how a spin dryer, which in fact is a centrifuge, works. Different materials are being separated.

However, the centrifugal acceleration occurring in everyday life is relatively low compared to that occurring during torque measurement.

- Centrifugal acceleration in a spin dryer is approximately 400 g ≈ 4,000 m/s² - depending on drum diameter and spin speed -,
- in a roller coaster it is approximately 5 g ≈ 50 m/s²,
- in rotating torque transducers, however, it amounts to several thousand g or m/s².

Gravitational acceleration affects calibration accuracy

Gravitational acceleration g is the acceleration on a body caused by the Earth's gravitational field. At different points on Earth, it averages ≈ 9.81 m/s², however, it varies depending on the centrifugal force of the Earth's center, the oblateness of the Earth and regional circumstances. It is not easy to specify the acceleration a human being can withstand without suffering permanent injuries. Literature gives a value of 9 g for trained test pilots wearing protective clothing, German DIN 4112 stipulates a maximum permissible vertical acceleration of 6 g [1].

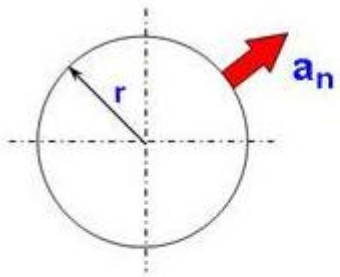
Knowing gravitational acceleration is also crucial to exactly representing and transferring the measurand torque, since the most accurate calibration machines consist of dead weights (masses) and lever arms. This acceleration was precisely determined in HBM's calibration laboratory which has been accredited by German Calibration Service; it is 9.810285 m/s² with an uncertainty of measurement of 0.000005 m/s².

Centrifugal acceleration and rotational speed

A torque flange in a powertrain test bench is a system rotating at angular velocity. This creates a centrifugal acceleration that depends on the diameter and rotational speed.

Multiplying this acceleration by a mass or a mass point gives a centrifugal force. Depending on the design, these centrifugal forces may limit the maximum permissible rotational speed. It is essential to take into account other influencing factors, for example, critical rotational speeds.

Centrifugal acceleration is the result of the square of angular velocity multiplied by the radius r.



$$a_n = \omega^2 * r$$

$\omega = 2\pi f = 2\pi n/60$

This results in

$$a_n = \frac{\pi^2}{900} \cdot r \cdot n^2$$

(equation with numerical values an in m/s^2 , r in m and n in rpm)

The table below shows which centrifugal accelerations occur with different torque flanges and selected diameters.

Type	Ø [mm]	n [rpm]	a [m/s^2]	g
T10F/100N·m	117	15000	144197	14699
T10F /10kN·m	254	8000	89043	9077
T10FS /100N·m	119	24000	375454	38273
T10FS /10kN·m	256	12000	201925	20584
			0	
T40 /200N·m	108	20000	236630	24121
T40 /10kN·m	239	10000	130914	13345
			0	
T12 /100N·m	116	18000	204981	20895
T12 /10kN·m	243	12000	191276	19498
			0	
T10FM /15kN·m	237	8000	83136	8475
T10FM /80kN·m	310	4500	34402	3507
			0	
T10FH /100kN·m	450	3000	22184	2261
T10FH /300kN·m	540	2000	11832	1206

Table 1: Centrifugal acceleration resulting from rotational speed and design

It is clearly visible that rotational speed is predominant over the diameter. This is obvious since rotational speed appears in the equation as a square value and the diameter only as a linear value.

The relevance of the flanges' individual nominal (rated) rotational speeds results from the different target applications. Please find below a list of examples of typical applications with rotational speeds specified in the unit rpm [3]:

- Globe approx. 0.000694
- Ship propeller (huge, commercial seagoing vessel) 70 to 150
- Main rotor of a helicopter up to 400
- Propeller of a small airplane 2,500
- Two-pole induction motor for 50 Hz mains voltage approx. 3,000
- Two-pole generator for 50 Hz mains voltage (e.g. Europe) 3,000
- Two-pole generator for 60 Hz (e.g. USA) 3,000
- Maximum rotational speed of a diesel engine approx. 5,500
- Maximum rotational speed of a gasoline engine approx. 9,000 up to 18,000
- Gas turbines 3,000 up to 100,000
- Turbo charger for combustion engines 100,000 up to 300,000

Centrifugal acceleration depending on rotational speed and design

Often torque flanges are not used at their nominal (rated) rotational speed. The example of the T10FS torque flange is to illustrate the effects of different rotational speeds and designs.

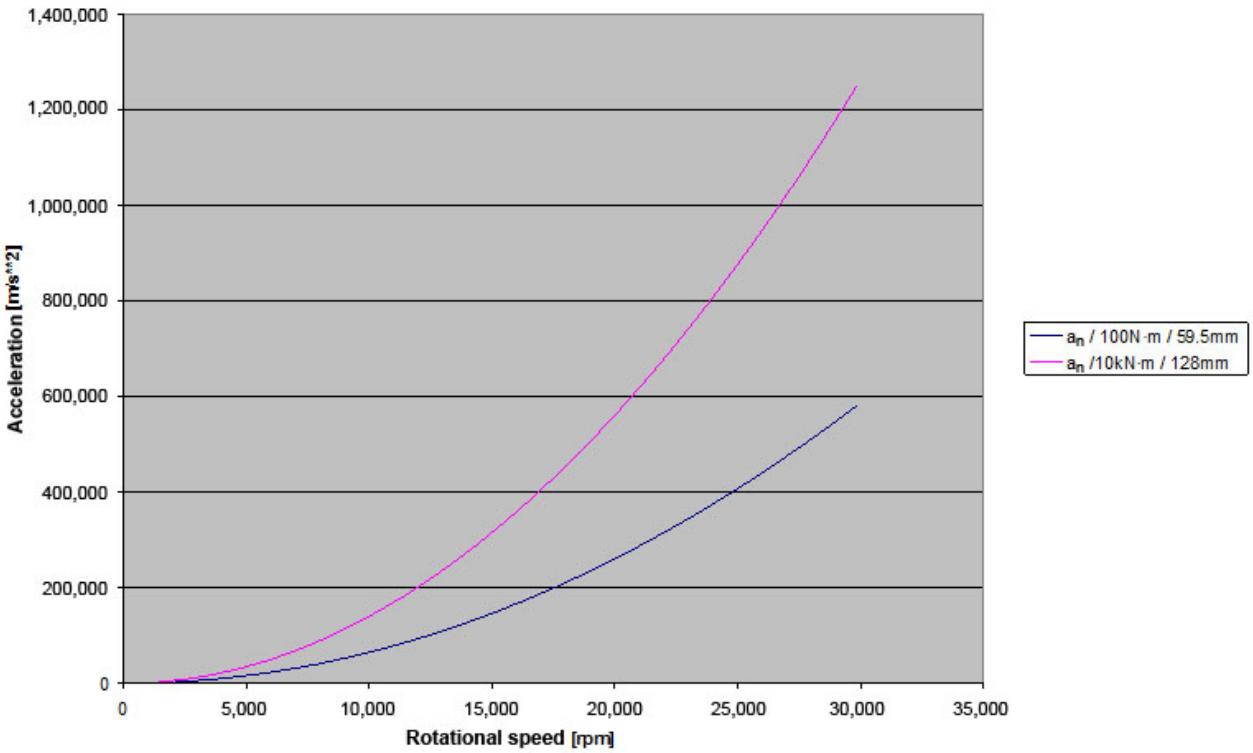


Fig. 1: Centrifugal acceleration depending on rotational speed and design

Using double logarithmic graphs, the resulting array of curves [4] facilitates identification of the centrifugal acceleration for selected radii.

For example, a rotational speed of 10,000 rpm and a radius of 250 mm results in a centrifugal acceleration of 273,878 m/s^2 ≈ 27,918 g, approx. 30,000 g.

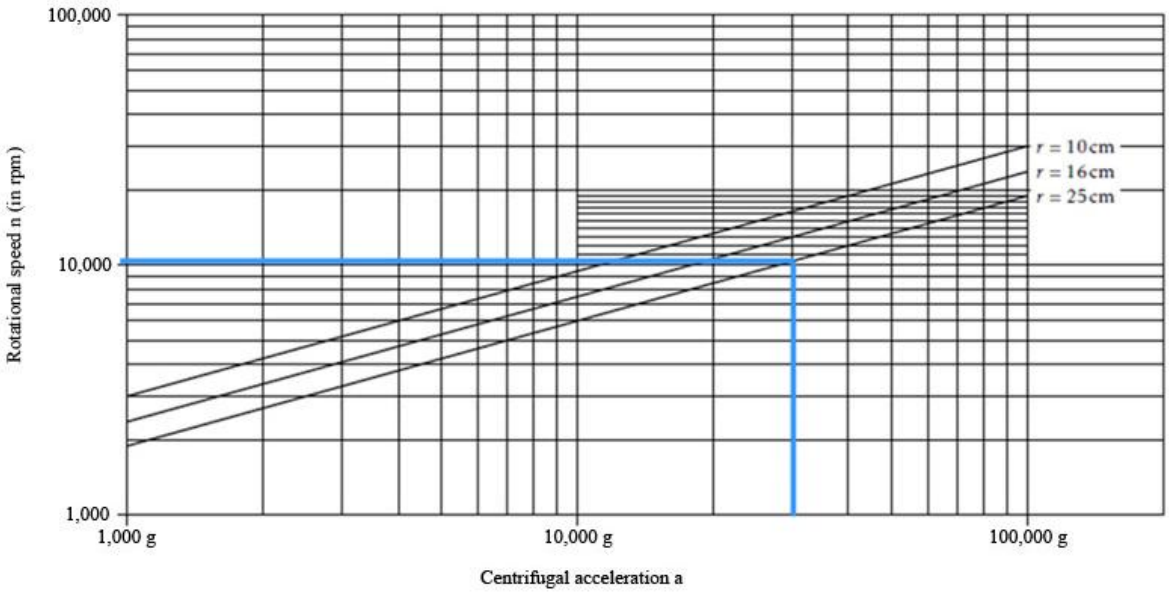


Fig. 2: Array parameter radius r of the circular path

Acceleration is uncritical as long as it does not affect a mass. Since in reality this is not the case, centrifugal force is of paramount importance. Therefore, with structures rotating at angular velocity/rotational speed it is essential to take into account the resulting forces instead of the accelerations.

The well-known relationship 'Force equals Mass times Acceleration'

$$F = m \cdot a$$

applies analogously for rotating bodies

$F_z = m \cdot \omega^2 \cdot r$ $\omega = 2 \cdot \pi \cdot f$ $f\,[s^{-1}] = n[rpm]/60$ $\omega\,[s^{-1}] = \cdot \pi \cdot n[rpm]/30$

The centrifugal force F_z is given by

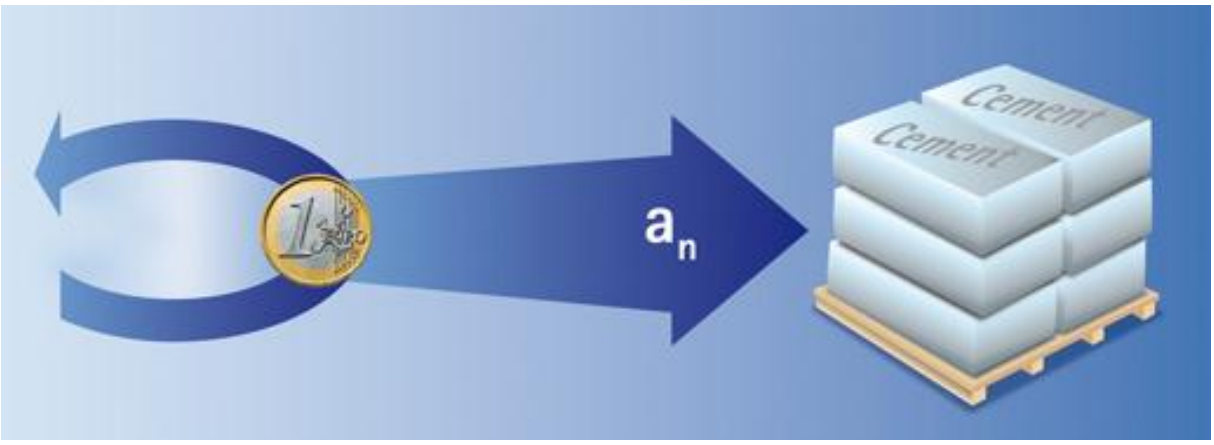
$$F_z = m \cdot \frac{\pi^2}{900} \cdot n^2 \cdot r$$

(equation with numerical values F_z in N, m in kg, r in m and n in rpm)

Considering the 1 euro coin with a weight of 7.5•10^{-3} kg and the maximum rotational speed of the T10FS/100 N•m torque flange, n = 24,000 rpm , r = 59.5 mm, provides an impressive example for this effect.

$$F_z = 7{,}5/1000 \cdot \frac{9{,}8596}{900} \cdot 24000^2 \cdot 59.5/1000 = 2819{,}9N$$

In the Earth's gravity field, this would correspond to ≈ 287 kg - about 6 cement bags each with 50 kg. Such a coin would be too heavy to be carried in a purse.



Conclusions

There are different kinds of acceleration. The centrifugal accelerations created by rotation are many times greater than the accelerations occurring in our everyday lives. The accelerations produced by rotation, the resulting forces and energies are difficult to imagine and need to be safely endured by the individual structures to protect persons and material from injury/damage. This is a matter for both manufacturers and users.

References

[1] Gunter Gebauer: Kalkuliertes Risiko: Technik, Spiel und Sport an der Grenze, Bibliografische Information der Deutschen Bibliothek

[2] Rainer Schicker, Georg Wegener: Measuring Torque Correctly, ISBN 3-00-008945-4, Published by Hottinger Baldwin Messtechnik GmbH, Darmstadt, www.hbm.com

[3] de.wikipedia.org/wiki/Drehzahl

[4] www.siart.de/lehre/zentrifuge.pdf

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