Alternative Concepts for High Precision Bearings in Torque Standard Machines

A. C. P. Bitencourt[1], R. Theska[2], A. Wagner[2], H. A. Lepikson[3], W. L. Weingaertner[1]
[1] *Universidade Federal de Santa Catarina, Brazil*
[2] *Technische Universität Ilmenau, Germany*
[3] *Universidade Federal da Bahia, Brazil*

a.carlos@emc.ufsc.br

Abstract

This paper focuses on solutions for high precision bearings to be used in a new design for Torque Standard Machines (TSM) for small torques. Increasing demand for the further reduction of uncertainty in the realisation and measurement of small torques by one order are driven by applications in the electronics industry, micromechanics and medical appliances, among others. This article presents a detailed assessment of bearing principles and examines the design requirements for small torque realization. Variants of bearings for small torque standard machines are discussed.

1 Torque Standard Machine (TSM)

TSM is the primary standard device that realizes pure torque with the best available metrological characteristics [1]. The state of the art in small torque realization is currently given by a TSM developed at PTB (*Physikalisch-Technische Bundesanstalt*), which can realize torques in a range of 1mNm to 1Nm with a relative expanded uncertainty $Ur=1x10^{-4}$, (k=2). Increasing demand for further reduction of the uncertainty in the realisation and measurement of small torques by one order are driven by applications in the electronics industry, micromechanics and medical appliances, among others [2].

Currently, the dead-weight principle gives the best metrological characteristic for TSM [3]. This principle consists of a beam balance with standard weights, levered by a counter-torque device, see Figure 1. The pure torque is realized by gravity force and reaction force acting on a given lever arm which plays the role of radius to a rotary axis. This axis needs to be realized by a high precision bearing. The nominal torque (M_N) is given by the local gravity (g) and the buoyancy caused by the immersion of the suspended masses, whose value and density are m and ρ_m, within a medium whose density is ρ_{air}.

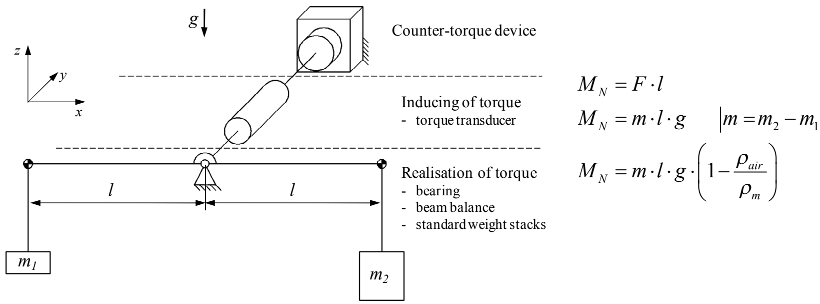

Figure 1: Torque realization by dead-weight principle

However, there is no pure torque realization due to the fact that the bearing has friction. Furthermore, there is a deviation in the position of the real axis of rotation. The real torque (M) is depicted in Eq. (1). Eq. (2) shows the assessment of the uncertainties sources in torque realization [3]. It shows that bearing characteristics, mass (m) and distance between the force action line and axis of rotation (l) are playing the most significant roles in the TSM metrological performance.

$$M = M_N + M_{fr} \tag{1}$$

$$\frac{u^2(M)}{M_N{}^2} = u_r^2(F_g) + u_r^2(l) + \frac{u^2(M_{fr})}{M_N{}^2} \quad \left| F_g = m \cdot g \cdot \left(1 - \frac{\rho_{air}}{\rho_m}\right) \right. \tag{2}$$

The bearing characteristics are influential in two of three terms of the relative uncertainty. The main influence is given by the bearing friction (M_{fr}). The bearing type also has a significant influence on the axis of rotation definition. Three bearing types: knife edge, flexure and aerostatic are the most frequently used in TSM [4].

2 Friction in bearing

Minor friction is the most common approach to use in choosing a bearing for the dead-weight principle because friction becomes more important in small torque ($u^2(M_{fr}) \cdot M_N{}^{-2}$). Table 1 shows that bearing influences are related to friction magnitude and type. The influence of the bearing characteristics becomes even more evident for the realization of small torques.

Table 1: Bearings versus friction type [5]

Bearing	Friction type	Uncertainty part from bearing type
Knife-edge	Rolling friction	≈ 10^{-5} (50 kNm)
Flexure	Internal material friction	≈ 10^{-5} (1 kNm)
Aerostatic	Fluid friction	≈ 10^{-5} (1 Nm)

The friction moment in knife-edge bearings is theoretically a systematic error that can be determined as a function of the knife and pan geometry, the material proprieties and the bearing position. Caused by Hertzian stress there is a risk of permanent deformation (flexible material) or fracture (rigid material) of knife and pan which ends up in a stochastic behaviour. Flexure bearings have no contact friction, but they show a retro torque due to atomic bounding force. If the angular motion is small enough to work in the material elastic zone, the retro torque becomes a systematic error and this is well determined through analytical equations. Aerostatic bearings have the smallest friction, but it is not easy to determine its magnitude during the TSM operation. Furthermore, the friction behavior in aerostatic bearings is a random phenomenon which is hard to compensate for [6].

3 Other important characteristics of bearings

Apart from small and predictable friction other requirements for bearings in TSM include high stiffness, stable definition of the rotary axis and high repeatability. These requirements cannot be attained without a significant improvement in the typical characteristics of the bearings. Therefore scientific investigation is required.

Knife edge bearings are frequently used in weighing machines and other high precision instruments due to their highly predictable behaviour. Unfortunately, knife edge bearings suffer from low stiffness and small load capacity. Semi precious stones are frequently used in knife edges, for lower friction and to avoid elastic and plastic deformations. Flexure bearings are used in precision engineering because of their zero backlash and high repeatability. The main disadvantage of flexure bearings is that in general they do not provide a fixed axis of rotation. However, there are configurations which could give an almost stable rotary axis, e.g. none symmetric cross spring. The exact mathematical formulation and simulation of the given kinematic behaviour of these bearings provides opportunities to compensate bearing errors because they become systematic characteristics, thus opening new alternatives for bearing solutions. Air bearings require cost driving air supply, superfine filtration, drying of the air and pressure stabilization. Even if air bearings are showing good repeatability it is randomly influenced thus hard to describe mathematically which makes it almost impossible to compensate for.

4 Conclusion

The article presents a detailed assessment of bearing principles and examines the design requirements for small torque realization. Variants of bearings for small torque standard machines are discussed. Knife edge bearings present a number of weaknesses. Air bearings show the best characteristics in terms of small friction and high repeatability of the rotation axis. However, these characteristics behave randomly which makes it hard to carry out failure compensation. Flexure bearings have the advantage of having highly predictable characteristics which make them systematic and relatively easy to compensate. For this purpose an additional measurement of the spring's deformations is needed. None symmetric cross-spring bearings appear to provide a predictable and stable definition of the axis of rotation and will be investigated in greater depth in the future.

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