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Research paper

Unified approach to bi-directional non-back drivable roller clutch design

Marco Controzzi[*], Lorenzo Bassi Luciani, Federico Montagnani

The BioRobotics Institute, Scuola Superiore Sant'Anna, Viale Rinaldo Piaggio 34, 56025 (PI), Italy

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ABSTRACT

A non-back drivable mechanism (transmission or clutches) is a device able to transmit torques from its input to the output axis and vice-versa to lock torques applied to its output. These devices are widely used in robotic, mechatronic systems and prosthetics in order to lock joints or to physically engage/disengage transmission axes. An efficient way to implement non-back drivability is to exploit the wedge phenomenon that occurs to rolling elements when they are compressed between circular and cam surfaces. The current literature describing such mechanisms and underlying equations is rather scattered and incomplete. In this paper, a relevant set of equations is presented to optimize their design, which is of particular interest in prosthetics to minimize weight of limbs. The conceptual framework and the general design are described. The relationship between the locking torque and the properties of the components are then derived. Moreover, the sources and effects of tolerance and of operational conditions are introduced. The contact pressures, the input torque required to unlock the clutch, the critical torque and the input backlash are finally analyzed. The final part of the paper is devoted to a step-by-step procedure useful in the design of non-back drivable roller clutches.

1. Introduction

A non-back drivable mechanism (transmission or clutch) is a two-axis component that transmits mechanical torque primarily in one direction; it exhibits low (ideally zero) resistive torque in one direction (from the input to the output), and high (ideally infinite) resistance in the other (from the output to the input). It can be deemed as the mechanical equivalent of a semiconductor diode in an electronic circuit.

In practice, non-back drivable mechanisms disengage the output of a mechanism from the source of energy that actuates it. Because of this, they are widely used in robotic and mechatronic systems. Non-back drivability is a mandatory safety constraint when a power supply failure represents a hazard for human operators. This is the case of robotic arms or of wearable exoskeletons that could collapse to the ground if the joints are not locked [1–3]. Similarly, they are of particular interest in battery-operated systems, e.g. artificial prostheses, because they prevent power consumption while the end effector is maintained in a fixed position [4–6].

There are several methods to implement non-back drivability, as reviewed in their recent work by Plooij et al. [7] or in Orthwein [8]. These mechanisms can be categorized based on the principle used to lock the transmission: mechanical

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[*] Corresponding author.

E-mail addresses: marco.controzzi@santannapisa.it, marco.controzzi@sssup.it (M. Controzzi), lorenzo.bassiluciani@santannapisa.it (L. Bassi Luciani), federico.motagnani@santannapisa.it (F. Montagnani).

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Nomenclature

τ	Locking torque
τ_{U}	Unlocking torque
τ_{OC}	Maximum octahedral shear stress
σ_{zz}	Maximum principal stress
S_y^C	Yielding compressive stress
S_y^T	Yielding tensile stress
α	Contact angle
α'	Limit value of the contact angle
$\alpha^{-,+}$	Minimum and maximum contact angles
α^O	Operational contact angle
α^A	Actual contact angle
β	Ratio between the inner and outer radius of the ring
F	Contact force
F'	Contact force during the unlocking process
F_T	Tangential component of the contact force
F_R	Radial component of the contact force
F_U	Unlocking force
F_k	Elastic force of the spring
ΔU	Unlocking gap
R	Radius of the ring
$R^{+,-}$	Maximum and minimum radius of the ring
L	Width of the ring
f	Radius of the internal pins
ρ	Radial deformation of the ring
r	Radius of the roller
$r^{+,-}$	Maximum and minimum radius of the roller
r_{lim}	Limit of service of the roller
l	Width of the roller
β	Ratio between the inner and the outer radius of the ring
h	Distance between the cam face and the axis of the mechanism
$h^{+,-}$	Maximum and minimum distances between the cam face and the axis of the mechanism
ε	Radial deformation of the roller
$E_{R/OR}$	Young's Modulus of the roller/ring
ν	Poisson's ratio
$\dot{\omega}$	Angular acceleration
I	Inertia
η	Reduction ratio
m	mass
G	Gravitational constant
$\mathrm{a}_{\mathrm{RC}}/\mathrm{a}_{\mathrm{R}}$	Semi-contact widths of the contact stress distributions
N	Number of rollers
μ_S	Static friction coefficient

locking, friction-based locking, and singularity locking. Moreover, it can be either passive or active in each category of device. Friction-based devices are the most common ones, due to the relative ease of generating friction and the ability to be locked in any position. Some examples are *non-back drivable gearings* (i.e. *lead-screw* transmissions and *worm-gear* pairs) and *free-wheels*.

In *non-back drivable gearings*, the transmission is designed in a way that the efficiency of the direct motion is lower than 0.5, as this causes the efficiency of the backward motion to be ≤ 0 (the condition for locking the backward transmission). Examples of this application are *lead-screw* transmissions [9,10] and *worm-gear* pairs [11,12]. The low efficiency of the direct motion requires larger motors, affecting the weight, size and power consumption of the robot. On a different note, the combination of large loads and large sliding velocities encountered with these transmissions causes wear of the components and heat that has to be dissipated by the housing.

The *free-wheel* (or *overrunning clutch*), largely employed in robotics [13,14], aerospace [15,16], and automotive transmissions [8,17], is a basic mechanism based on the coupling between an inner member (the input) and an outer member (the output) by means of rolling elements (spheres, cylinders or sprags). The inner member has cam surfaces on opposite sides and carries the rollers along the ring-shaped outer member; the rollers can either wedge or un-wedge against the outer