On the performance of actuators with harmonic drive speed reducers

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Abstract:
Harmonic Drives (HD) are commonly used in robotics because of zero-backlash and compactness. This makes them ideal for several mechatronic applications. Despite their wide use, there is no compelling literature on their performance, and to date it is not clear how they fare in a complete actuation setup. In this work we evaluate the joint structure we currently install on the iCub humanoid robot comprising an HD speed reducer showing that their efficiency is not optimal.
Keywords: Harmonic Drive, efficiency, backdrivability, humanoid robots

Introduction

Harmonic Drive (HD) speed reducers have unique characteristics that make them essential for several mechatronic applications. Indeed HD are one of the few transmission types that is not affected by backlash. This characteristic, for example, is essential for torque control applications where transmission backlash is known to rapidly induce the onset vibrations.
Another very important characteristic of HD is their low weight compared to other speed reducers with similar torque rating. Moreover their particular operating principle allows to construct very compact units. These two key features make them ideal for mobile robotics; indeed HD have become the de-facto standard solution in the field of electrically powered humanoid robots.

Fig. 1: *The iCub Humanoid robot*

Despite their wide use, there is no compelling literature on their performance [1, 2], and to date it is not clear how they fare in a complete actuation setup. In this work we evaluate the joint structure we currently install on the iCub humanoid robot [3] comprising an HD speed reducer showing that their efficiency is not optimal.

Actuator Description

Our actuators comprise a frameless brushless DC (BLDC) Kollmorgen RBE 01211 motor [4] and a “flat type” frameless HD speed reducer (see Fig. 2). For what concerns the HD speed reducers we tested a CSD-17-100 2A GR model from Harmonic Drive [5] and a LCD-17-100-P-I-S25 model from Leader Drive, both controlled with two electronic boards. A brushless logic board processes the various signals provided by the sensors and generates the control signals that govern the motion of the motors. These signals are then passed to a brushless power board which contains the actuator power drivers: the motor voltages are controlled by the amplifiers with pulse width modulation (PWM). The continuous rated power of the system is 150[W].

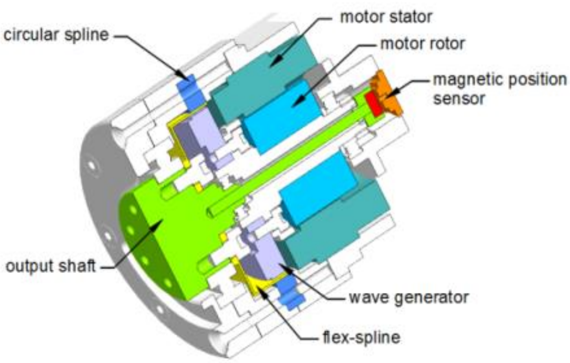

Fig. 2: *Cross section of the actuator under test*

Setup description

All the data presented in this paper were acquired with a dedicated setup (see Fig. 3) that comprises:

- a compensated Xantrex DC power supply (1)
- a Yokogawa WT3000 precision power meter (2)
- a Magtrol 1PB85-D6-6000 dynamometric magnetic powder brake (3)
- a Magtrol DSP6001 brake control unit (4)
- a digital thermometer (5)
- a control PC (not shown)
- a motor and gearbox unit (6)
- the actuator control unit (7)

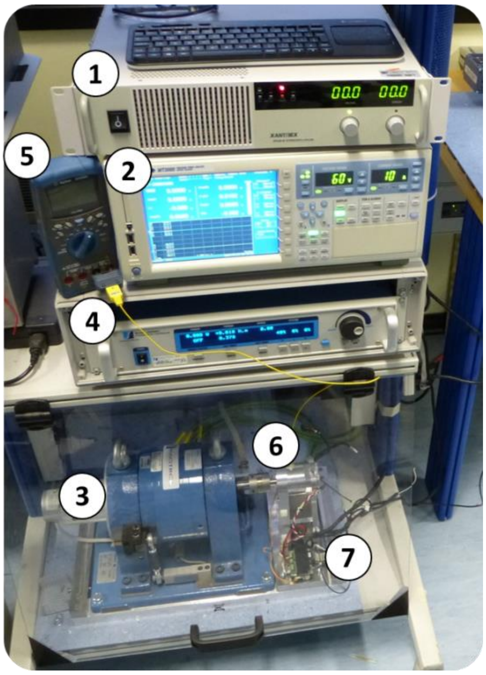

Fig. 3: *Photograph of the test setup. The elements of the setup have been labelled corresponding to the numbered items in the main text.*

Our setup allowed to measure the motor input current and voltage, the motor angular position, as well as the output torque, and angular position. The angular velocities of the systems were computed by numerical differentiation.
It is important to note that our setup did not allow for a direct control of the actuator temperature. We chose this simplification in order to simplify the experimental rig. However it is known that HD efficiency is strongly dependent on temperature. Therefore to acquire data at different temperatures we simply exploited the natural tendency of the gearbox to heat up when operated. Our setup allowed us to measure the following quantities: motor voltage, motor current, motor electrical power, actuator frame temperature, actuator torque, actuator angular velocity, and actuator output mechanical power.

Experiments

To evaluate the performance of the actuator we conducted tests on the starting torque and the actuator efficiency.
The starting torque test is important to characterize the back-driveability of the actuator. Indeed lower values of starting torque generally correspond to lower levels of actuator mechanical impedance.
The actuator efficiency test is, on the other hand, the standard benchmark to characterize the "goodness" of a transmission.

Starting torque test

To evaluate the value of starting torque we gradually increased the motor torque by increasing the duty cycle of the PWM signal. The moment motion began we recorded the value of the applied voltage and computed the corresponding motor torque. We conducted the same test several times at various temperatures. The results of the test are shown in Fig.4. Indeed the LCD-17-100-P-I-S25 gearbox has very high starting torque values if compared to the CSD-17-100 2A-GR gearbox. This is likely due to the special proprietary tooth profiles patented by Harmonic Drive [6, 7].

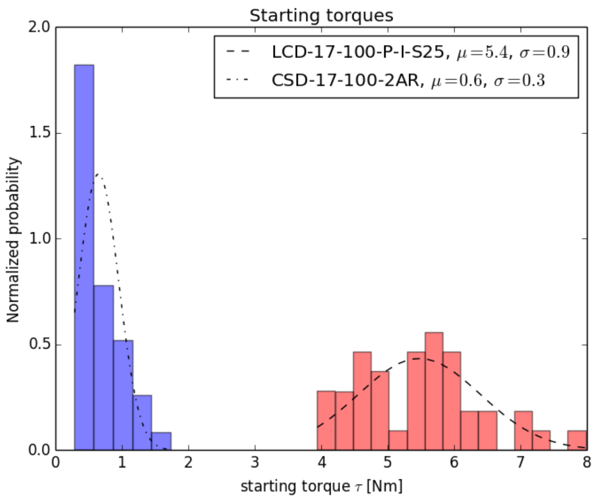

Fig.4: *Starting torque test results. The figure shows the results of the starting torque test for the two actuators being compared. The corresponding normalized gaussians have been superimposed in the plot. Their corresponding averages and standard deviations are indicated in the legend.*

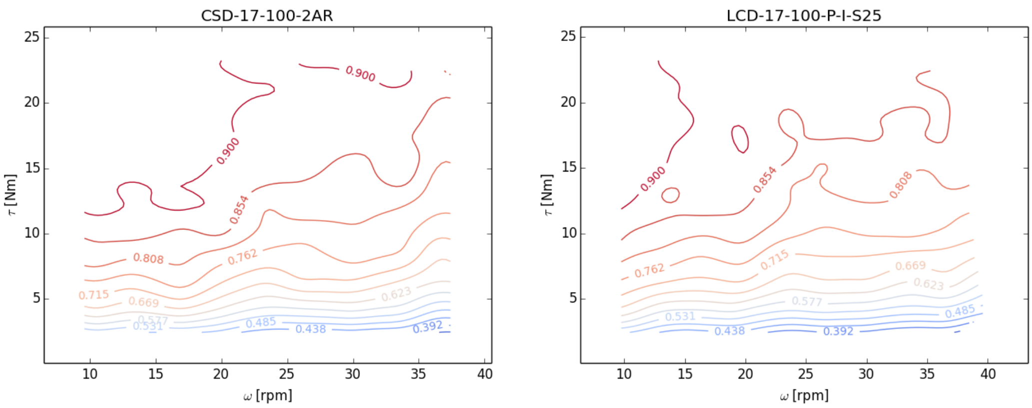

Fig.5: *Transmission efficiency plots. The figure represents the contour plots of the averaged efficiencies as a function of the braking torque and the angular velocity.*

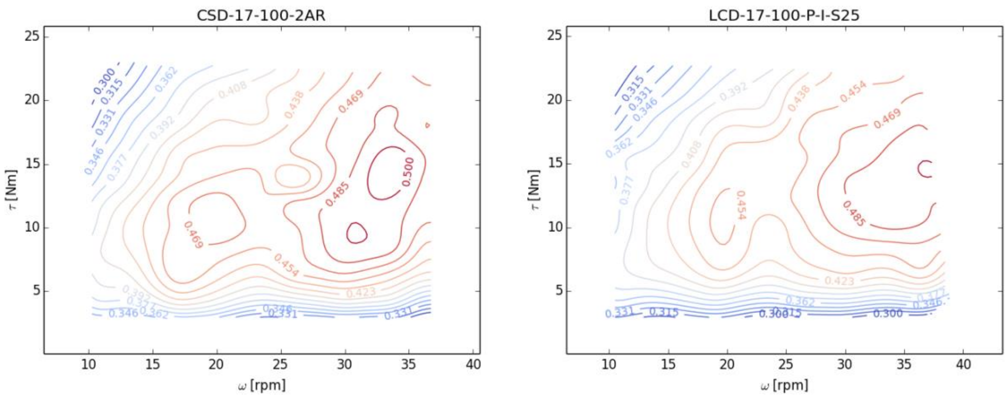

Fig.6: *Actuators efficiency plots. The figure represents the contour plots of the averaged efficiencies as a function of the braking torque and the angular velocity.*

Efficiency test

For the actuator efficiency test we mapped the behaviour of the system on its operating range. The braking torque values were recorded from 0 to 28[Nm] in steps of 2[Nm]. The angular velocity values were recorded from 6.6[rpm] to 40.3[rpm] in steps of 3.7[rpm].

The data were acquired by photographing the instruments displays with a digital camera. The images were later processed with a Python script linking the Tesseract OCT library [8] to extract the data for all the recorded operating points.

The data were processed to compute both the transmission and the actuator efficiencies.

Moreover the transmission efficiency data were fitted with a model of the form:

$$\eta = a\omega + b(\tan^{-1}(c\tau)\ ) + d(\tan^{-1}(et)\ ) + f$$

where η is the actuator efficiency, ω is the actuator output angular velocity, τ is the braking torque, t is the actuator frame temperature, and a, b, c, d, e and f are the model parameters. This was done to provide the interested reader with reference values for the experiment. We chose to fit the data with a model that is a linear function of the angular velocity, and is the logarithm of the braking torque and the temperature. The choice of the inverse tangent as the base function is somehow arbitrary but matches well experimental data reported in the Harmonic Drive product catalogue for CSD speed reducers [5]. The data processing was performed with the Scipy [9] open-source Python scientific library. The results presented here derive from four acquisition runs.

The parameters fitted for the two different actuators under test are reported in Tab.1.

As can be seen the values of the fitted parameters show a nice correspondence with the exception of parameter f.

As can be seen there is a marked dependence of the actuator efficiency on the braking torque. Moreover the actuator efficiency is above 50% only in a very narrow region at low speeds.

These data are extremely important for the design of our humanoid robot system. Indeed a large part of the power fed to the system will eventually be dissipated in thermal energy. Sound thermal management design will be required for systems in continuous operation.

	CSD-17-100 2A-GR	LCD-17-100-P-I-S25	Units
a	0.00384	0.00329	[1/rpm]
b	0.61491	0.60975	[1/Nm]
c	0.34914	0.32714	[-]
d	-0.13886	-0.13770	[1/°C]
e	0.054683	0.04365	[-]
f	-0.030216	-0.00452	[-]

Tab.1: *Parameters of least squares fit for the two actuators under test.*

Conclusions

The results presented in this document show that, in normal operating conditions, the performance of electric actuators with Harmonic Drive speed reducers with high reduction ratios tends to be rather low in terms of energy efficiency and back-drivability. Furthermore this evidence suggests the potential for possible improvements to be obtained by questioning the current widely adopted design paradigm.

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