Balancing low mass

To increase the accuracy as well the production speed of industrial machines, dynamic balance is becoming a key issue. Instead of applying complicated control strategies to reduce machine vibrations, and damping systems to suppress vibrations, in dynamic balancing the mechanism parts are considered and designed such that the machine does not vibrate at all. Surprisingly however, dynamic balancing techniques are not yet widely applied. This is probably due to the lack of knowledge of dynamic balancing and the fact that in general relatively a lot of mass and inertia is added to obtain a dynamically balanced mechanism. This study focuses on the reduction of the additional mass and the additional inertia with dynamic balancing. For that purpose common balancing principles are analyzed and compared, guidelines for low mass and low inertia dynamic balancing are formulated, and new balanced mechanisms that have a low mass and low inertia are synthesized.

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Due to motion of mechanism parts, reaction forces (shaking forces) and reaction moments (shaking moments) are exerted to the base of a mechanism (i.e. machine, robot). This is a major source of vibrations, inducing noise, wear and fatigue problems, and discomfort. Common solutions to reduce the influence of vibrations on the performance of the mechanism are the application of damping and including waiting times in the motion cycle to wait until vibrations have died out. With dynamic balancing however, the mechanism is designed such that all vibrations are eliminated. As a result, balanced mechanisms can have both shorter cycle times and higher accuracy.

Generally, a mechanism is (shaking) force-balanced if the linear momentum of all the mechanism parts is constant and a mechanism is (shaking) moment-balanced if the angular momentum of all mechanism parts is constant. A constant linear momentum implies that the center-of-mass (COM) of a mechanism must be stationary or move with constant velocity. A drawback of dynamic balancing is that (counter-)mass and (counter-)inertia needs to be added, which can lead to a higher power consumption.

Balancing principles

In literature, three generally applicable dynamic balancing principles can be found [1]. In Figures 1-3 these balancing principles are shown as being applied to balance a link. The link is modeled as a lumped mass m with inertia I at a distance l from the center of rotation. Figure 1 shows the balancing principle with Separate Counter-Rotations (SCRs). For the force balance, a countermass (CM) m^* is added to the link such that the COM of the link is at pivot

and low inertia addition

O. For the moment balance of the (force-balanced) link a separate counter-rotating element is mounted somewhere at the base and connected to the link with a pair of gears.

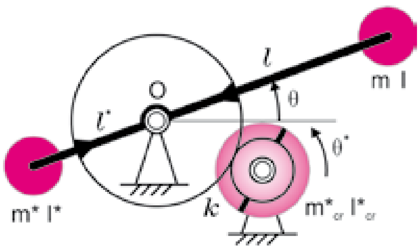

Figure 1. Balancing principle with a Separate Counter-Rotation (SCR).

The inertia of the CM, however, can also be used for balancing the moment of the force-balanced link, omitting the addition of a SCR. This solution of using Counter-Rotary Counter-Masses (CRCMs) is shown in Figure 2. To have the CRCM rotate in opposite direction of the link, a pair of gears can be used and can be applied in three different ways. In Figure 2a a chain (or belt) is used with one gear (or pulley) being mounted to the CRCM and another being mounted to the base, coinciding with the pivot. In Figure 2b an additional external gear is used and Figure 2c shows a solution with internal gears.

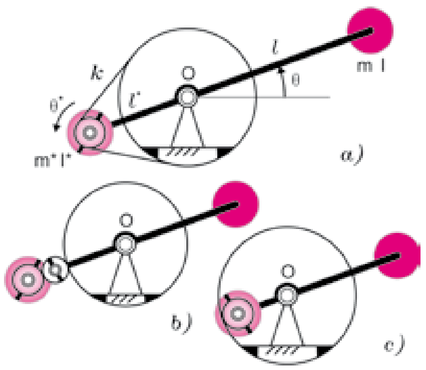

Figure 2. Balancing principle with a Counter-Rotary Counter-Mass (CRCM) configuration with: (a) gears and chain, (b) external gear, (c) internal gear.

A third way to achieve dynamic balance is by applying axial and mirror duplicates of the initial mechanism that move synchronically, as shown in Figure 3. Because a mirror duplicate mechanism produces equal but opposite reaction forces and moments, the horizontal mirror duplicate balances the horizontal force and the moment of the link, and vertical mirror duplicates are used to balance the vertical force.

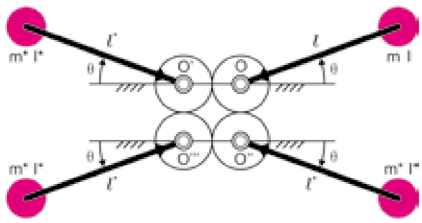

Figure 3. Balancing principle with axial mirror duplicates of the initial mechanism (DM).

Analysis and comparison

Two comparative studies of the balancing principles were done and both showed that using CRCMs instead of SCRs, is favorable for low mass and low inertia [1] [2]. One study compared the balancing principles applied to a rotatable link, which are the configurations in Figures 1-3. The second study compared the balancing principles applied to a double pendulum (or dyad).
The double pendulum is found suitable for a fair comparison, representing a large category of mechanisms. This is because many mechanisms can be synthesized from double pendulums, the balancing performance of an open-loop mechanism does not change by constraining its motion to obtain a closed-loop mechanism (i.e. the mechanism is balanced for any motion), and in practice mechanisms are balanced link by link. A rotatable link is most suitable for the detailed study of the balancing parameters.

The relation between the reduced inertia of the rotatable link (the inertia that an actuator feels when driving the mechanism) and the total mass for each principle are obtained theoretically and illustrated by a numerical example in Figure 4. All masses were modeled as discs with thickness 0.01 m made of steel (ρ = 7800 kgm^{-3}) and the parameter values were chosen as m = 0.3 kg, l = 0.25 m, and I = 184 kgmm^2. The curve for the CRCM principle remains below the curves of the SCR principle. However, the DM principle, which has a single value, is even lower. This implies that improving on the DM principle result is not easy to achieve.
Another interesting observation is the necessary trade-off between the addition of mass and the addition of inertia. Clearly it is not possible to balance a link by having both a low mass and a low inertia. The results of the comparative study with the balancing principles applied to a double pendulum are similar.

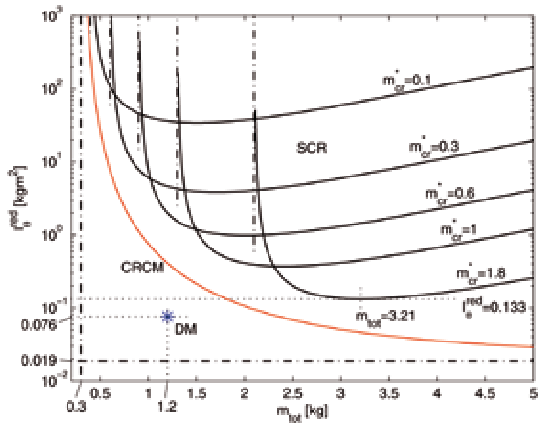

Figure 4. Comparison of balancing principles; relation between inertia and total mass.

Synthesis

A double pendulum is a useful ‘building element’ in the synthesis of a wide variety of mechanisms. Equivalently, a dynamically balanced double pendulum is a useful ‘building element’ in the synthesis of dynamically balanced mechanisms. In fact, combining independently balanced mechanisms results in mechanisms that are also balanced. There are various ways to balance a double pendulum, for instance by applying the DM principle for the lowest mass and lowest inertia addition. However the balanced mechanism then becomes rather large and complex. The DM principle is advantageous if in practice four of the same mechanisms are needed and they can be placed such that they balance each other.

Figure 5 shows a double pendulum that is balanced with two CRCMs and is characterized by having a low inertia, since the transmission of gears is designed such that the rotation of I^*_2 is not influenced by link 1 [3]. Figure 6 shows how a double pendulum can be fully dynamically balanced with a single CRCM, of which the counter-

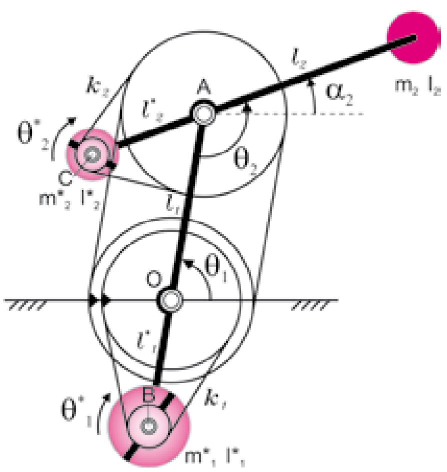

Figure 5. CRCM-balanced double pendulum with low inertia.

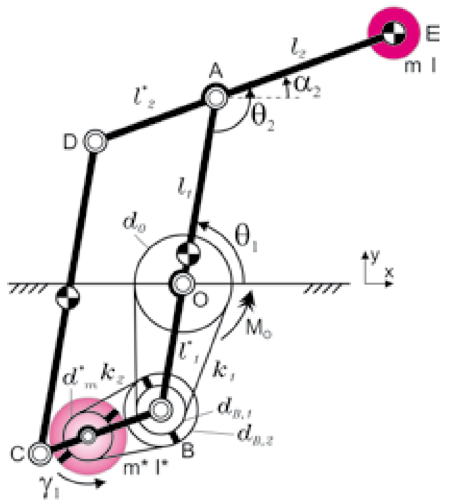

Figure 6. Actively CRCM-balanced double pendulum with a single CRCM for complete dynamic balance.

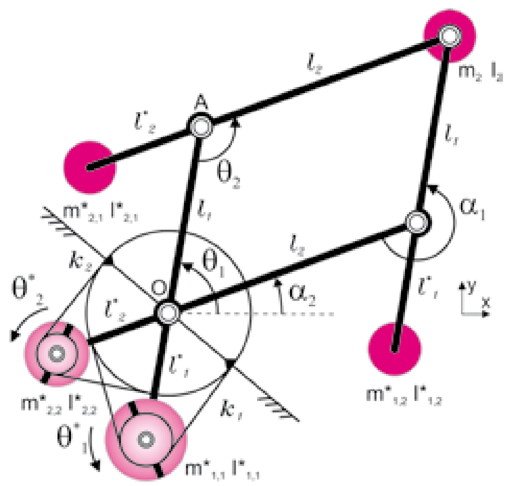

Figure 7. 2RRR five-bar mechanism balanced with two CMs and two CRCMs [6].

rotation is actively controlled with an additional actuator at the base [5]. In this case, fixed gears cannot be used, since the inertia tensor of the mechanism about the base pivot is not constant for any motion.

By combining two CRCM-balanced double pendulums, the balanced 2RRR five-bar mechanism of Figure 7 is obtained. $m^*_{1,2}$ and $m^*_{2,1}$ could be CRCMs (as in Figure 5), but if the links are such that the mechanism is a parallelogram (parallel links have equal angular velocity), these can be fixed CMs and only two CRCMs are needed for the moment balance of the complete mechanism.

In Figure 8, a balanced crank-slider mechanism is shown, which was derived from Figure 7 by guiding the endpoint along a line and changing the dimensions of one side. Because of the parallelogram, one of the CMs can be taken

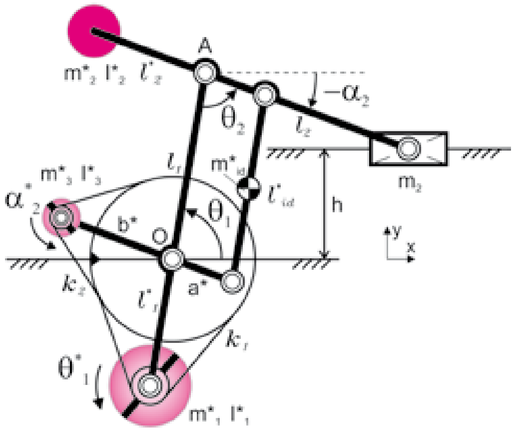

Figure 8. CRCM-balanced crank-slider mechanism deduced from Figure 7.

out (this can also be done in Figure 7). By using CRCM-balanced (single and) double pendulums, an unlimited number of multi-DOF, planar and spatial balanced mechanisms can be created. Just start puzzling!

Innovative solutions

For crank-slider mechanisms it is often difficult to attach gears and other elements to the coupler link (link 2), for instance if the mechanism is large or if additional elements interfere with the workspace. Figure 9 shows a crank-slider mechanism that is dynamically balanced with a CM on the coupler and a single CRCM at the crank. This CRCM

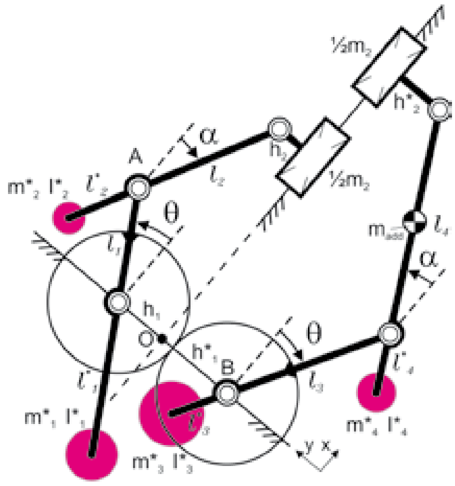

Figure 10. Balanced crank-slider by specifically designed counter-mechanism.

balances the moment of both crank and coupler. This is achieved by a specific transmission, mounted on a third link (link 3) which runs parallel with the coupler. In fact this transmission is a mechanic 'summator', adding the angular velocities of both links and changing its sign to have a counter-rotation. The advantage is that this balancing system can be scaled to a small size and is situated away from the workspace.
The DM principle showed to be advantageous for low mass and low inertia. This is mainly because links are used for balancing the moment. These counter-rotating links have a

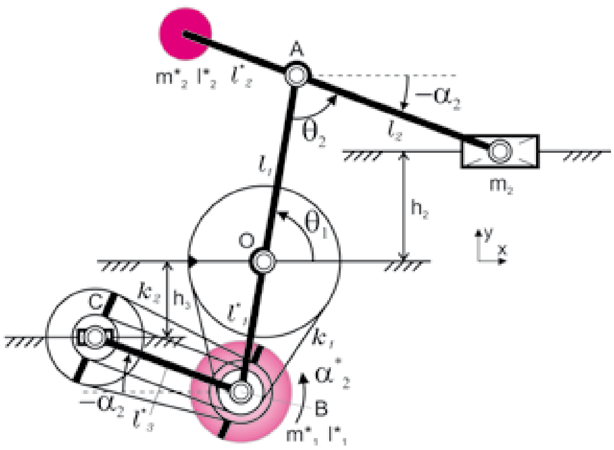

Figure 9. Balanced crank-slider mechanism with balancing elements away from the workspace.

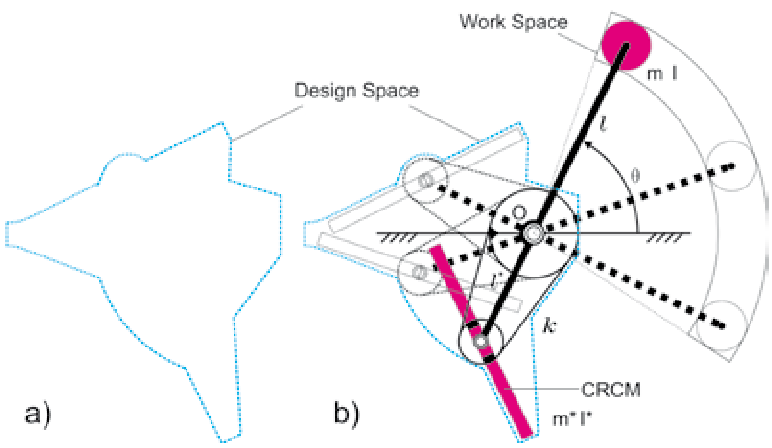

Figure 11. Counter-rotating links for balancing within a small space.

relatively low mass and high inertia, by which the (counter) rotational velocities are low and therefore the reduced inertia of the mechanism is low as well. Instead of adding three mirror duplicates, Figure 10 shows how a specifically designed counter-mechanism can be used for balancing. A crank-slider mechanism (l_1-l_2) is balanced with a counter-mechanism (l_3-l_4) which is also a crank-slider. Both mechanisms are force-balanced individually and move synchronically and opposite of each other by gears. The moment balance is obtained if the inertia of link 2 and 4 are equal and the inertia of link 1 and 3 are equal.

Design space
For the designer it is always challenging to design all machine parts within a small area, and it even becomes more challenging when also the balancing parts have to be included. Counter-rotating links that do not have full revolutions appear to be advantageous for balancing within a small space. As an example, the configuration of Figure 2a, but with the CRCM designed as a link and driven with a transmission ratio of -1, is shown in Figure 11. In this way the counter-rotating link can move in between the other machine parts.

Guidelines
From this study, general guidelines for low mass and low inertia dynamic balancing have been obtained [4]. The use of CRCMs is advantageous especially if the CRCM is designed with low mass and high inertia (e.g. as a link). For a low mass addition, counter-masses have to be placed far from the center of rotation, while for a low inertia addition they have to be placed close to the center of rotation. For low inertia addition, counter rotations should be rotating slowly, which is also achieved by balancing with duplicate mechanisms and counter-mechanisms. For a low mass, it should be omitted to balance CMs with other CMs.

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Recent work includes the development of an actively dynamically balanced xy-robot (in cooperation with Stamhuis Lineairtechniek, Ternet, and Control Techniques) and a dynamically balanced Delta Robot (in cooperation with Blueprint Automation).

Author's note
Volkert van der Wijk is a PhD student in the Department of Biomechanical Engineering of Delft University of Technology. He is the recipient of the Wim van der Hoek Award 2008.

References
[1] Van der Wijk, V., Herder, J.L., Demeulenaere, B., 2009. "Comparison of various dynamic balancing principles regarding additional mass and additional inertia". *Journal of Mechanisms and Robotics (in print)*.
[2] Van der Wijk, V., Herder, J.L., Demeulenaere, B., Gosselin, C.M., 2009. "Comparative analysis and optimization for low-mass and low-inertia dynamic balancing of a rotatable link balanced by a counter-rotary counter-mass". *Journal of Mechanisms and Robotics (accepted)*.
[3] Van der Wijk, V., and Herder, J.L., 2009. "Synthesis of dynamically balanced mechanisms by using counter-rotary counter-mass balanced double pendula". *Journal of Mechanical Design (in print)*.
[4] Van der Wijk, V., Herder, J.L., 2009. "Guidelines for low mass and low inertia dynamic balancing of mechanisms and robotics". *German Workshop on Robotics, Braunschweig*.
[5] Van der Wijk, V., Herder, J.L., 2008. "Dynamic balancing of mechanisms by using an actively driven counter-rotary counter-mass for low mass and low inertia". *Proceedings of the Second International Workshop on Fundamental Issues and Future Research Directions for Parallel Mechanisms and Manipulators, Montpellier*, pp. 241-251.
[6] Menschaar, H.F., Ariens, A.B., Herder, J.L., Bakker, B.M., 2006. "Five-bar mechanism with dynamic balancing means and method for dynamically balancing a five-bar mechanism", *Patent number WO 2006/080846*.

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