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The main cover photo (the T-Flex parallel manipulator) is courtesy of Mark Naves, University of Twente. Read the article on page 19 ff.

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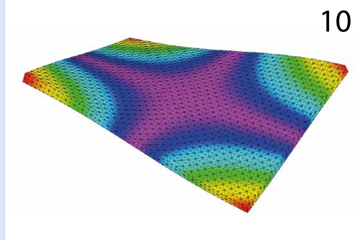
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FEATURES

PRESENTING THE CASE FOR DESIGN PRINCIPLES FOR PRECISION MECHATRONICS

The first phase in the realisation of a precision design principles 2.0 textbook has been successfully concluded. First results of this joint venture of Dutch precision mechanics and mechatronics professors, DSPE and the Dutch high-tech industry will be presented during the coming Precision Fair.

The Dutch design principles for precision mechanical engineering and mechatronics have been one of the pillars of the success of the Dutch high-tech industry for over fifty years. They originated from the Philips Centre for Manufacturing Technologies (Philips CFT) and were compiled by Wim van Der Hoek in the 1960s and 1970s. His successors Rien Koster, Nick Rosielle, Herman Soemers and Susan van den Berg refined and augmented Van der Hoek's The Devil's Picture Book (*Des Duivels Prentenboek*, DDP).

The reason for the success of the Dutch School of precision engineering is threefold. First and foremost, it presents a clear and powerful design approach based on principles such as statically constrained design, application of friction- and hysteresis-free flexures, and lightweight and stiff design. Next is the fact that all books present a variety of design examples that can be easily applied or serve as an inspiration for new designs. Moreover, all authors were or still are talented teachers who educated generations of engineers.

Two years ago, professors from the three Dutch universities of technology – Dannis Brouwer (Twente), Just Herder (Delft) and Hans Vermeulen (Eindhoven) – and the undersigned on behalf of DSPE decided to produce a new and fully reviewed version of DDP, building on the basic principles while adding new principles such as damping and over-actuation. The book will be titled "Design Principles for Precision Mechatronics" (DPPM).

Crucially, it was also decided to gather at least 100 new design cases, to be supplied by Dutch industry. To this end, an Industry Board was installed. From the very beginning, Industry Board members were very inspirational and really supportive in bringing all the cases together. This represents one of the strengths of the Dutch high-tech industry, the willingness to collaborate and share knowledge, which in the end will benefit the industry as a whole.

The Industry Board also declared that just a new book would be too limited in the current era of internet and digitalisation. Therefore, a website was developed to present 100 or more cases grouped according to the ten newly defined principles. This will offer optimal accessibility to engineers, as well as flexibility in expanding the collection of cases when engineers have become inspired to also share their knowledge.

At the forthcoming Precision Fair, on 16-17 November in Den Bosch (NL), we will present the results of the first phase in the realisation of DPPM: a website explaining the ten design principles and presenting at least 50 cases representative of the various principles. From then on you can be inspired by the first 50 cases and challenged to apply the underlying principles at *www.dspe.nl/knowledge/dppm-cases*.

As a non-profit organisation for and by engineers driven by a passion for precision engineering, DSPE offered a great network to build a strong Industry Board for DPPM. We are proud to contribute to publishing and disseminating this unique body of knowledge.

Pieter Kappelhof
Director Technology of Hittech Group and DSPE board member
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UPDATING DDP

An initiative to produce updated design principles for precision mechatronics has been developed by Dutch universities of technology in association with DSPE, in close collaboration with the Dutch high-tech industry. Building on the legacy of Wim van der Hoek, the Dutch doyen of design principles, the aim of the initiative is to collect over 100 cases that demonstrate the proper application of contemporary design principles. The cases will be presented on a dedicated website and collected in a new textbook, preceded by an extensive, in-depth introduction of the design principles.

Initiators

The initiative to update the design principles for precision mechatronics came from the professors of precision engineering and mechatronics at the three Dutch universities of technologies – Delft, Eindhoven and Twente – in association with DSPE.




From left to right:
Dannis Brouwer is professor of Precision Engineering at the University of Twente, Enschede (NL).
Just Herder is professor of Interactive Mechanisms and Mechatronics at Delft University of Technology, Delft (NL).
Pieter Kappelhof is vice president of DSPE, director of Technology at Hittech Group, located in Den Haag (NL), and hybrid teacher of Opto-mechatronics at Eindhoven University of Technology (TU/e), Eindhoven (NL).
Hans Vermeulen is part-time professor of Mechatronic System Design at TU/e and senior principal architect EUV Optics System at ASML, located in Veldhoven (NL).

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Production mechanisation

The Dutch school of design principles for mechanical precision engineering originated in production mechanisation at Philips, where in 1949 Wim van der Hoek (Figure 1) started working after having studied mechanical engineering at Delft University of Technology. In the 1950s and 1960s, production mechanisation generally concerned machines for assembling discrete products, such as electron tubes or semiconductor components, often with feeding, positioning and fixing processes, requiring accuracies of 1 micrometer or better at speeds of 2,000 to 3,000 products per hour. To gain a competitive advantage, better control was needed to improve positioning accuracies and increase production speed.

It prompted Van der Hoek, who was appointed part-time professor of Design and Construction at Eindhoven University of Technology in 1961, to focus on the dynamic behaviour of cam mechanisms. Through his work, he gained insight in the disastrous effect of backlash in a machine on the accuracy of movement and positioning, all under the dominant limitation of a mechanism's natural frequency (the first eigenfrequency). It helped him to predict the contribution of dynamics to positioning errors in a mechanism. It also resulted in qualitative and quantitative insight into the mechanical design measures that had to be taken to control these positioning errors. 'Stiffness' instead of 'strength' became the leading design paradigm.

The Devil's Picture Book

Van der Hoek included all this in his lecture notes, titled "Predicting Dynamic Behaviour and Positioning Accuracy

In 2020, DSPE published a book (in Dutch) about Wim van der Hoek, covering his career at Philips and Eindhoven University of Technology, his breakthrough ideas on achieving positioning accuracy and control of dynamic behaviour in mechanisms and machines, and their reception and diffusion. See also page 52 ff.

of constructions and mechanisms" (*Het voorspellen van Dynamisch Gedrag en Positionerings-nauwkeurigheid van constructies en mechanismen*). In addition, he started to collect examples of good and bad practices in precision engineering and included them in "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP). These cases were primarily intended as an invitation to engineers to consider their work in terms of design principles and, if possible, improve upon their designs.

The first topic in DDP was realising lightweight structures with high stiffness in order to raise the eigen-frequency of mechanisms in fast-moving machines; the second was avoiding backlash. The collection was soon extended to other topics: elastic elements, degrees of freedom, manipulation and adjustment, friction and hysteresis, guiding belts and wires, and energy management. Table 1 gives an overview of the design principles for accuracy and repeatability, the foundations for which were laid by Wim van der Hoek, and their evolution.

Evolution

In the last decades of the previous century, the design of mechatronic devices and machines such as CD players and lithography machines had raised the bar. To meet their challenging specifications, thermal effects had to be addressed more extensively and new design concepts introduced, such as:

- 'virtual' servo stiffness, to achieve good servo performance through high-bandwidth motion control;
- 'zero' stiffness, to eliminate disturbances due to contact with the (vibrating) environment via force actuators;
- dual stage, comprising an accurate short-stroke stage carried by a course long-stroke stage; and
- mass balancing, to filter out reaction forces to frames.

Driven by Moore's Law, mechatronic design rose to new levels of sophistication in the 21st century. This urged the design community to question established design principles, such as minimisation of hysteresis. The demand for ever-higher control bandwidths could no longer be fulfilled only by lightweight and stiff design. Therefore, passive damping,

Table 1
Overview of the design principles for accuracy and repeatability, as of ~1970, and their evolution, as of ~2000 (in green) and ~2010 (in red).

	Design principle	Implementation
1	Kinematic design	• Exact constraints • Mechanical decoupling via flexures and elastic hinges
2	Design for stiffness	• Structural loops with high static stiffness and favourable dynamic stiffness
3	Lightweight design	• Design for low mass and high eigenfrequencies
4	Design for damping	• Energy dissipation that slows down motion without introducing position uncertainty
5	Design for symmetry	• Symmetry in geometry and external loads • Over-actuation
6	Design for low friction and hysteresis	• Minimisation of friction and virtual play in high-precision structures, connections and guideways
7	Design for low sensitivity	• Thermal centre and thermal (compensation) loops with high stability • Low-expansion materials • Isolation of disturbances, e.g. via isolated metrology loop • Offset minimisation, e.g. Abbe principle and Bryan principle, and drive-offset minimisation relative to the centre of mass • High-bandwidth feedback control
8	Design for stability	• Minimisation of heat dissipation and microslip in interfaces • Minimisation of material creep and drift
9	Design for load compensation	• Weight compensation, reaction force compensation and (parasitic) stiffness compensation • Position-dependency compensation
10	Design for minimal complexity	• Balancing and hence minimisation of complexity and related cost via a multidisciplinary system approach

USING TRANSMISSION RATIOS AND MODE SHAPES FOR OPTIMISING PASSIVE DAMPING

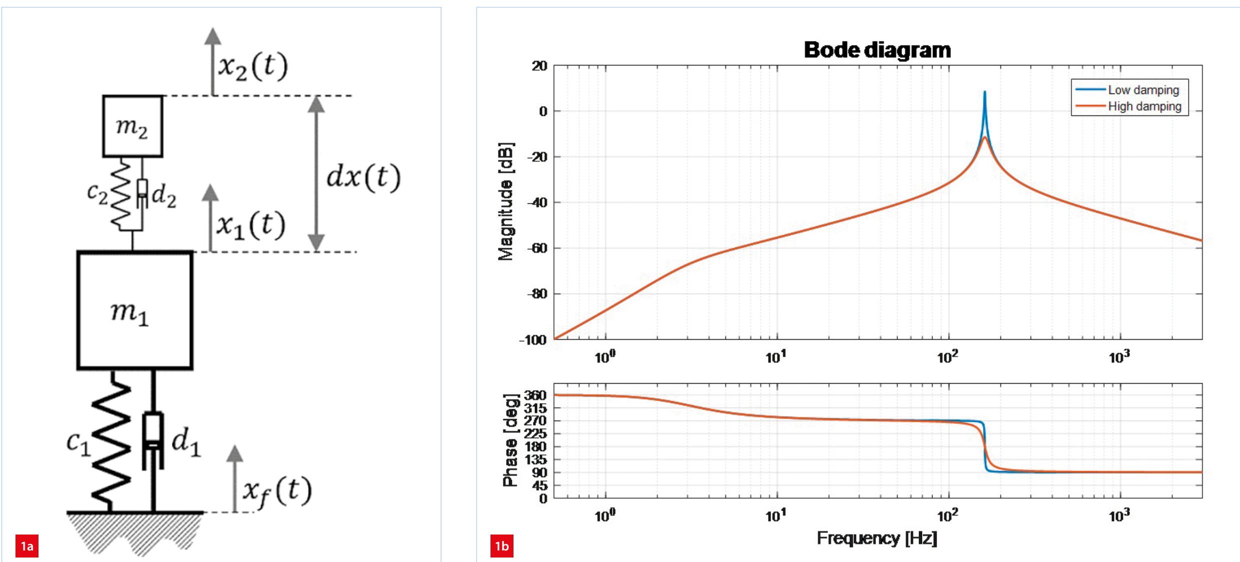
A broad range of mechanical engineering techniques, from smart design principles to advanced motion control, is available for achieving dynamic performance. Somewhere in the mix, however, the field of passive damping is often overlooked. This article attempts to extend the understanding of mechanical engineers towards thinking in terms of dynamics and mode shapes. To that end, analogies between stiffness and modal mass in terms of transmission ratios and their effect on system performance are presented. This may provide insight, not only for where to place passive dampers, but also more generally into how a control system 'feels' the different vibration modes.

KEES VERBAAN

Introduction

The precision machine building community finds itself continuously facing new challenges in terms of requirements for dynamic performance. Precision machines have become faster and more accurate over time and this trend has not stopped, and will not stop in the future, as far as we can look. A large range of mechanical engineering techniques is available for achieving dynamic performance, ranging from sophisticated mechanical design principles – such as statically determined design – to complex and intelligent control and software solutions, such as advanced motion control and feedforward solutions. Somewhere in between these topics, and often stepped over, is the field of passive damping.

Passive damping has been studied since approximately the 1960s [1], but for many years was not usually applied in precision machine designs. This is in contrast to many other fields, such as structural engineering and aerospace engineering, where passive dampers have been integrated into designs for many decades, to counteract disturbances from wind, traffic, earthquakes, etc. and effectively limit the resulting deformation – and thereby, stress – in these



The effect of damping on machine dynamics.
(a) Dynamic model with dx(t) as point of interest (POI), which is the relative displacement output between mass 1 and mass 2.
(b) The Bode diagram shows the transmissibility from floor vibrations to this POI: $dx(t)/x_f(t)$.
The difference in damping value is visible at the resonance frequency around 160 Hz.

AUTHOR'S NOTE

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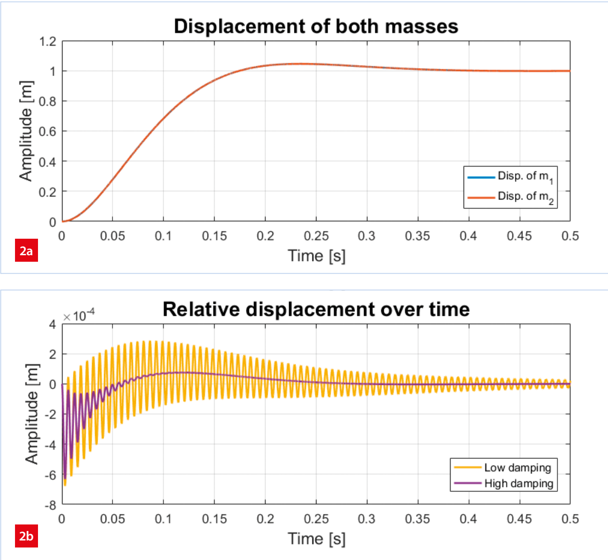

Responses of the system of Figure 1.
(a) Displacement of masses 1 and 2.
(b) Relative displacement between the two masses, at low and high damping values for the resonance at 160 Hz.

structures. The cause of this relatively late application of damping in the field of precision engineering seems to have a relation to the required accuracy of the high-tech systems involved. Accuracy, but primarily repeatability and reproducibility, need to be high, in contrast with the structures in other engineering fields that used damping much earlier. For these structures, mainly deflection was important, which relates directly to stress and safety factors. In the field of precision engineering, however, this is significantly different, as the focus lies on design for stiffness, low hysteresis, low friction, etc.
Over the last two decades, slowly but steadily, damping has been adopted in the field of precision engineering, enabled by improved computational power and ease of dynamic modelling. Material models have become more accurate [2], and experience has been gained in how to apply these materials in precision designs, as well as in dealing with the results in terms of system characteristics. Currently, this has resulted in multiple passive damper solutions in the field of precision machine design, even to being implemented in sub-nanometer precision machines.

The effect of damping

To zoom in on the topic of damping, we will divide precision machines into two categories, the first being fast machines that move quickly and need short settling times. These machines are typically limited in their performance by the high-frequency dynamics, which restricts the bandwidth of the feedback control loop and introduces transient oscillations in the settling phase (after the accelerations have ended). The second category includes machines that require good standstill performance.

In this case, the flexible dynamics is also problematic, as it is typically excited by various vibration sources, such as floor vibrations, acoustics, noise from electronics, etc.

In both cases, passive damping can help improve performance by adding damping to the flexible dynamics. For the first category of machines, this leads to short settle times, because the kinetic energy is dissipated more quickly. For the second category (standstill performance), higher damping values lead to less amplification of the oscillations at resonance frequencies, resulting in smaller steady-state vibration amplitudes.

As an example, Figure 1 presents a dynamic model of a machine. The input is – for simplicity – a random floor displacement spectrum (white noise), and the output is the relative displacement at the point of interest (POI), which is the position difference between the two masses ($dx(t)$ = relative output). The transmissibility from floor displacement to relative displacement at the POI is given in Figure 1b, which clearly shows the effects of the vibration isolation characteristics at 3 Hz and the internal dynamics at 160 Hz. The blue curve shows the transmissibility for low modal damping on the flexible dynamics, the red curve for a tenfold increase of the modal damping. The result is a lower amplification factor (a lower resonance peak).

Figure 2 shows a step response of the two masses of Figure 1a in the upper plot and the relative displacement in the lower plot. When the modal damping of the resonance at 160 Hz is changed, the upper plot hardly changes, because its characteristics originate mainly from the isolation system at 3 Hz. However, the lower plot shows a significant difference in settling time. Figure 2b shows the effect of this damping increase, at the resonance at 160 Hz, on the POI and in the time domain. The increased decay rate of the oscillation is clearly visible.

Note that this difference in vibration amplitude is caused by the increased damping of the internal dynamics only. In addition, for motion-control systems it is the increase of damping at resonance frequencies that enables higher bandwidths (open-loop cross-over frequency at 0 dB). As damping is increased, the resonance peaks are attenuated (see Figure 1b) and higher feedback gains can be applied with equal stability margins.

Increasing natural frequencies first

The field of passive damping adds a tool to the mechanical designer's toolbox. Once a mechanical design has been created according to the rules of precision engineering to maximise stiffness and minimise moving mass (i.e. maximise natural frequencies), damping can help to further improve performance.