DECREASING STIFFNESS AT THE COST OF EMERGING HYSTERESIS

Minimising power dissipation is critical for applications in cryogenic environments. Experimental results show that the guiding stiffness, and with that the associated motor-current-induced dissipation, of a voice-coil-actuated positioning stage can be significantly decreased using a stiffness-compensation mechanism, as demonstrated by JPE. However, as expected, the contribution of hysteresis from the compensation mechanism becomes noticeable in the force-displacement graph.

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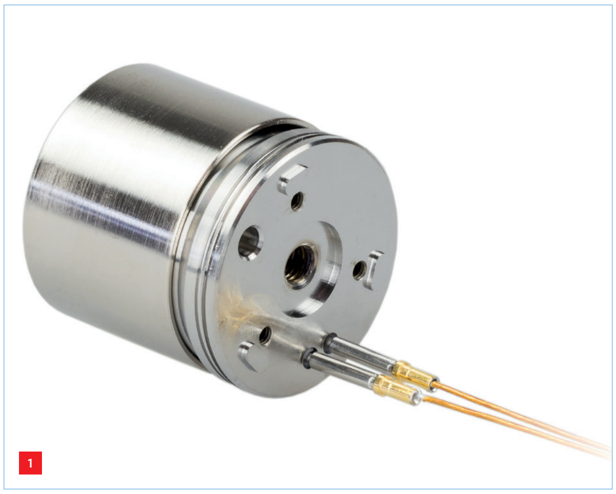
Dissipation under cryogenic conditions

Cryogenic environments are becoming more relevant for high-tech applications and state-of-the-art scientific research. At cryogenic temperatures, generally below 120 K, the motion of particles is inhibited and 'permanent' gases begin to liquify. Additionally, various material properties change substantially under cryogenic temperatures.

Since a cryogenic environment is typically achieved in a vacuum (or even an ultra-high vacuum, UHV), cooling is performed by conductive heat transfer. For most materials, thermal conductivity decreases with decreasing temperature, which makes it more difficult to continue cooling the materials further down. Therefore, achieving a cryogenic environment is a slow process, which is highly sensitive to power dissipation as well. Hence, it is important to consider the thermal behaviour of the system and minimise dissipation for temperature stability during the experiment.

A more beneficial change in material properties is the decrease of electrical resistivity, which is quite significant for some materials, such as copper. This change results in an increased efficiency of Lorentz-force-based actuators. JPE has developed a UHV- and cryo-compatible voice-coil actuator (Figure 1) that is optimised for efficiency while minimising dissipation. The actuator constant, which is given as the generated force per unit of dissipation, is increased from 2.07 $NW^{-1/2}$ in ambient to 58.2 $NW^{-1/2}$ at 10 K, which is an improvement of almost a factor 30. Although these actuator properties seem very beneficial for cryogenic temperatures, the eventual application must be considered carefully.

In positioning applications, it is important to consider the load that the actuator must carry. For example, a vertical positioning application would require the actuator to carry the weight in full, and thus a continuous power dissipation is required to maintain the neutral position. Therefore,




1 The CVCA, a UHV- and cryo-compatible voice-coil actuator developed by JPE.

AUTHOR'S NOTE

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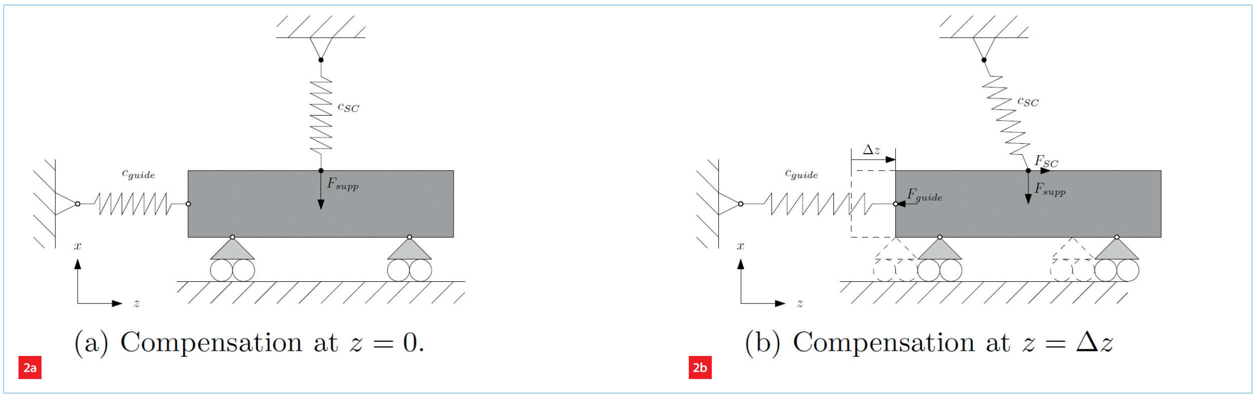


Schematic representation of the stiffness-compensation principle.
(a) At $z = 0$, only a parasitic force F_{supp} is generated.
(b) Under displacement of the moving body, a compensation force F_{SC} is generated in the guiding direction.

a weight-compensation mechanism may be crucial to prevent unacceptable power dissipation and maintain the desired cryogenic conditions.

Furthermore, demanding positioning applications typically integrate a flexure-based guidance mechanism, which introduces a significant guiding stiffness. Therefore, the actuator has to continuously deliver a force proportional to the guiding stiffness in order to maintain its position, other than the neutral position. The larger the stroke of the mechanism, the higher these forces become, which possibly need to be maintained for relatively long durations. A stiffness-compensation (SC) mechanism is able to improve the performance of such a positioning system and minimise the power dissipation.

To summarise, although the efficiency of a voice-coil actuator increases substantially under decreasing temperatures, it is important to minimise power dissipation of an accurate positioning system in order to reach and maintain cryogenic temperatures. This article elaborates upon a stiffness-compensation mechanism that is incorporated in a 1-DoF (degree-of-freedom) voice-coil-actuated positioning stage designed for cryogenic conditions. The stage contains a linear guidance mechanism based on two parallel leaf-springs and is mainly flexure-based. Additionally, a cryo-compatible resistive linear sensor developed by JPE is integrated in the system for closed-loop positioning.

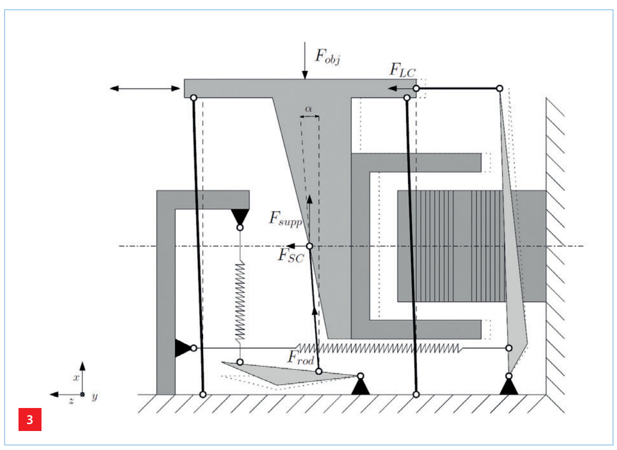
Stiffness compensation

The stiffness-compensation principle used in the positioning stage is schematically depicted in Figure 2. The addition of a compressed spring mounted on the moving body basically introduces a negative stiffness, which results in a lowered effective guiding stiffness. The stiffness-compensation force F_{SC} in the $z = 0$ position is zero, since the stiffness-compensation spring is perpendicular to the guiding direction. However, when the moving body is displaced, the added spring will generate a force F_{SC} in the guiding direction, depending on the rotation of the spring α with respect to the vertical axis and its preload force F_{rod}, following $F_{SC} = \sin(\alpha) \cdot F_{rod}$.

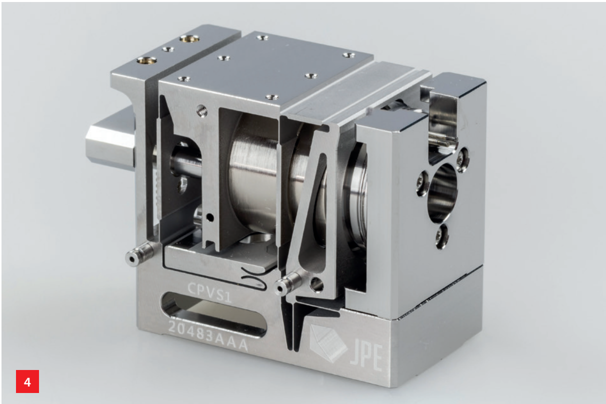
This stiffness-compensation principle has been integrated in the positioning stage by means of a knife-edge bearing and a lever connected to an adjustable spring, which can be used to adjust the preload force F_{rod} and therewith the amount of negative stiffness. To prevent instability, the effective stiffness must be greater than zero, which is the limiting factor for the adjustment. Figure 3 shows a schematic representation of the positioning stage with the parallel leafspring guidance, voice-coil actuator and stiffness-compensation mechanism.

Efficiency improvement and hysteresis

Experiments conducted on the realised positioning stage prove its functionality and show that the stiffness due to the compensation has become approximately a factor 16 smaller. Thus, the force necessary to achieve the full stroke



Schematic representation of the positioning stage under displacement, showing the (vertical) parallel leafsprings, voice-coil actuator (on the right) and stiffness-compensation mechanism. The force F_{rod} is introduced via a (vertical) pressure bar (rod) connected to a knife-edge bearing (bottom centre). F_{LC} can compensate constant loads, for example a mass in vertical motion (in the case that this stage has been rotated over 90°), and is not further discussed here.



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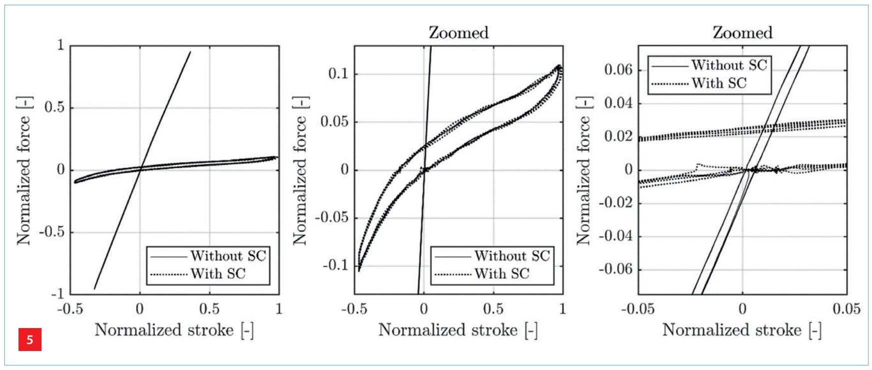
Positioning stage as realised by JPE, in agreement with the schematic of Figure 3.



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The normalised force-displacement curve of the positioning stage without and with stiffness compensation (SC), showing a significant decrease in effective stiffness due to the stiffness compensation. Zoomed windows are shown in the middle and on the right.

(which here amounts to 5 mm) is only 1/16th, or 6%, of that in a system without stiffness compensation, and the power dissipation of the system is reduced by 16^2, to only 0.4% of the non-compensated situation.

Of course, due to the low drive force, hysteresis plays, relatively speaking, a more significant role in the system. The frictional components in the positioning system, in this case the resistive position sensor and the knife-edge bearing, cause hysteresis in the system, which can distinctly be observed in the force-displacement curve shown in Figure 5.

The force-displacement relation is therefore also depending on the previous stage position and its direction of motion. It is observed that for the uncompensated case, without the knife-edge bearing, the amount of hysteresis is not that much different from the compensated case. However, in the compensated case the relative contribution of the static friction is substantially increased. The positioning system follows almost the textbook hysteresis curve in clockwise direction, showing the practical consequences of the phenomenon.

Conclusion

It is important to minimise power dissipation for applications under cryogenic conditions in order to maintain stable and low temperatures. Although the efficiency of a voice-coil actuator significantly increases for decreasing temperatures, the relevance of guiding stiffness has been addressed for positioning applications. A stiffness-compensation mechanism that is integrated in a voice-coil-actuated positioning stage designed for cryogenic conditions has been elaborated and experimental results show the achievable improvement. However, these results also expose the increased relevance of hysteresis.