

# A PIVOTAL TECHNOLOGY

Scanning mirrors are widely used in optical systems to direct reflected light. Existing products such as galvanometers and resonant scanners are intended for accurate positioning at a low-frequency range and for fast scanning at a specified high frequency, respectively. However, when a wide frequency range is involved, these devices may not be able to fulfil the requirements. In this project, carried out at Hittech Multin, a novel solution was proposed, by tuning the resonant frequency of a scanning mirror and exciting higher-order modes to cover a wide frequency range of 500 Hz to 5 kHz. A test set-up has been developed, of which the results demonstrate that this frequency range can be covered, with a scanning angle range of 1 mrad for the reflected beam.

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## Introduction

A scanning mirror is an important device in many optical systems for changing the direction of the beam in a scheduled manner [1]. It is widely used in applications for optical communications, material processing, microscopy, etc. [2, 3]. A conventional scanner usually has a galvanometric configuration with a closed-loop control system such that it can achieve the desired angles with high accuracy and resolution [4]. However, when operating at high frequency, high driving power is often needed, which means high energy consumption. Furthermore, due to a large rotational moment of inertia and nonlinear effects at high scanning speed, especially outside the control bandwidth, distortion of the output can be expected [5, 6].

## Resonance

To achieve stable high-frequency scanning, a resonant scanner can be used. This has distinguishing features such as high stiffness, low mass and high  $Q$ -factor [7]. By making use of resonance, it is easy to achieve high-frequency oscillation with low power input and a simple electrical circuit [8]. However, most of these resonant scanning mirrors are designed to operate at the specified frequency. In some applications, such as live-cell imaging and high-resolution imaging in a scanning microscope, both high-frequency scanning (at a few kHz) and low-frequency scanning (at a few hundred Hz) are required [9]. Therefore, resonance should be used to achieve a high frequency, and tuning to cover a certain frequency range.

For generating mechanical resonance, mechanisms can contain elastic elements to provide a certain stiffness. One example is a resonant scanner in a clamped-free cantilever beam configuration, where a mirror is mounted at the tip, orthogonally to the axial direction [10]. But the scanning motion does not have a fixed rotational axis. Resonant scanning can be achieved by a torsional beam, with the rotational axis at the twist axis [11, 12]. In a resonant scanning device with a crossed-flexure configuration, the

resonance can be generated by the crossed flexure itself [13]. A crossed flexure can also be used as a guiding, where the resonance is provided by an extra torsional resonator [14]. Even the rotational axis of the crossed flexure can shift during scanning, but this is rather negligible for small deflections [13].

All of these resonant scanners, however, are not tuneable, which means that they can only be operated at one intended resonant frequency. Some designers have attempted to make the resonant frequency adjustable, but this was only intended for error correction in a small range, in order to cope with manufacturing errors, mechanical wear, change of working conditions, etc. [15].

## Application background

In the application of a scanning microscope system, a scanning mirror is needed. The basic principle is shown in Figure 1. A biological sample marked by a fluorescent substance is placed on a sample plate. On top of that, there are multiple scanning electron beams, each of which can

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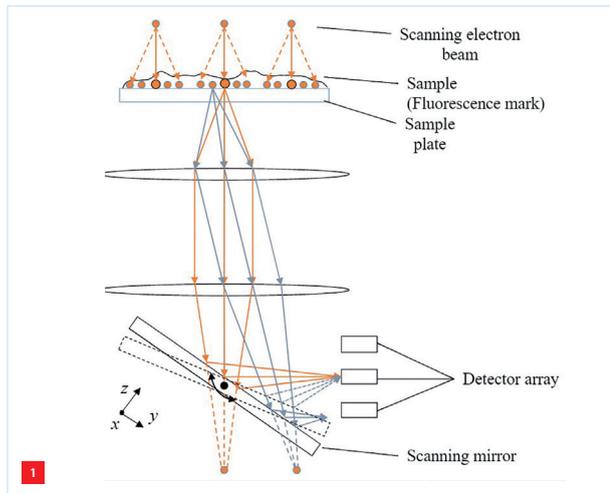
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## Hittech Group

Hittech Group is a first-tier system supplier in mechatronics and optomechatronics. Within the framework of its technology programme, Hittech carries out research on laser scanning. In the quest for new technologies, Hittech defined a research project together with the Opto-mechatronics research group at Delft University of Technology. This concerned the development of a tuneable resonant scanning mirror, as described in this article. The project was carried out at Hittech Multin, a system supplier that combines development, value engineering, supply chain management and assembly.

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Basic system principle and application background of a tuneable resonant scanning mirror.

scan its corresponding region. Once an electron beam hits the sample, fluorescent light is generated, captured by an optical system and focused on the corresponding detector in the detector array. It can be seen that the scanning motion of the electron beam modifies the optical beam path (from the orange one to the grey one), and therefore the mirror should rotate to compensate for this beam motion such that the focal point will always remain fixed at each of the detectors during scanning. To be able to achieve both high-resolution scanning and live-cell imaging, a wide frequency range needs to be covered.

#### Objectives and design requirements

- Frequency range: the resonant frequency of the scanner can be tuned in the range of 500 Hz to 5 kHz.
- Range of motion: the reflected beam is able to scan an angle in the range of 0-1 mrad; note that this means 0-0.5 mrad for the rotation  $R_x$  of the mirror.
- Beam size: the scanning mirror is able to cope with a beam size of 11 mm in diameter.
- Size: the device fits within 70 mm × 70 mm × 150 mm.

Note: no specific requirements on accuracy and resolution were set at the start of this ‘proof of concept’ project. These will be addressed in a subsequent control design phase.

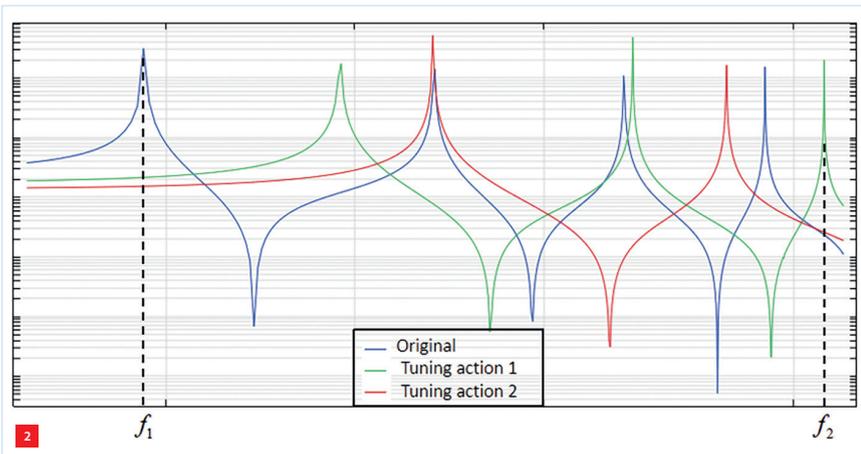
No literature has been found about resonant frequency tuneable devices for such a wide range in macroscale applications. Here, a flexure-based mechanism is presented that meets all the above criteria, as well as a new way of tuning the resonant frequency for a wide range. The end application of this device is to be integrated into a scanning microscope system (Figure 1).

## Design and analysis

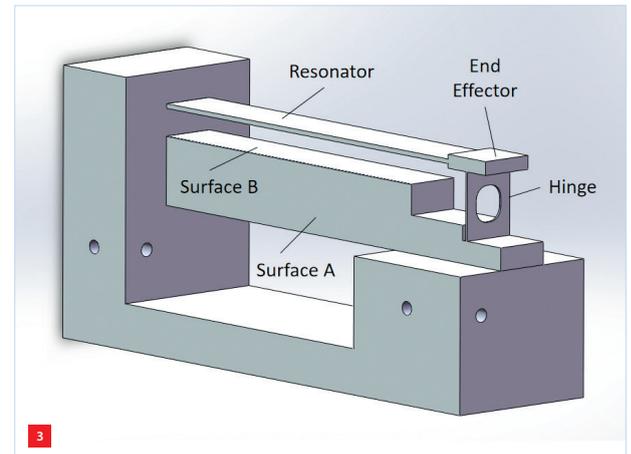
### Concept

The desired frequency range is an order of magnitude (i.e., a factor of ten), which corresponds to two orders of magnitude change in the stiffness if the mass is unchanged. This is quite difficult when only one resonance mode is considered. Therefore, the basic concept to cover a wide frequency range is to combine the tuning action with exciting higher-order modes. Figure 2 shows a non-specific example of frequency tuning for a given range between  $f_1$  and  $f_2$ . By applying the tuning action, the system response curve shifts from the original one (blue) to the right. It can be seen that the second and third peaks of the green curve have passed the third and fourth peak of the blue curve, and that the first peak of the red curve is coincident with the second peak of the blue curve. Therefore, the entire intended frequency range,  $f_1$  to  $f_2$ , can be covered from the original curve to tuning action 2.

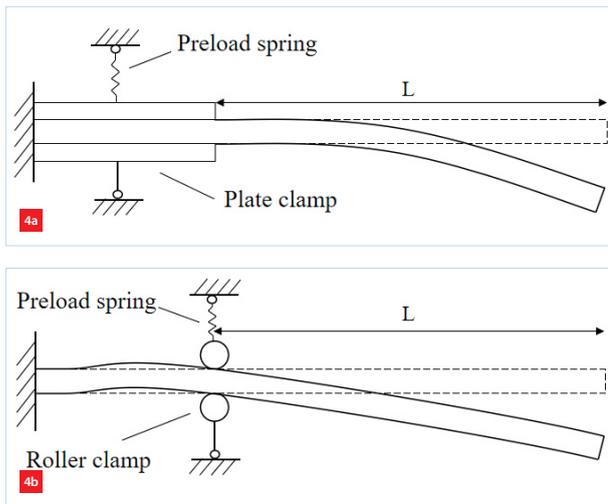
The design of a tuneable resonant scanner consists of two parts, a resonant scanner to provide one rotational degree of freedom (DoF) in resonant motion, and a frequency-tuning mechanism. The resonator inside the scanner mechanism is a cantilever beam, and the tuning action changes its effective length by clamping at different positions.



Concept of using higher-order modes for wide-frequency tuning.



Design of the resonant scanner mechanism.



Schematic of a cantilever with clamping.  
 (a) Plate clamping.  
 (b) Roller clamping.

**Resonant scanner mechanism**

To achieve 1-DoF resonant scanning, use can be made of guiding mechanisms that have one rotational DoF, such as a crossed flexure or a notch flexure that has low rotational stiffness and high stiffness in other DoFs, while resonance is provided by a separate ‘resonant actuator’. However, based on the resonator configuration and chosen tuning method, this design scheme may lead to a complicated mechanism. Alternatively, the cantilever can be treated as a leafspring that constrains three DoFs, and a mechanism can be synthesised using the freedom and constraint topology (FACT) method [16, 17]. The mechanism is then equivalent to a clamped-hinged cantilever.

The proposed design model is shown in Figure 3, where the hinge is a leafspring. A cut at its middle decreases its mass and hence further increases its first eigenfrequency, so that it will not interfere with the resonance motion of the

cantilever. At the same time, this can reduce the rotational stiffness of the hinge guiding (and hence the required actuator force) as well as reduce the over-constraining effect of the entire mechanism; both effects are beneficial. The cantilever beam resonator is designed with dimensions of 12 mm × 1 mm × 90 mm such that the eigenfrequencies of the 1<sup>st</sup> to 4<sup>th</sup> bending modes are close to or remain in the range between 500 Hz and 5 kHz.

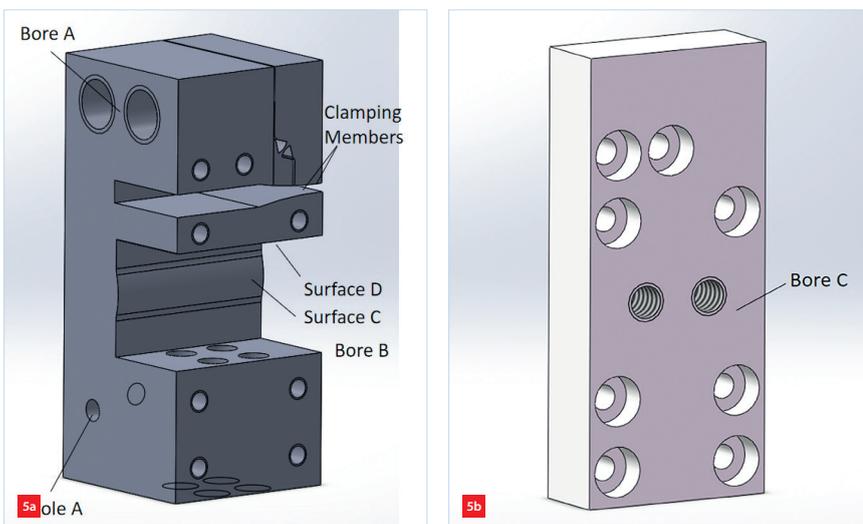
**Frequency-tuning mechanism**

To change the effective length of a cantilever, two clamping members can be used to clamp at different locations of the cantilever, with one fixed and the other preloaded by a spring; if the reaction force at the clamping position is less than the preload force, clamping members will stay in position. To make sure the clamping will function well, Hertzian contact must be considered as well; it is preferable to have a high Hertzian contact stress (< yield stress of the material), as it gives low-hysteresis clamping [18] and high contact stiffness. This means a small contact area with a high preload force will be favourable, and a large radius of curvature if a curved surface is involved. In this sense, using a clamping plate (Figure 4a) is intuitive to predict because the effective length  $L$  is well defined as the distance between the clamping end and the end effector, but this may lead to unwanted microslip. Clamping with a Hertzian line contact (Figure 4b) will be more suitable; a standard roller bearing can produce a line contact, but this will require tight tolerances in assembly. Furthermore, a large radius of curvature can lead to a bulky device.

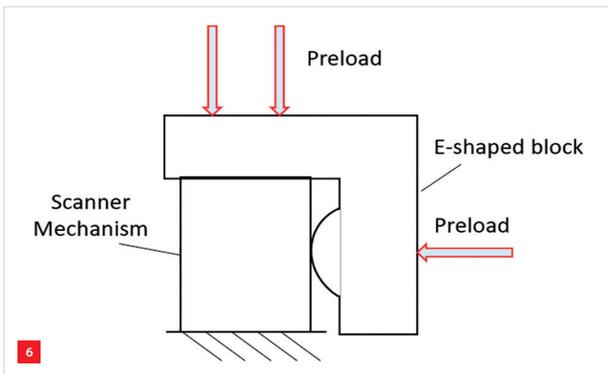
The proposed design has two parts, the first one being an E-shaped block, as shown in Figure 5a. It comprises two clamping curved surfaces with a large radius of curvature, provided with a diamond-like carbon (DLC) coating to enable sliding. A preload of clamping is applied by two springs (bore A) through a notch flexure, which is oriented in accordance with the direction of the reaction force. Between the second and third arm of the ‘E’, there is a curved surface C, which will be in contact with the plane surface A at the side of the scanner mechanism, whereas the plane surface D will be in contact with the surface B. In this way, these surface contacts constrain five DoFs of the E-shaped block, with a preload from the bottom (bore B) and side (bore C) to keep the block in position. This configuration is exactly constrained, as shown in Figure 6. After tuning, the block is locked by a flexible strut through hole A. It is therefore mounted in a statically determined manner. The second part, shown in Figure 5b, is designed to close the E-shaped block and strengthen it.

**Finite-element modelling**

The design has been analysed using finite-element modelling, with aluminium alloy 7075 T6 selected as material. A mirror



Clamping design.  
 (a) E-shaped block.  
 (b) Closing unit.



Exactly constrained contact configuration between scanner mechanism and E-shaped block, for defining the clamping position.

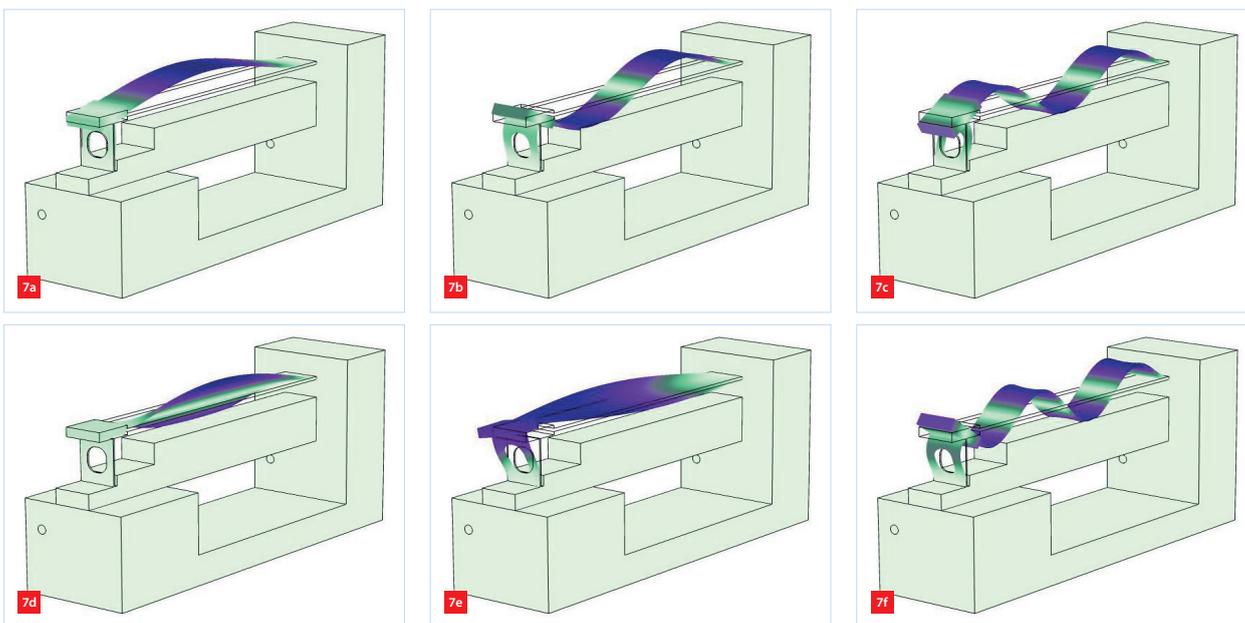
is placed at the end effector, with fused silica as material and dimensions of 10 mm diameter and 2 mm height. Modal behaviour and dynamic performance have been simulated. The first six eigenmodes of the scanner are shown as Figure 7, where Figures 7a, 7b, 7c and 7f show the 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup> bending mode of the resonator, respectively. It can be seen that there are other unwanted modes, which are a torsional mode (Figure 7d) and a transverse mode (Figure 7e). Therefore, it is important to eliminate modal coupling so that the scanning motion can be relatively pure. It will be difficult to eliminate the transverse mode and torsional mode (and their higher-order modes) of a cantilever in the range of 500 Hz to 5 kHz while its bending modes are in this range, especially when starting the tuning of the bending modes, when other unwanted modes will be tuned as well. To avoid modal coupling, modal behaviour with respect to the clamping position has been studied by modal analysis (the cantilever resonator has a length of 90 mm).

Figure 8 shows an estimation of the modal behaviour of the bending and unwanted modes. It can be seen that by moving the clamping block to around 45 mm, all four bending modes can connect or overlap with their higher ones. Drops of the eigenfrequency occur in some particular ranges of the clamping position, due to the elastic mode of the beam between the clamping block and the base, of which the eigenfrequency decreases with increasing length, as realised by moving the clamping block further from the base. These regions can hardly cause any amplitude at the end effector, and therefore should be avoided.

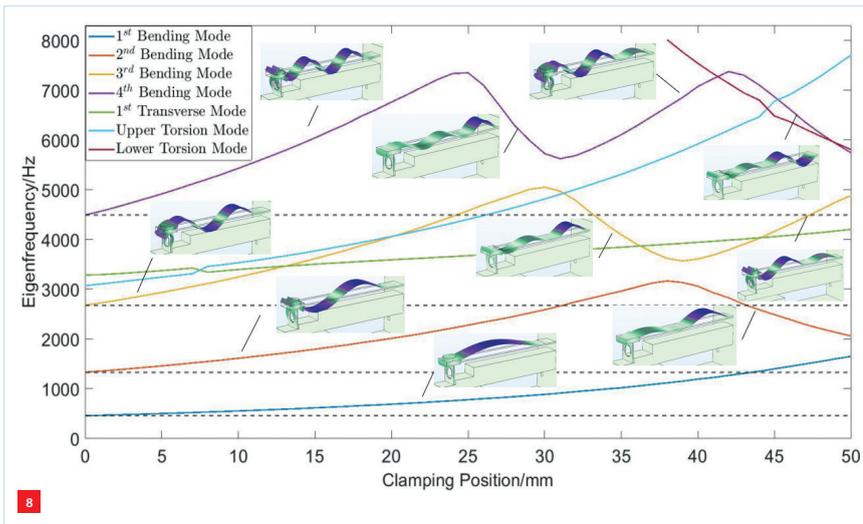
The 1<sup>st</sup> transverse and the upper torsional mode (between the end effector and the clamp) start from around 3,000 Hz, and couple into the 3<sup>rd</sup> bending mode at a clamping position of around 13 mm and 20 mm, respectively, as denoted by intersecting lines in Figure 8. When the clamping block is near 45 mm (halfway the cantilever), the lower torsional mode (between the clamping block and the base) starts to appear close to the working frequency range. At this clamping position, coupling between the transverse and the 3<sup>rd</sup> bending mode is seen again. It is therefore necessary to be aware that modal coupling between bending and unwanted modes will take place in the range between 3 and 4 kHz, and larger input power can be expected, since unwanted modes will consume energy. To minimise this coupling, accurate alignment of the actuator should be realised such that the force acts at the centre line in the bending direction. In addition, to ensure that the resonance generates a scanning amplitude, only regions with positive slope could be considered as usable ones.

### Test set-up

The scanner mechanism and E-shaped block of the frequency-tuning mechanism have been monolithically



Vibrational modeshapes at the first six eigenfrequencies.  
 (a) 457.61 Hz. (b) 1,321.5 Hz. (c) 2,638.7 Hz.  
 (d) 2,993.6 Hz. (e) 3,195.6 Hz. (f) 4,413.3 Hz.



Modal behaviour with respect to clamping position.

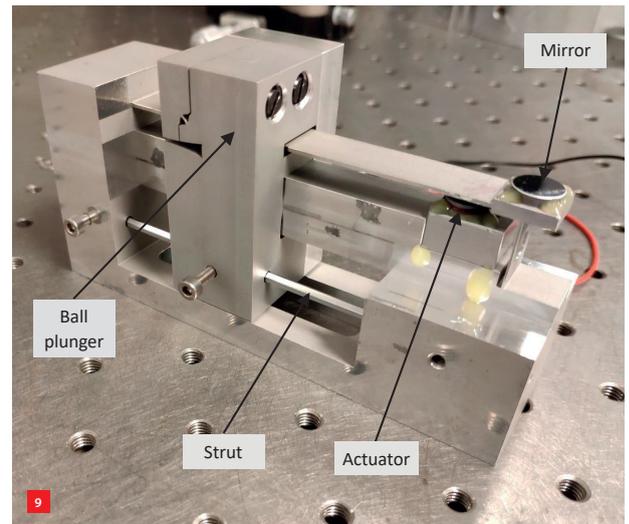
machined by spark erosion. The assembled system is shown in Figure 9. A mirror is glued to the end-effector stage, and a magnet is glued to the bottom side of the resonator beam. A coil is aligned underneath according to the magnet position. Preload is applied by a ball plunger; its tip is a ball connected to a spring, and the outside is threaded. After tuning, a strut is used with screws perpendicularly tightened in order to lock the frequency tuning mechanism.

To measure the scanning angle, a power meter is placed at a distance  $L$  away from the mirror, and a knife-edge is placed in front of the power meter to block part of the reflected light beam. During the scanning, the displacement  $d$  of the reflected beam spot at the power meter is obtained from the detected power change, and the scanning angle is calculated as  $R_x = d/(2L)$ .

During the measurement, firstly, a chirp signal is applied to locate the resonant frequencies. The frequency response function is measured from actuator current (input) to scanning angle (output), and then normalised by the first peak at the 0-mm clamping position. Secondly, an excitation is applied at resonance such that the scanning angle is equal to 0.5 mrad, and the corresponding amplitude is used to locate frequencies with half that gain to determine the  $Q$ -factor, which is calculated as  $Q = f_r/\Delta f$ , where  $f_r$  is the resonant frequency and  $\Delta f$  the difference between the two frequencies corresponding to half the gain at resonance. Then, the clamping position is changed and the two steps are repeated.

### Results and discussion

Figure 10 shows the frequency response within the 500 Hz to 5 kHz range at clamping positions of 0 mm, 9 mm, 26 mm, 31 mm and 49.15 mm (maximum stroke) from the base; the gain is normalised by the gain of the first peak at the 0-mm clamping position. This is the 1<sup>st</sup> bending mode of the resonator beam itself. At 0-mm clamping, the



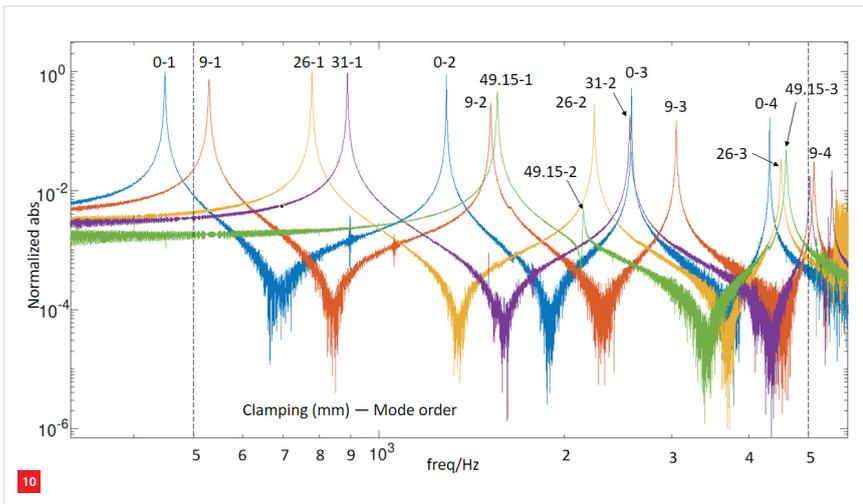
The scanner and test set-up, showing the mirror, the ball plunger, the strut and the electromagnetic actuator (magnet plus coil).

measured current for a 1-mrad angular movement of the reflected beam at modes 1 to 4 is around 20 mA, 24 mA, 64 mA and 224 mA, peak-to-peak, respectively. For various (practical) reasons, not all modes at the other clamping positions could be measured.

It can be seen that the frequency range of 500 Hz to 5 kHz can be covered by moving the frequency-tuning mechanism within its range. At around 26 mm, 31 mm and 46 mm clamping position, the 3<sup>rd</sup>, 2<sup>nd</sup> and 1<sup>st</sup> bending mode can connect to the 4<sup>th</sup>, 3<sup>rd</sup> and 2<sup>nd</sup> bending mode of the resonator beam itself, respectively, and at the 9-mm clamping position, the 4<sup>th</sup> bending mode is at 5,102.3 Hz.

The measured  $Q$ -factor stays within the range of around 200 to 500, but no clear regular pattern (for example, a decay with increasing mode order) can be found. It can be pointed out that starting from the 2<sup>nd</sup> peak of the resonator itself, amplitudes of the frequency response drop by a certain negative slope, and this may be partly due to the cut-off frequency of the actuator, because of the limited accuracy and a relatively large gap between the coil and the magnet that remained after hand alignment. An improvement can be achieved by adding an iron core inside the coil to strengthen the magnetic field and reduce the magnetic reluctance, while the air gap between the magnet and the coil can be reduced by a more sophisticated alignment.

Figure 11 compares measurement (circular dot) and simulation (line) of the resonant frequencies of the bending modes 1 to 4. At the 0-mm clamping position, the measured resonant frequency of the first four bending modes is 448.8, 1,288.8, 2,577.6 and 4,324.1 Hz, respectively, with an error (difference between measured and simulated value) of 1.93%, 2.47%, 2.32% and 2.02%, respectively. This error is mainly due to manufacturing tolerances. With manual

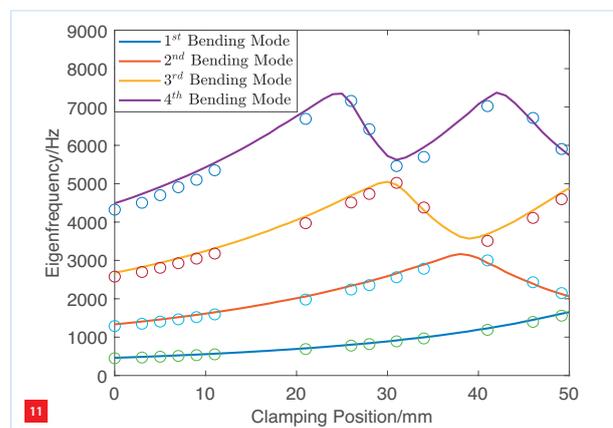


Normalized current-to-angle frequency responses at several clamping positions in the range of 500 Hz to 5 kHz. Gain normalised to the first peak at 0 mm clamping. The numbers at each peak indicate the clamping position (0, 9, 26, 31 and 49.15; all in mm) and the mode order (1, 2, 3, 4).

positioning of the frequency-tuning mechanism, a clamping position accuracy of 50  $\mu\text{m}$  can be achieved. Regarding the error, this can be bounded within 5%.

### Conclusion

A flexure mechanism design of a tuneable resonant scanning mirror has been presented. The scanner mechanism contains a bending cantilever as resonator and a cut-leafspring as hinge guiding to provide one rotational DoF. The tuning method is to change the effective length of the resonator beam, and this is realised by two clamping surfaces with a large radius of curvature, one of which is fixated and the other is preloaded. This provides a large contact stiffness and low hysteresis clamping. Sliding is enabled by DLC coating and therefore the clamping position can easily be changed. A novel tuning concept has been proposed, based on exciting higher-order modes of the resonator, so that the scanner can achieve resonant motion over a wide frequency range.



Comparison between the measurement (circular dots) and simulation (curve) resonant frequencies with respect to the clamping position.

Finite-element analysis has demonstrated that by clamping from 0 mm to around halfway the cantilever, the first four bending modes can cover the intended frequency range of 500 Hz to 5 kHz. However, it is necessary to be aware that some frequency regions exhibit modal coupling or hardly generate a scanning amplitude.

The design has been realised in hardware. The performance, as specified by the requirements above, has been verified by measurement on a prototype:

- Frequency range: 500 Hz to 5 kHz, achieved by moving the frequency-tuning mechanism from 0 mm to around 46 mm from the base.
- Range of motion: 1 mrad scanning angle, although at high frequency a relatively large current amplitude is needed, which is partly due to the cut-off frequency of the actuator.
- Beam size: end effector of 12 mm  $\times$  12 mm, on which a mirror with 12 mm diameter is placed.
- Size: 127 mm  $\times$  35 mm  $\times$  68.9 mm.

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