



- 1- The force feedback control can achieve higher band width and therefore the PI integral time constant  $\tau_p$  should be tuned to maintain the high bandwidth of the system
- 2- The presence of the force sensor and the internal force feedback loop makes the stage stiffer. This should be taken into consideration when tuning the PI controller which requires higher proportional gain  $k_p$  than the case of a similar stage without a force feedback sensor. However, increasing the proportional gain will magnify the impact of the sensor noise on the response of the system. Generally speaking, increasing the proportional gain  $k_p$  will reduce the rise time at the expense of increased noise amplification, oscillations and overshoot.

### 3. Results

The tuning procedure described in the previous section was demonstrated on a Queensgate NPS-X-15A stage. The stage is fitted with an internal force sensor and the control structure is implemented using the hardware controller NPC-D-5110 from Queensgate. The command signal was applied and the response is measured using the Nanobench software.

The identified open loop frequency response of the stage is shown in Figure 2. The resonance frequency occurs in the range  $(2-3) \times 10^4$  rad/s. The tuning criteria used are maximum bandwidth with no oscillation. The achieved parameters for this tuning are listed in Table 1.

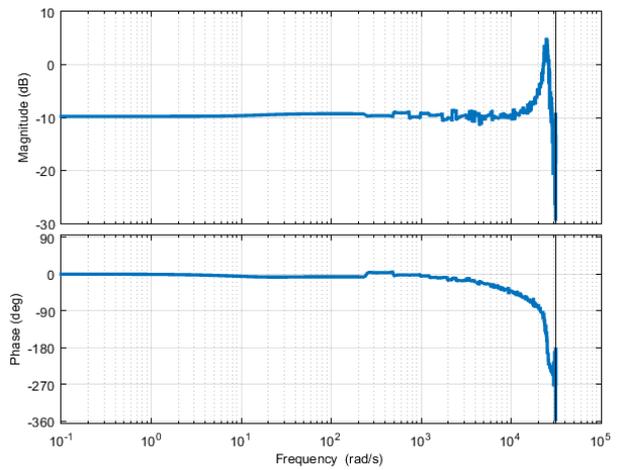
In order to demonstrate the robustness of the system under load variations, the stage was loaded with 800 g mass under the same tuned controllers. Figure 3 depicts the frequency response of the closed loop system for both cases, the nominal case with no load and with 800 g load.

### 5. Conclusion

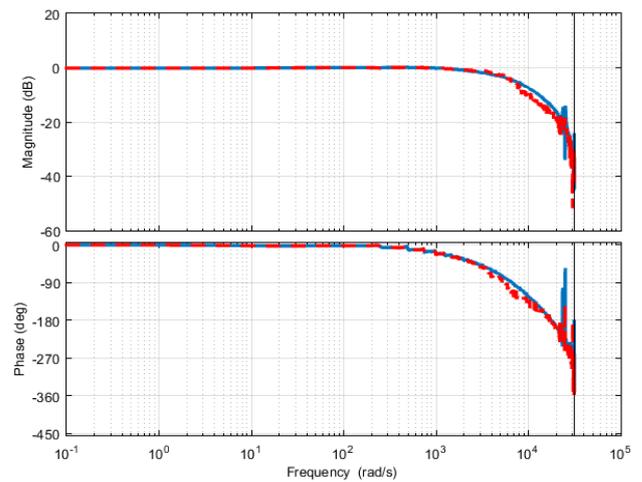
Dual sensor technology has been introduced as an effective control solution to achieve accurate, robust and fast nanopositioning stages. However, to exploit the advantages of this technology, the configuration requires careful tuning and implementation. This paper gives a brief introduction to practical aspects of the tuning and implementation of a specific structure of force feedback control for single axis nanopositioning stages to achieve satisfactory performance.

**Table 1:** Control parameters tuning

Parameter	Value	Parameter	value
$\tau_p$	$4 \times 10^{-4}$	$k_f$	1
$k_p$	1	$k_u$	0.1503
		$\tau_f$	$9 \times 10^{-5}$



**Figure 2:** Identified open loop frequency response from the input  $u$  to the displacement  $p$ .



**Figure 3:** Closed loop frequency response with force feedback control: the nominal case with no load (solid blue line) and the case of 800 g load (dashed red line).

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