PREDICTION AND IMPROVEMENT
OF THE MAXIMUM ACHIEVABLE DAMPING
WITH COLLOCATED CONTROL

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Abstract

Active damping can be realised robustly through the use of a position actuator, a collocated force sensor, and control based on 'Integral Force Feedback' (IFF). Instead of a pure integrator, it is also possible to use a first-order lowpass-filter in the feedback loop ('leaking IFF'). For both cases, the maximum achievable relative damping for a certain vibration mode can easily be predicted. If the achievable damping is too low, it is possible to improve this by means of 'crosstalk-compensation'. A close look at these strategies reveals that there is a one-to-one relation between 'leaking IFF' and 'crosstalk-compensation'. The presented theory is verified by means of active damping experiments within the lens support of a wafer stepper.

INTRODUCTION

High-precision machines typically suffer from small but persistent vibrations. As it is difficult to damp these vibrations by passive means, research at the Drebbel Institute at the University of Twente is aimed at the development of an *active structural element* that can be used for vibration control (Holterman, 2002). The active structural element, popularly referred to as 'Smart Disc', is based on a piezoelectric position actuator and a piezoelectric force sensor.

   One of the main problems in active control is to ensure stability. In this respect it is often advantageous to consider the use of so-called *collocated* actuator-sensor-pairs, as this enables to actively implement a passive control law, which is robustly

stable, irrespective of structural modelling errors. Within the context of vibration control for lightly damped structures, collocated actuator-sensor-pairs are known to be well suited to achieve robust active damping (Preumont, 1997). The Smart Disc concept, based on a position actuator and a collocated force sensor, as such may be used to provide robust active damping within high-precision machines.

The Smart Disc concept is schematically depicted in Fig. 1. The Smart Disc itself can be modelled as a stiffness element k_s in series with a position actuator, embedded in a general mechanical structure $P(s)$. The elastic force that is present in the piezoelectric material is measured (F_{sens}), and fed to the Smart Disc controller $C(s)$, which in turn should generate a desired position for the actuator (x_{act}), so as to damp the measured vibrations.

In order to achieve robust active damping, the only model knowledge that is needed, is the fact that the position actuator and the force sensor are collocated. By 'collocation' we mean that the associated signals for the actuator and the sensor are 'power-conjugated': the product of the actuated *velocity* and the measured compressive *force* represents the *power* that flows from the controller to the mechanical structure. This implies that, if we impose a linear relation between the measured force F_{sens} and the actuated velocity v_{act} (in Fig. 1: $H(s) = K_{IFF}$), we are effectively implementing a viscous damper (valued K_{IFF}^{-1}) in series with k_s. It is easily seen that this behavior is achieved by incorporating an integrator in the feedback loop $C(s)$:

$$C(s) = \frac{x_{act}(s)}{-F_{sens}(s)} = \frac{K_{IFF}}{s} \quad \rightarrow \quad x_{act}(s) = -\frac{K_{IFF}}{s} F_{sens}(s) \quad \rightarrow \quad v_{act}(s) = -K_{IFF} F_{sens}(s) \quad (1)$$

This active damping strategy is referred to as *Integral Force Feedback* (IFF; Preumont *et al*., 1992; Preumont, 1997).

Paper organisation

In this paper we will first show the results of active damping experiments, obtained by applying IFF to Smart Discs that have been embedded in the lens suspension of a wafer stepper, a high-precision machine that is used for Integrated Circuit manufacturing. Subsequently, we will discuss two modifications of the basic IFF control law presented above: 'leaking IFF' and 'crosstalk-compensation'. The effect of these two modifications on the

Figure 1 Illustration of power dissipation based on Integral Force Feedback within the Smart Disc

maximum achievable damping will be explained, and illustrated by experimental results. The paper is concluded by a comparison between the two modifications.
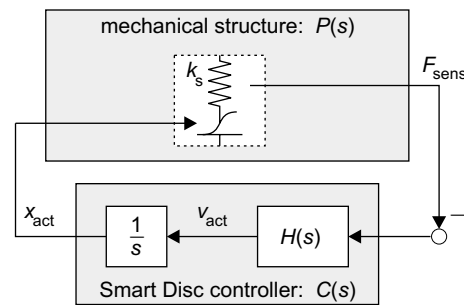
WAFER STEPPER LENS VIBRATIONS

As an example of an industrial high-precision machine, in this paper we will consider the *wafer stepper*, which is at the heart of Integrated Circuit (IC) manufacturing. It is used to transfer a circuit pattern from a photomask to a thin slice of silicon (the *wafer*), from which the ICs are cut out in the end. The circuit pattern is projected onto the wafer through a carefully constructed lens, which is in fact a complex system of lenses (Fig. 2). The most important variable to control in the IC manufacturing process is the line width of the circuitry on the wafer, as this width has direct impact on the IC speed and performance. The current IC line width is about 0.1 μm.

One of the bottlenecks in decreasing the line width may in future be caused by badly damped micro-vibrations of the lens of the wafer stepper. Up till now, micro-vibration problems within high-precision machines could often be relieved by means of adequate *isolation* of equipment from the floor, through which most of the disturbing vibrations enter. However, once the equipment is sufficiently isolated from the floor, an other disturbance source becomes dominant: acoustics. It is practically impossible to come up with isolation means for acoustic vibrations. *Damping* of the lens vibrations by passive treatments has also turned out to be practically impossible. The wafer stepper thus constitutes a challenging test-bed for evaluation of the active damping potential of the Smart Disc concept (Holterman and De Vries, 2003).

In order to have a close look at the troublesome lens vibrations in the wafer stepper, Fig. 3 schematically depicts the parts of the wafer stepper that are important to us. Besides the lens, this figure shows the main-plate, which serves as a positional reference for all other parts of the machine. The main-plate is resiliently isolated from the floor, both passively and actively, by means of so-called airmounts. The lens is held in a flange, which is connected to the main-plate by means of three symmetrically located lens support blocks, only two of which are in sight in Fig. 3.

The lens support blocks are 'simple' steel blocks, equipped with flexure hinges, designed as much as possible according to kinematic design principles, in order to prevent the position of the lens being overconstrained. As a consequence, the overall stiffness of the lens suspension, and the related resonance frequencies of the machine, can not be increased infinitely. Rather than further increasing the *stiffness* of the lens suspension, it has been tried to actively increase the *damping* by incorporating Smart Disc functionality within the lens support blocks (Holterman, 2002).
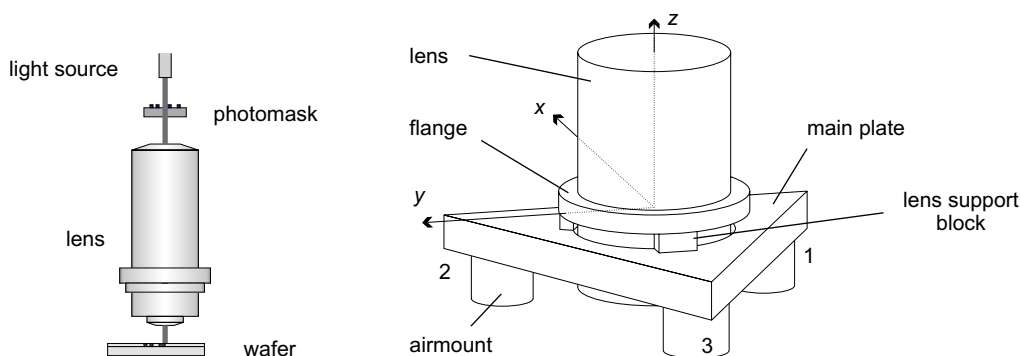

Figure 2 Wafer stepper principle   *Figure 3 Schematic view on wafer stepper*

The experimental results shown in Fig. 4 serve as an illustration of the vibration problems in the wafer stepper, and the positive effect of active damping. For these experiments, the airmounts of the wafer stepper have been used to apply controllable 'disturbance' forces upon the main-plate. For the excitation signal, band-limited white noise has been chosen. The acceleration at the top of the lens has been measured, and is shown in the upper plot of Fig. 4 (grey: Smart Discs off; black: Smart Discs on). The Power Spectral Density (PSD) and the cumulative PSD for these signals are shown in the middle and the lower plot of Fig. 4.

From the grey curves in the PSD plots it can be seen that the acceleration at the lens-top is mainly due to badly damped vibration modes around 70 and 110 Hz. From modal analysis that has been performed on the experimental set-up, it is known that these modes correspond to movement of the lens relative to the main-plate. From the black curves in the PSD plots it can be seen that these vibration modes are damped very well by the Smart Discs in the lens support blocks.

SMART DISC CONTROLLER DESIGN

Whereas in the previous section we have pointed out the positive effect of active damping, in this section we will take a look at some interesting issues in controller design within the Smart Disc concept. Starting point for controller design is the open-loop Smart Disc frequency response (refer Fig. 1):

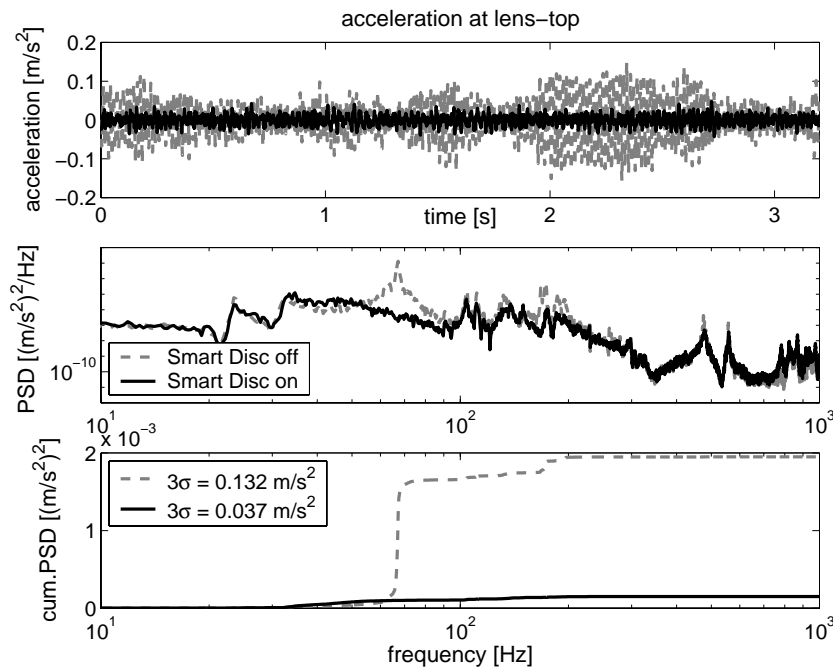$$P(j\omega) = \frac{F_{\text{sens}}(j\omega)}{x_{\text{act}}(j\omega)} \tag{2}$$

Figure 4 Active damping results in wafer stepper lens suspension

Due to the collocation in the Smart Disc concept, this frequency response is characterised by an alternating pattern of resonances and anti-resonances. Fig. 5 shows an example of the Smart Disc frequency response for a structure with two vibration modes. The corresponding pole-zero-pattern is shown in Fig. 6. In this figure also the root-locus is drawn that results upon the application of IFF (the extra pole in the origin represents the integrator in the feedback loop). All braches of the root-locus are drawn into the left half of the *s*-plane, which implies that all resonances are damped (Preumont, 1997).

In Fig. 6 the location of the closed-loop poles is shown for two values of the feedback gain: $K_{IFF} = \beta$, indicated by the triangles, and $K_{IFF} = 3\beta$, indicated by the stars. It can be seen that initially, up to a certain level, a higher feedback gain yields higher damping. Beyond this level, the closed-loop poles tend to move towards the open-loop zeros on the imaginary axis, and damping decreases again.

Maximum relative damping for pure IFF

Preumont and Achkire (1997) have derived a simple formula for predicting the maximum relative damping that can be achieved by means of Integral Force Feedback, under the assumption that the Smart Disc frequency response $P(j\omega)$ is dominated by a single vibration mode. In that case the open-loop transfer function of the mechanical structure in series with the IFF-controller can be denoted by:

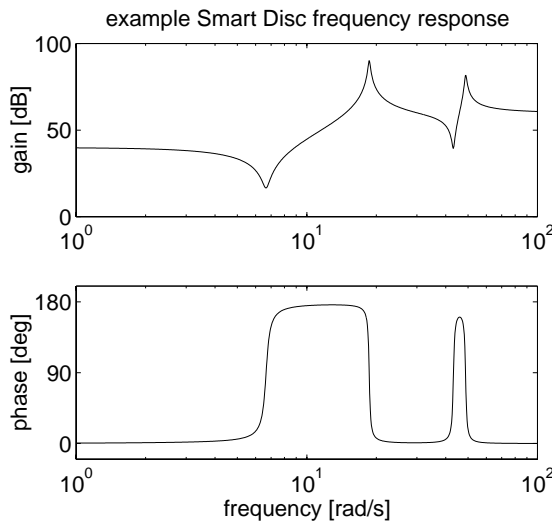$$C(s)P(s) = K_{ol} \frac{s^2 + \omega_a^2}{s(s^2 + \omega_e^2)} \qquad (3)$$

with:

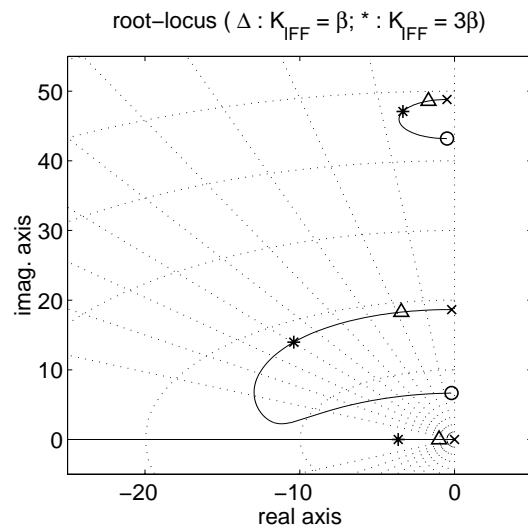*Figure 5 Example of a Smart Disc frequency response*

Figure 6 Example of a root-locus upon application of Integral Force Feedback

- w_e: the resonance frequency of the dominant vibration mode;
- w_a: the dominant anti-resonance frequency ($w_a < w_e$), which can be shown to correspond to the dominant resonance frequency of the mechanical structure if the Smart Disc were removed from the structure (Preumont, 1997);
- K_{ol}: the overall open-loop gain, i.e., the product of the feedback gain K_{IFF} and the high-frequency level of the Smart Disc response $P(jw)$.

The maximum achievable relative damping for this single-mode case then is given by (for $w_a > \frac{1}{3} w_e$):

$$z_{max} = \frac{w_e - w_a}{2 w_a} \tag{4}$$

This simple formula can conveniently be used in Smart Disc controller design.

Leaking Integral Force Feedback

Preumont (1997) advises not to implement a pure integrator in the feedback loop, "...because it would lead to saturation. A forgetting factor can be introduced by slightly moving the pole of the compensator from the origin to the negative real axis. This does not affect the general shape of the root-locus and prevents saturarion." The integrator in the control law (eq. 1) then changes into a first-order low-pass filter:

$$C(s) = \frac{x_{act}(s)}{-F_{sens}(s)} = \frac{K_{IFF}}{s + p_{IFF}} \tag{5}$$

This is referred to as 'leaking Integral Force Feedback' (Holterman, 2002).

Though the general shape of the root-locus is not affected by this change, the value of p_{IFF} should not be increased too much, because this leads to a decrease of the maximum achievable damping (Holterman, 2002). This phenomenon has also been observed during the Smart Disc experiments within the wafer stepper. Fig. 7a shows the effect of an increasing value of p_{IFF} on the cumulative PSD of the acceleration at the lens-top (zoomed in at the frequency range from 0 to 100 Hz). For an increasing value of p_{IFF}, the curve around 50 Hz turns steeper, which indicates that the damping of the vibration modes decreases considerably.

In order to account for the non-zero controller pole in the prediction of the maximum achievable relative damping (eq. 4), Scholten (2002) has performed a simulation study, from which the following formula has been deduced (for $p_{IFF} \ll w_a$ and $w_a > \frac{1}{3} w_e$):

$$z_{max} \approx \left(1 - \frac{p_{IFF}}{w_a}\right)\left(\frac{w_e - w_a}{2 w_a}\right) \tag{6}$$

Just like eq. (4), the above formula can conveniently be used for Smart Disc control.

Due to the fact that the above 'prediction formulas' hold for a structure with a single dominant vibration mode, and the wafer stepper set-up is characterised by many more interfering vibration modes, this formula could not be verified quantitatively in practice.

Improvement of the maximum relative damping

From eqs. (4) and (6) it is obvious that, in order for a Smart Disc to add considerable active damping to a mechanical structure, ω_a should be sufficiently small, or equivalently, the low-frequency level of the Smart Disc response should be sufficiently low. The low-frequency level, referred to as 'crosstalk' between actuator and sensor, can be lowered artificially by performing so-called *crosstalk-compensation*, according to (Holterman, 2002):

$$F_{\text{fb}}(t) = F_{\text{sens}}(t) + k_{\text{cc}} x_{\text{act}}(t) \tag{7}$$

and subsequently performing (leaking) Integral Force Feedback from F_{fb} (the new force signal that is available for feedback) to x_{act}.

Rather than an explanation of the details involved in crosstalk-compensation, we present in this paper some results that have been obtained for the Smart Disc experiments within the wafer stepper. Fig. 7b shows the cumulative PSD of the acceleration at the lens-top, for two levels of crosstalk-compensation ('half' and 'full') compared to a situation without crosstalk-compensation. From these results, it can be seen that crosstalk-compensation indeed allows for higher damping. (Note: these experimental results may not be compared directly with the results in Fig. 7a because the settings for the airmount-noise had accidently been changed.)

Crosstalk-compensation versus leaking Integral Force Feedback

Though Figs. 7a and 7b may not be directly compared, they look rather similar: an increasing value of p_{IFF} *raises* the cumulative PSD, whereas an increasing (negative) value of k_{cc} *lowers* the cumulative PSD. For that reason we conclude this paper by
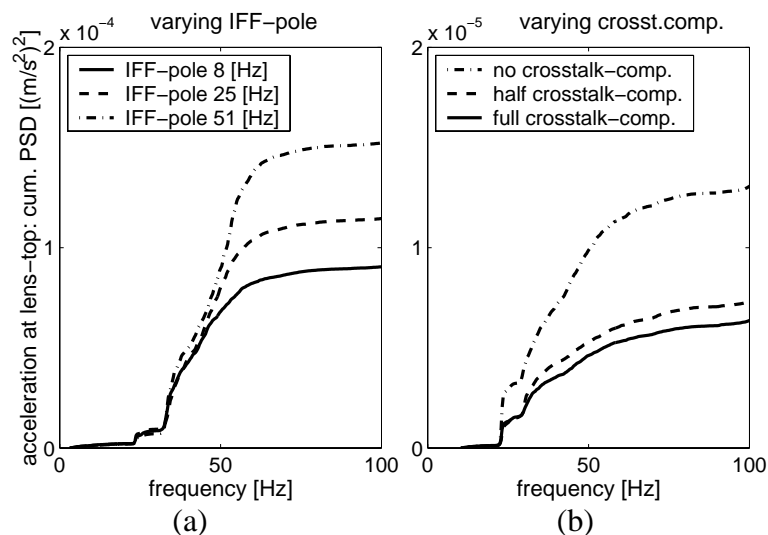

Figure 7 Cumulative PSD plots for the measured acceleration at the lens-top for various values of (a) the IFF-pole and (b) the level of crosstalk-compensation

taking a closer look at the actual feedback controller that has been realised. Combining eqs. (5) and (7) gives:

$$x_{\text{act}} = -\frac{K_{\text{IFF}}}{s + p_{\text{IFF}}} F_{\text{fb}} = -\frac{K_{\text{IFF}}}{s + p_{\text{IFF}}} \left(F_{\text{sens}} + k_{\text{cc}} x_{\text{act}} \right)$$

$$\rightarrow \quad \left(s + p_{\text{IFF}} \right) x_{\text{act}} + K_{\text{IFF}} k_{\text{cc}} x_{\text{act}} = -K_{\text{IFF}} F_{\text{sens}} \quad \rightarrow \quad \frac{x_{\text{act}}}{F_{\text{sens}}}(s) = -\frac{K_{\text{IFF}}}{s + p_{\text{IFF}} + K_{\text{IFF}} k_{\text{cc}}} \tag{8}$$

The latter equation clearly illustrates that there exists a one-to-one relation between the amount of crosstalk-compensation and the value of p_{IFF}. Moreover, the actual controller pole that is implemented is given by $p_{\text{IFF}}^* = p_{\text{IFF}} + K_{\text{IFF}} k_{\text{cc}}$.

Examination of the values for p_{IFF}, K_{IFF} and k_{cc} during the wafer stepper experiments has revealed that, by performing crosstalk-compensation, we have actually implemented an open-loop unstable feedback controller ($p_{\text{IFF}}^* < 0$). This controller however performed very well, and did allow for the achievement of higher damping levels.

CONCLUSION

In this paper we have presented the results of active damping experiments on the lens suspension of a wafer stepper. Active damping has been realised by applying Integral Force Feedback (IFF) to active structural elements (so-called Smart Discs) that were embedded in the lens support blocks. Two modifications to the basic IFF control law have been presented: 'leaking IFF' and 'crosstalk-compensation', and it has been discussed how these modifications affect the maximum achievable relative damping. Moreover, it has been shown in this paper that there exists a one-to-one relation between the two modifications. The final conclusion is that in practice it may be beneficial to implement an unstable IFF-controller, in order to achieve high damping levels.

REFERENCES

J. Holterman, *Active Structural Elements for High-precision Machine Vibration Control*. (Ph.D. Thesis, Control Laboratory, University of Twente, Enschede, The Netherlands, 2002)

J. Holterman, T.J.A. De Vries, "Active damping within an advanced microlithography system using piezoelectric Smart Discs", (to appear in) Mechatronics (2003)

A. Preumont, *Vibration Control of Active Structures*, *An Introduction*. (Kluwer Acedemic Publishers, Dordrecht, The Netherlands, 1997)

A. Preumont, Y. Achkire, "Active Damping of Structures with Guy Cables", AIAA Journal of Guidance, Control and Dynamics, **20**(2), 320-326 (1997)

A. Preumont, J.P. Dufour, C. Malékian, "Active Damping by a Local Force Feedback with Piezoelectric Actuators", AIAA Journal of Guidance, Control and Dynamics, **15**(2), 390-395 (1992)

J.M. Scholten, *Practical applicability of "Preumont's formula"*. (Individual assignment report 018CE2002, Control Laboratory, University of Twente, Enschede, The Netherlands, 2002)