Experiences from FTF NanoScience Lab at the University of Lund: Use of a 2-stage isolation system with very low natural frequency

Claes R. Fredö[1*], Jonas Brunskog[1,2**]

Ingemansson Technology AB, Box 276, SE-40124 Gothenburg, Sweden[1]

Dept. of Engineering Acoustics, Lund University, Box 118, SE - 221 00 Lund, Sweden[2]

ABSTRACT

A new clean room facility is in progress at the Division of Solid State Physics / Nanometer Consortium (FTF) at Lund University. On site measurement from road excitation at a speed bump located at a distance of 25 m from the site and from main roads situated at a few hundred meters distance revealed high vibration levels. A complicating matter was found in high lateral vibration levels at the 2 Hz to 3 Hz range. Various set ups using piling and dig out were investigated and found not to improve the situation. A vibration isolation system with very low natural frequency was found to be the only way left to use the site. A modular set up has been used such that the system can be either 1-stage isolated or 2-stage isolated.

1. INTRODUCTION

A new clean room facility is in progress at the Division of Solid State Physics/ Nanometer Consortium (FTF) at Lund University. This facility is added to existing lab resources The lab layout was influenced by integration aspects with exiting facilities and the creation of an efficient work flow for activities across the lab, e.g. activities where access between the 1st and 2nd floor facilities is of importance. The lab is research, rather than production, oriented. The higher performance parts of the lab are costly to build and operate. The end users therefore wished to make high performance parts compact.

Large portions of the building consist from simpler types of floor isolation and lower grades of clean room performance (grade 10000). Two rooms are given high clean room performance (grade 100). These clean rooms are divided into two sections depending on the vibration sensitivity. This paper describes work that involves a UV litho lab section (8.5 by 4 m^2) with sensitive (VC-E) and an EBL lab (7 by 6.5 m^2) with highly sensitive equipment (designed towards machine requirements), Figure 1.

Lund university is located in the city of Lund, i.e. at an area with common suburban traffic. Initial measurements were made and identified road excitation from a nearby road bump and a main road situated at a few hundreds meters distance to be the major sources of excitation. Simple solutions like the removal of the speed bump or relocation to other sites were discarded by the project as these would inflict other, graver problems on project lead time and not guarantee satisfactory end performance in the long run. The decision was to build at the selected site and design towards current vibration exposure as long as a solution could be engineered within reasonable budget limits.

The initial design set up was to use piles and a dig out of the ground to anchor the building to the ground while suppressing surface waves. A geometric survey was made to investigate the soil properties of the site. The soil at the site is pre-glacial sea bed. Soil properties near the surface were found to resemble that of stiff rubber.

A FE model of the soil with the parts of the building was set up. However, simulation quickly showed that it was futile to use this approach as high lateral vibration arose at low frequency.

The high lateral vibration levels were unexpected, partly as the highest response was found in the lateral direction for a source applied in the vertical direction, partly as the worst effect response was found at low frequency (2 Hz to 3 Hz) and focused into lateral vibration along the line of sight from the source with ten times lower response in the other directions.

Initial measurement was made in the vertical direction only and a new set of measurements were therefore made to accept or reject the findings of the FE model. The new measured data did verify the simulated results which corroborated that the project truly did face a serious design problem for the site.

The approach used to forward the design was to re-design a vibration isolation set up that had successfully be used by Ingemansson for isolation of heavy main generators of an offshore oil and gas platform some years previously. This set up was made from a highly damped 2-stage isolation set up using air-spring isolators and a tilt and leveling control system.

The original plan called for system evaluation in June 2005, but the go ahead decision was delayed. However, construction of the FTF site is currently in progress and the lab is expected to be finished late in autumn 2005.

Figure 1. Site overview. Speed bumps are located on the road on the RHS of the figure at a distance of ~25 m from the site. The UV-litho lab will use a single 'sandwich' type slab suspended from four isolator supports. The EBL lab will use two ('split') slabs where both slabs are suspended from four supports using a 1-stage set up. One of the slabs will be used for the SEM machine and use a 1-stage isolation set up. The other slab is used for the E-beam machine and will use a 2-stage set up.

2. CLEANROOM VIBRATION CRITERIA AND ON-SITE VIBRATION

Vibration of the clean room slab surface was required not to exceed the VC-E criterion with the requirement extended down to 1 Hz for any of the labs, while the EBL was desired to meet the machine requirements. The on-site measured vibration and the vibration criteria are shown in Figure 2. The measurements were made on the ground surface using highly sensitive 500g accelerometers. Excitation was made by a loaded truck, cars and sledge with and without frozen top soil.

Comparison of the lateral (y-axis) vibration at ~4 Hz versus the machine criterion shows that isolation of (25/0.5 =) ~50 times, or ~34 dB is required for the lateral direction at low frequency. Evaluation at 3.15 Hz suggest 32 dB isolation, 10 Hz suggests 36 dB.

Similarly, for the machine requirement and the z-axis we receive the requirement (2.5/0.5=) 5 times, or 14 dB at 3.15 Hz, (20/0.5=) 40 or 32 dB at 10 Hz , and (30/1=) 30 times or 30 dB at 20 Hz.

Note that the machine requirement 0.5 μm/s from the 16 Hz third octave band and lower applies down to zero frequency.

Figure 2. The worst case envelope for on-site vibration, the VC-E limit, [1], and the machine criterion [2]. Velocity is stated in [m/s] and frequency in [Hz]. Data shown are third octave band values.

3. INITIAL CONSIDERATIONS

Before continuing, note that the dimensioning factor is vibration isolation in the lateral direction.

As a rule of thumb, a gain of 6 dB /Octave is achieved for single stage isolation. A requirements of 34 dB at 3 Hz isolation suggests the fundamental system resonance should be at $(4 \cdot 6/34 =)$ ~0.7 Hz or lower. Similarly, a system resonance of 0.56 Hz or lower is suggested to obtain 32 dB isolation at 3.15 Hz.

A few observations can be made from these estimates and the requirements listed in section 1.

☐ The only industrial grade spring system capable of such low frequency is air-springs with electronic tilt and level control.

☐ Coupling volumes must be added to have a natural frequency of 0.5 Hz or lower.

☐ Low natural frequency yields long reverberation time with high displacement amplitudes at resonance. The authors were therefore concerned to add system damping to shorten settling times and reduce magnification at resonance.

☐ The lateral spring stiffness is only weakly modified by additional volume. Therefore, the lateral direction isolation is dominant and governs the isolator selection.

☐ A well designed single stage isolation system tends to receive 30 dB to 40 dB isolation, so performance is going to be at the limit of what we may expect from a single stage system, in particular if damping is to be added.

☐ The frequency range 3-4 Hz is typical for fundamental building resonance. The performance of a single stage isolation system depends not only of the slab and the isolator stiffness, but also on the foundation stiffness. One must therefore be open to the idea of using a double stage isolation system to assure system performance as this leads to a safer design.

Adding damping to a vibration isolation system ruins much of its performance and, thusly makes system requirements even more extreme, i.e. the requirements on low natural frequency are strengthened. However, viewing the observations that are listed above shows that system performance can be made into the extreme at very little extra cost.

Coupling volumes can be made larger at very little extra cost. The primary impact of added volume is on the air-spring compression stiffness, i.e. on vertical (z-axis) and rotation (RX and RY) modes. The main concern is packaging of such volumes.

As a rule of thumb, a two stage isolation system yields 12 dB/Octave isolation. One may therefore analyze the system such that 6 dB/Octave is achieved between f_1 and f_2 and 12 dB/Octave is achieved at frequencies above f_2. An isolation of 32 dB and 3.15 Hz suggests the frequency f_2 to lie at ~1.2 Hz or lower.

An air-spring has a maximum lifting capacity. A part of this lifting capacity will be consumed by the weight of the intermediate mass of a two stage isolation system. The weight of the intermediate mass is

$$m \approx 4M \frac{f_1^2}{f_2^2} \ , \tag{1}$$

where M and m signify the system and intermediate mass weights, respectively, and f_1 and f_2 denote the system global and the intermediate local natural frequencies, respectively. Equation (1) shows that a low weight for the intermediate mass requires a small natural frequency ratio f_1/f_2.

A search for air-springs with documented and low lateral spring stiffness revealed ContiTech 751 N.10 that has a lateral stiffness of ~55 kN/m and a lift capacity of ~155 kN at 6 Bar (conventional air supply pressure). Examination of various set ups revealed four supports with intermediate mass, m, of ~5 ton and a system weight, M, of 40 ton to be a suitable compromise between performance and lifting capacity, thus suggesting a system natural frequency f_1 of .~0.12 Hz.

A quick check of the system mass and the lateral spring rates shows a lateral global system natural frequency, f_1, of 0.28 Hz which is higher than the required 0.12 Hz. However, a review of the analysis assumptions reveals firstly that analysis is approximate and does not cater for the effects of damping, that analysis assumes perfect (zero length) mathematical spring behavior, and that we ignore completely any effects from rotation inertia from the slab and intermediate components. This suggests that initial considerations for the air-springs has progressed as far as is sensible and that it is time to use numerical simulation with more degrees of freedom.

A system that is insensitive to external excitation receives increased sensitivity to internal excitation. Having decided on a highly isolated system, initiated a review of internal excitation sources. Newton's 2nd law of motion, dictate the sensitivity to internal excitation to be

$$(j\omega M)^{-1} \tag{2}$$

which for a 40 ton slab implies the sensitivity ~4/f μm/s/N, i.e. ~4 μm/s/N at 1 Hz, ~2 μm/s/N at 2 Hz etc. The sensitivity combined with the 0.5 μm/s machine criterion tells us that we can withstand only small dynamic loads in the order of 1/10 N.

Therefore, walking (a force in the order of 1 kN) will be made on a separately supported floor. The EBL and UV litho labs will have most of its equipment anchored to the building wall. There is a single machine in the UV litho lab that can disturb other equipment in some of its work phases, but such cross talk is planned to be handled simply by 'lab culture'. The EBL lab uses two machines, a SEM and a Raith 150 E-beam machine. The former is manually operated with cranks and levers, while the latter is maneuvered through the control of electronic stepper motors. It was expected that manual operation of the SEM machine would lead to dynamic loads well in excess of 1/10 N and, thus that cross talk between the machines could ruin performance. Another aspect is that the SEM machine tends to be operated with significantly shorter cycle time than is the case for the E-beam. The project decision was therefore to split the slab into two separate systems for the EBL lab. The installation thus was expanded from two to three isolated slab systems.

Other sources of internal excitation are wind pressure fluctuation from ventilation, which is handled by a rigid wind cover attached to the building structure that is located above the slab surface and a cover over the SEM and EBL machines. Infra sound may or may not be an issue and will be examined at system installation and, if needed be addressed with active noise control. Magnetic excitation was not considered to be an issue by the end users and is discarded from the discussion.

The overall system layout was governed by the installation floor height. The project decided to build the system from the installation flow and downwards. The air-springs and some of the coupling volumes are in a separate 'ditch' located below the slab. Access below the slabs is achieved via separate entrances from outside of the building. This set up is convenient as it enables system maintenance and fine tuning work without interference with the clean room, Figure **.

The whole system is protected by hard stops that will handle loads in the case of servicing, malfunction or unexpected loads. The hard stops will be actively used during the system buildup. The slabs will be built on and rest on the steel

columns that act as hard stops when the air-spring system becomes operational. Similarly, the intermediate masses will rest on its hard stops until the air-spring system is operational. The last installation step will be the damper links.

Before continuing, it can be observed that the vibration isolation set up appears to be as costly, or less costly than the originally anticipated piling set up.

4. DETAILED DESIGN

4.1. A conservative evaluation procedure

The evaluation procedure is made such that the transmissibility between slab and ground is computed at the top surface slab corners using the FE model. The highest transmissibility is extracted and combined with the highest measured vibration response for each direction.

This procedure is conservative partly because the transmissibility is the worst case, the vibration input represents the worst situation from several excitation cases and, partly because the vibration will be reduced once a building is erected at the site. In particular, vibration at 1 Hz and lower is expected to drop as the housing structure is expected to stiffen the ground in this frequency range.

4.2. The source and soil models

The excitation source was modeled both as a point and as line load at the location of the speed bump. Similar results were found for both source models and the point load was used in the project.

The soil was modeled as a circular disc for which the ends are provided with increased damping, Figure 3. The disc is 40 m high and displacement is blocked at edges and at the bottom to mimic the boundary condition provided by bedrock. The disc diameter was reduced with increasing frequency, thus keeping the number of elements constant for the model. Soil data was generated from a geophysical survey of the site [3] and the material data for various depths was input to the FE model. The shear modulus varies from 37 MPa (0 m) to 126 MPa (9 m) and 1000 MPa (11 m) and Poisson's ratio is 0.49, i.e. material properties resemble those of stiff rubber (lower values) and plastics (higher values). Both layered (as indicated by the geophysical data) and homogenous soil models were tested. Analysis is made using direct frequency analysis.

a)   b)
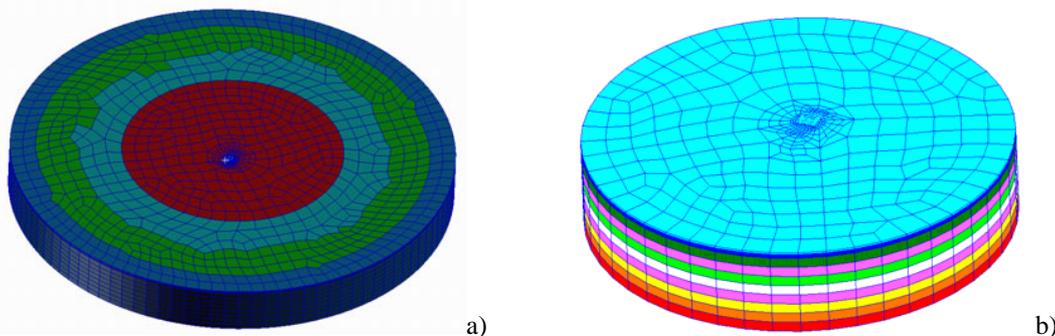
Figure 3. .Model details. A) Material zones. Damping is increased to 25%, 50% and 100%, respectively in the three outer layers. B) Inner material zone and layers of varying soil properties..

4.3. The slabs

All slabs have a height of 700 mm. The UV Litho lab has an area of ~9 m by ~4 m of sandwich type, Figure 4. The cavities inside of the slab will be used to house coupling volumes for the upper air-springs. .

As mentioned above, the EBL lab is split into two solid slabs of the dimensions ~6 m by ~3.4 m. The work reported herein uses a solid concrete slab for the EBL lab, but these slabs have later been converted into sandwich type slabs to contain coupling volumes for the upper air-springs.

The 1st flexible natural frequency of the EBL lab solid slab was analyzed to be at ~60 Hz and the UV Litho lab sandwich slab natural frequency is at ~30 Hz. The slab systems are considered to have sufficient stiffness for the task.

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b)

c)
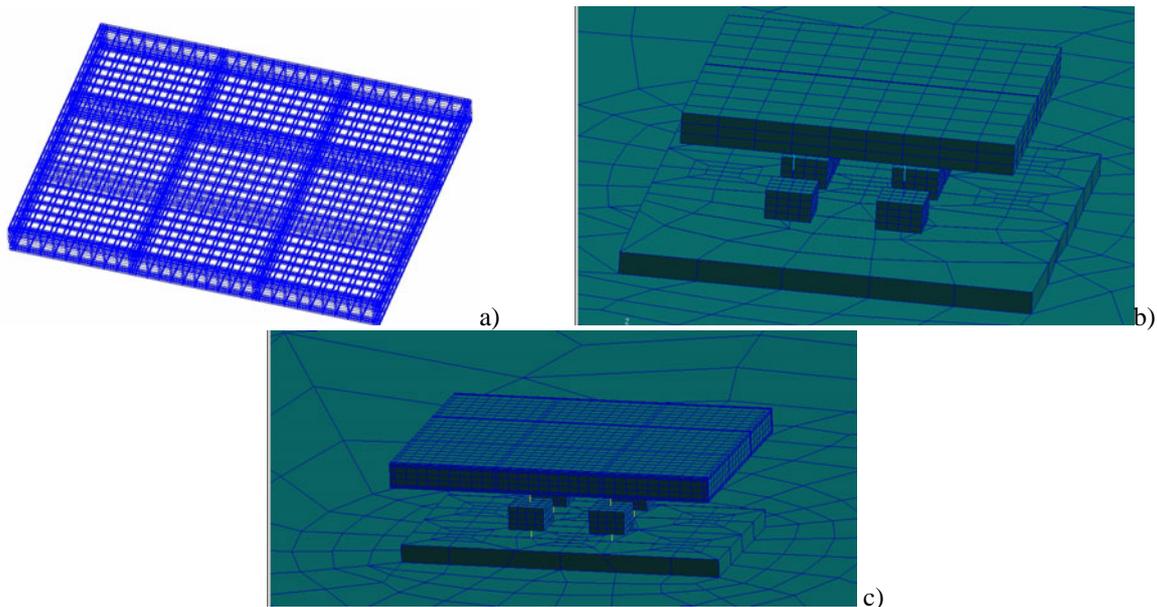
Figure 4. A) UVLitho lab sandwich slab, 0.7 m high, area 9 m by 4 m with a symmetric build up. The upper and lower slabs are 100 mm thick. The sides and stiffening crosses are 150 mm thick. K30 concrete was used in the simulation. Simulation shows the first flexible 'twisting' resonance to be at ~30 Hz. Slab dimensions and location of stiffeners are subject to change at later design stage. Different dimensions, but a similar build up is used for the slabs of the EBL lab. B) 1-stage and 2-stage set ups, solid and (two independent) split slabs. C) 1-stage and 2-stage set up, sandwich slab.

4.4. The isolators

Insights gained through FE simulation are that the use of mathematical (zero length) spring models does not capture real isolation behavior when there is significant offset between slab and ground. The authors used BUSH elements as implemented in Nastran where the isolator length is taken into account. Rotation stiffness was assumed to be one hundredth of the translation stiffness to couple rotation to lateral translation.

Adding rotation stiffness to the air-springs, as expected, reveals that there is a coupling between slab rotation and lateral translation that significantly lower some of the system natural frequencies. Another finding is that we receive isolation by up to (6+6=) 12 dB/Octave or (12+12=) 24 dB/Octave when such coupling occurs. Exploiting rotation yields a design variable that works to our advantage, but is not 100% under control. However, we do know that large rotation inertia is beneficial and that rotation to lateral translation coupling is beneficial and can attune the system into such behavior to improve performance.

The air-spring is of the type ContiTech 751 N.10 which has the lowest lateral spring stiffness we have been able to find, Figure 5. This air-spring is conventionally used to support train cars from boogie vibration.

The air-spring volume is 88 dm^3 and the coupling volume is 1 m^3. This implies that the vertical air-spring stiffness will shift from a lower stiffness value (governed by 1 m^3 + 88 dm^3) to a higher stiffness value (governed by 88 dm^3) as frequency increase. The exact frequency for this frequency shift was not known at the time of system design, but it was deemed possible to design the coupling volume such that the coupling volume would be acting at frequencies below 5 Hz. The design was simply verified towards the higher air-spring stiffness value for frequencies from 5 Hz and higher. Figure 5(d) shows the frequency varying air-spring stiffness when a 1 m^3 coupling volume is used.

The air-spring lifting capacity is 155 kN at 6 Bar. This leaves a lifting capacity of ~100 kN per support when 5 ton intermediate masses are supported. Four supports yields a total weigh capacity of ~40 ton. The project recommendation is to use 35 ton as slab weight, while adding the remaining 5 ton as equipment and dummy weights.

Stacking two air-springs on top of each other may or may not lead to an unstable system. However, the coupling volume of 1 m^3 lowers the compression stiffness to a magnitude which is similar with that of the lateral direction. A stability test is being executed by ContiTech before installation in august 2005.
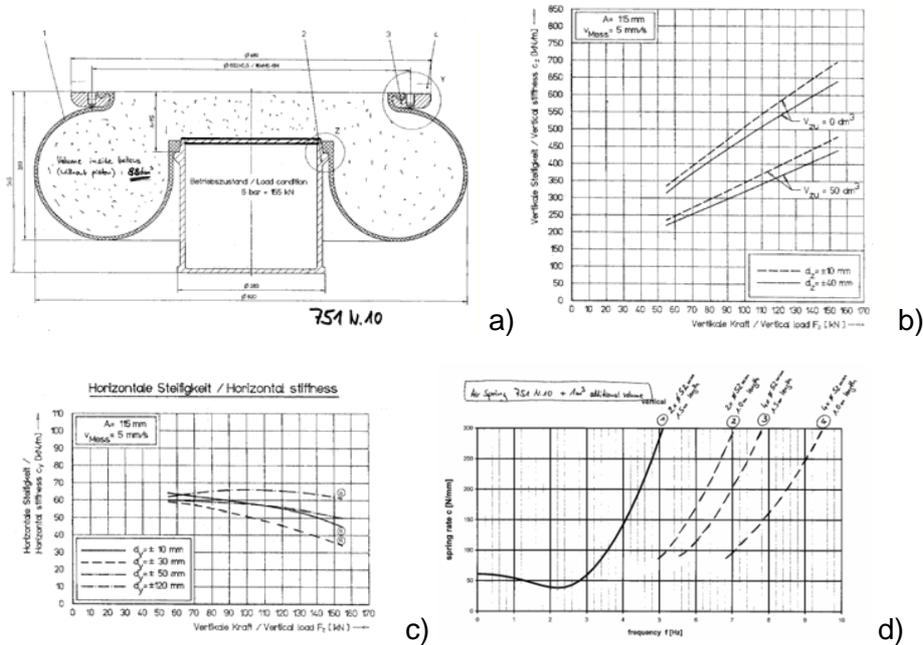
Figure 5. Data for the air-spring 751 N.10 as received from ContiTech. A) Physical size, air-spring volume, recommended operation height. B) Vertical spring stiffness. C) Lateral spring stiffness. D) Stiffness with 1 m^3 added volume as a function of frequency.

4.5. Electronic tilt and level control

The function of this system has not been relied on in the design of the set up, but it may serve as a tool in fine tuning of the system performance. The system will be fitted with an electronic tilt and level control system to avoid changing height and tilt with environmental conditions. The system will be controlled by a PID regulator that may or may not be used to actively control vibration at low frequency. The level and tilt control system will be able to control slab system response for at least three global system resonances and, possibly also for some of the intermediate mass responses.

4.6. System damping

A design variable to tune is the system damping. System damping is to be provided by shear damper links that extend from the ground to the intermediate mass and from slab to the intermediate mass (two separate links). The damping added by these links can easily be modified after installation.
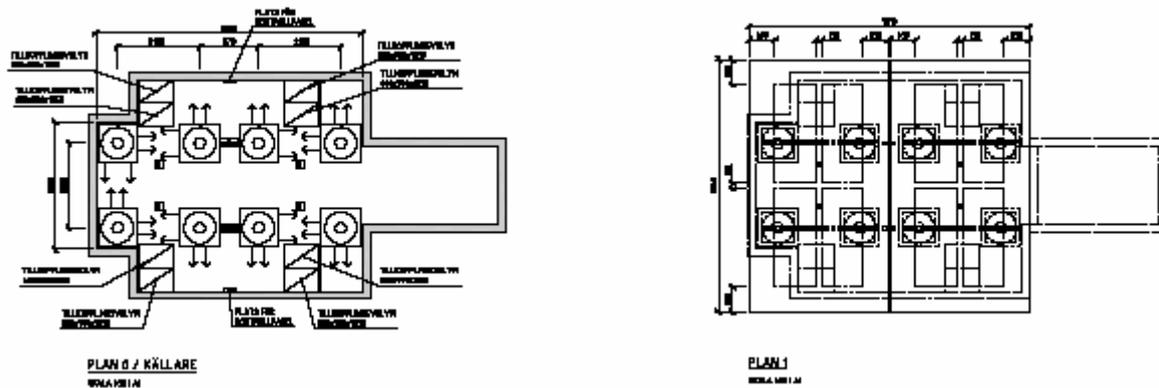
Figure 6. General arrangement of supports (RHS), the structure damper links (LHS), and the coupling volumes of the bottom air-springs for the EBL lab.

4.7. System Crosstalk

Measurement was made on the SEM and the E-beam machines when operated between measurement. Raith kindly provided data on the isolated machine weight and the transmissibility across the internal isolation system. The forces estimated to act on the slab when samples are loaded and positioned is listed in Table 1 and, as expected, shows forces to be well in excess of 1/10 N. Loads were of comparable size for hand operated and the electronically operated machines. The forces involved are small, and can probably be made smaller yet with ramp up of stepper motors.

System cross talk led to the decision of a split slab in the EBL lab. This solves the issue of cross talk between the SEM and EBL machines, but does not allow a second machine that is vibration sensitive to be positioned on either of the slabs. Designing a system with one machine per slab is costly. System cross talk is expected to become of growing importance as isolation probably will become more of routine use as lower vibration limits are to be reached and, thus the sensitivity to machine cross talk is expected to rise.

A first recommendation is to consider a simple approach to handle cross talk simply by setting up a very simple standardized handshaking protocol between machines. A machine that is about to vibrate should signal its intention to other machines so that they can pause execution if needed. The handshaking protocol is simply an electronic version of sensible 'lab culture' where operation of one machine is not allowed to ruin the work of the other machines.

A second recommendation is for machine vendors to make electronic system control user configurable such that sites with a high sensitivity to cross talk can execute some of the machine phases slower than other sites.

The case described herein shows that documentation on the loads exerted by a machine on the slab is necessary to be able to truly design the lab. Most machine vendors put requirements on slab vibration, but the fact that operation of their machine can be expected to lead to system excitation as well is not discussed. A third recommendation is therefore for customers to put demands on maximum allowed dynamic machine loads for the vendors. The need for vibration and load requirements is clearly bidirectional between the customer and the machine vendor.

Table 1 Forces listed in third octave bands between operation of the Raith 150 E-beam machine, [4].

Frequency [Hz]	Force on machine, vertical [N]	Force on machine, horizontal [N]	Force on slab, vertical [N]	Force on slab, horizontal [N]
1	1,8	2,0	*0,8*	*0,8*
1,25	1,7	2,4	*1,1*	*0,9*
1,5	2,0	3,7	*1,6*	*2,2*
2	2,7	5,6	*2,6*	*7,1*
2,5	3,9	2,8	*6,2*	*2,8*
3,15	3,3	1,6	*14,8*	*3,3*
4	2,0	1,7	*2,2*	*6,9*
5	2,4	1,5	*1,9*	*1,7*
6,3	2,8	1,5	*0,6*	*0,5*
8	3,8	2,3	*0,3*	*0,4*
10	4,3	2,0	*0,2*	*0,2*

4.8. A building block approach

As above discussed, there may or may not be a need to downgrade the 2-stage set up due to unforeseen problems with static stability or, there may be a present or future need to upgrade a system from a 1-stage to 2-stage set up.

Therefore, a building block approach has been applied in the project. All slabs are installed with top air-springs and coupling volumes mounted inside of the slabs. The top air-springs are mounted in intermediate masses at all slabs. The intermediate masses are supported either on a second air-spring layer in the case of a 2-stage set up, or on a rigid support in the case of a 1-stage set up.

This approach enables upgrading or downgrading as needed in the project.

5. Results

Figure 7 shows the response for various system configurations. Note that data below 1 Hz must be treated with caution as measured values are extrapolated, the FE mesh was not designed for analysis at this frequency range, and because the building stiffness is expected to effect the response in this frequency range. The level and tilt control system may or may not be actively used to control response. Comparison of the response of the 2-stgae sandwich slab, Figure7(h), with the 2s-atge solid slab, Figure 7(j), shows that slab rotation moment of inertia and spring moment stiffness effect vibration.

The interpretation of the end results are that a highly damped 1-stage set up suffice to meet the extended VC-E criterion and is the start out configuration for the UVLitho lab and the slab supporting the SEM machine in the EBL lab, and that a 2-stage set up meet the machine requirement of the Raith 150 E-beam machine.

Figure 8 shows some result details, e.g. that building rigid body motion and soil stiffness may affect the results and that base plate bending may be of importance as well. The 1-stage set up is more sensitive to such changes than the 2-stage set up.

a)

b)

c)

d)

e)

f)
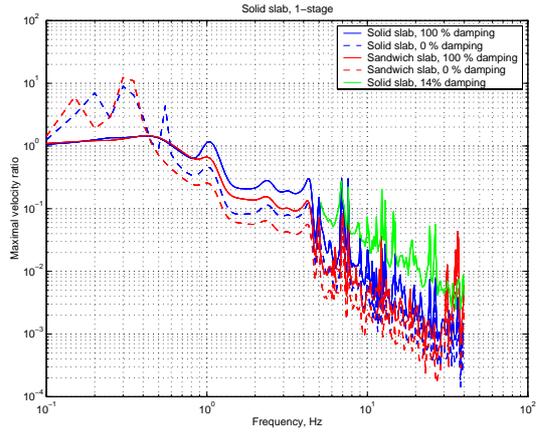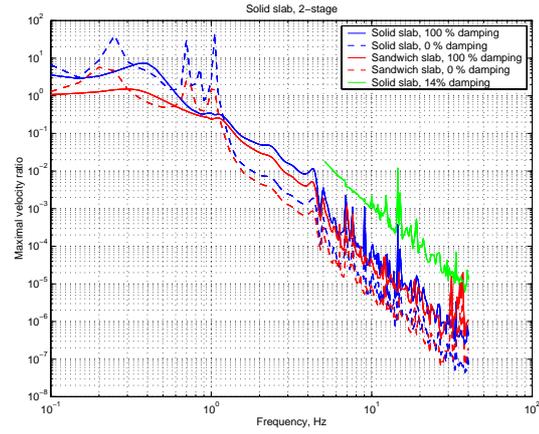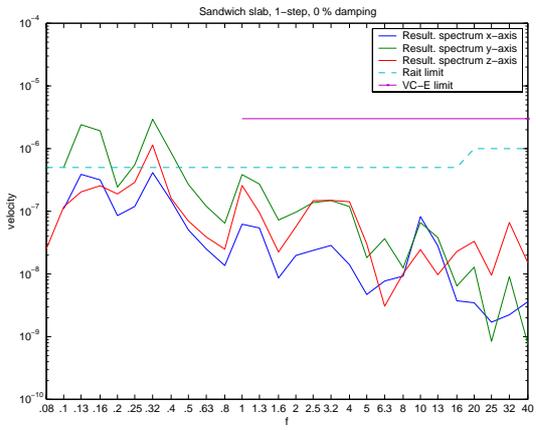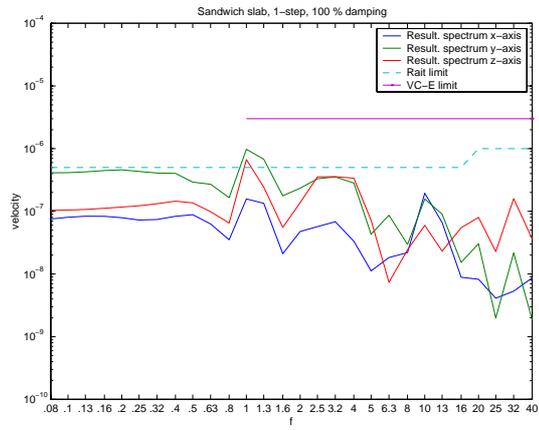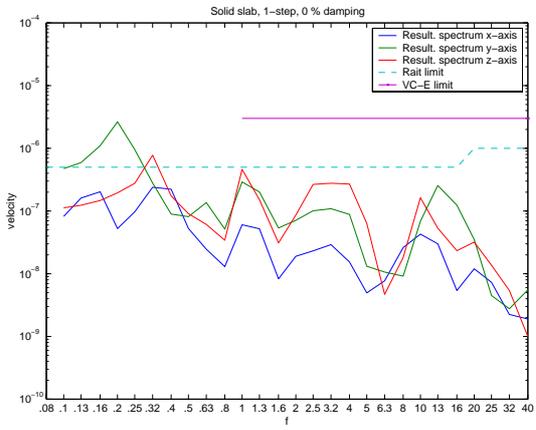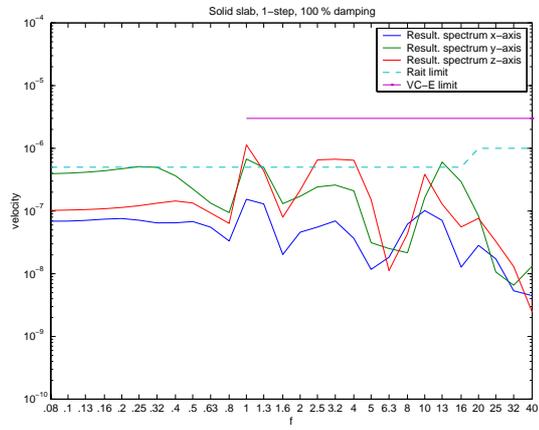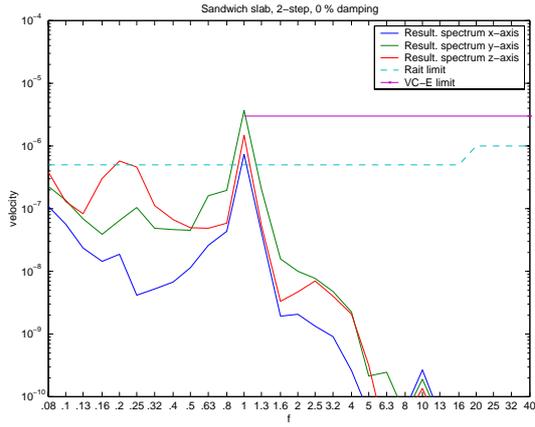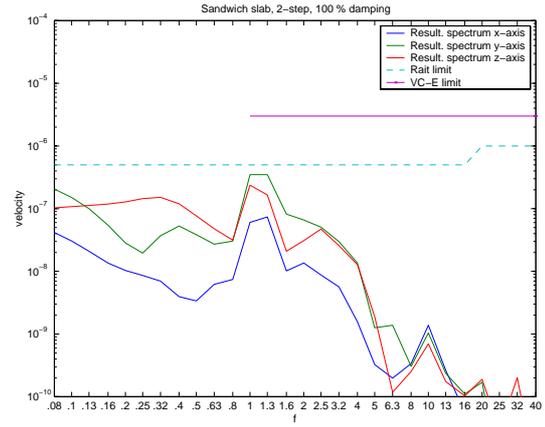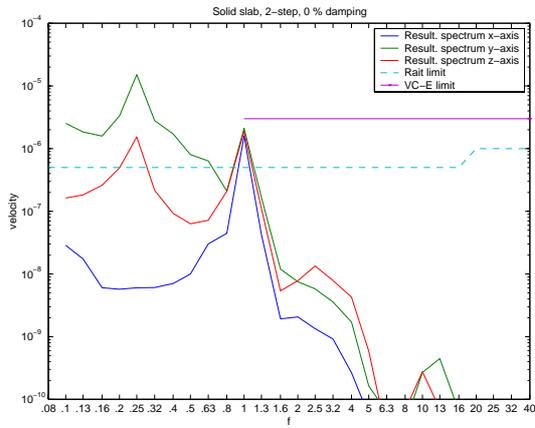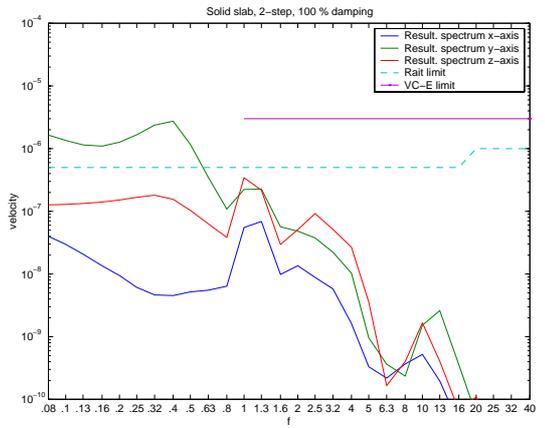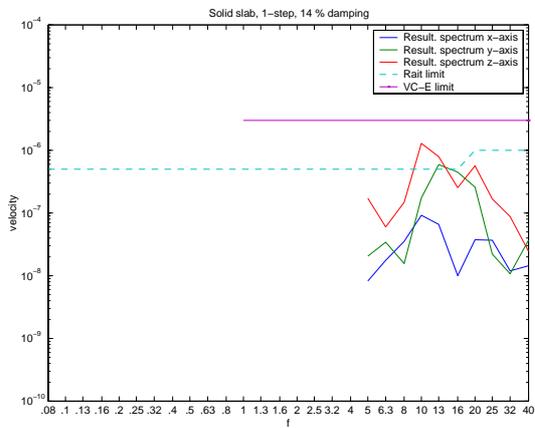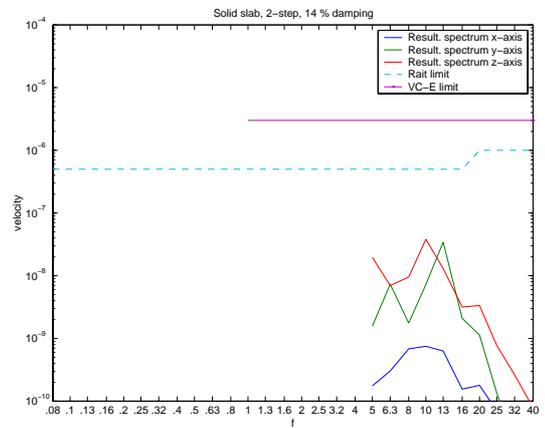
Figure 7. A)Transmissibility 1-stage set up. B) Transmissibility 2-stage set up. C) 1-stage 0% damping sandwich slab (of UV Litho lab). D) 1-stage (η) 100% damping sandwich slab. E) 1-stage 0% damping solid slab (of EBL lab). F) 1-stage (η) 100% damping solid slab (of EBL lab). G) 2-stage 0% damping sandwich slab (of UV Litho lab). H) 2-stage (η) 100% damping sandwich slab. I) 2-stage 0% damping solid slab (of EBL lab). J) 2-stage (η) 100% damping solid slab (of EBL lab). K) 1-stage solid slab with the higher vertical spring stiffness (which yields 14% damping). L) 2-stage solid slab with the higher vertical spring stiffness (which yields 14% damping).
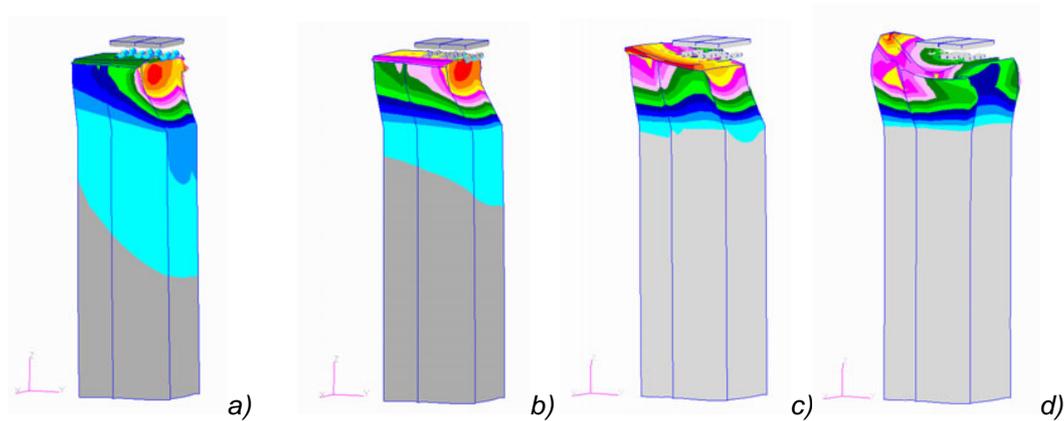
Figure 8. Result details at frequencies with reduced isolation. A) ~2.5 Hz lateral Y-direction vibration. Note the high amplitudes in the y-direction and the focus effect on the wave propagation. B) ~4.5 Hz increased Z direction response can be seen from the decreased ground-intermediate mass distance. C) ~7Hz 'rigid' base plate –soil interaction. D) ~10 Hz base plate bending.

6. CONCLUSIONS

The FTF clean room is built at a site with poor soil properties that force a design with an isolated system with very low natural frequency to meet strict requirements on vibration. The critical design factor is low frequency lateral direction vibration isolation. A highly damped set up using 1-stage and 2-stage air-springs with coupling volumes and electronic level and tilt control was designed to meet requirements.

The extended VC-E criterion can be fulfilled with a 1-stage set up while fulfillment of the machine criterion, 0.5 μm/s and 1 μm/s at frequencies below and above the 16 Hz third octave frequency band, respectively. The system being highly isolated from exterior becomes highly sensitive to interior excitation and, thus a wind cover is introduced to remedy flow fluctuation from the ventilation system. Infra sound is planned to be handled with active noise control should it be an issue.

A building block approach allows modification between a 1-stage and 2-stage configuration.

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*claes.fredo@ingemansson.se; phone +463177474 00; fax +46317747474; www.ingemansson.com

**jonas.brunskog@ingemansson.se; phone +46406647480; fax +4640128210; www.ingemansson.com