A Large Size Sample Stage for High Resolution 2-D and 3-D X-ray Imaging

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Abstract. The ESRF and the Belgian company Leuven Air Bearings have jointly developed a new sample stage utilizable for multiple applications. The instrument has been designed for the accurate positioning and scanning of large samples for computed tomography (3-D imaging). The main novelty of this development lies in the integration of all the necessary devices to scan large samples in closed-loop control mode into one accurate sample stage, although its design was not intended to meet the ultimate mechanical properties available. The sample maximum dimensions must be comprised in a volume of 400 mm diameter x 600 mm height whilst their weight may reach 300 N. Thanks to its large horizontal translation, the sample stage also allows the 2-D scanning of large samples over a 500 x 600 mm² area. Finally, in addition to being transportable to various measurement stations in a large facility, one major characteristic of this versatile tool remains its affordable cost in comparison with the sub-micron final imaging resolution that may be reached.

1. Introduction
In the frame of its Upgrade programme, the ESRF has promoted the development of a “Palaeontology Facility” utilizing instruments and techniques located at several beamlines: mainly ID19, ID17 and BM05. The “narrow” beam (up to 80 mm wide), high resolution experiments, like multiscale microtomography, laminography, are performed at the ID19 High-resolution Diffraction Topography beamline. ID19 currently benefits from the recent introduction of a “Transfocator” that permits imaging with high-energy “pink-beam” at different energy and focusing values. The maximum propagation distance has also been increased to 16 m.
When imposed by the sample sizes, the wide beam (up to 150 mm) and lower resolution imaging experiments are performed at the ID17 Biomedical beamline. BM05 is used with some configurations similar to ID19, but with less capabilities on high resolution, high energy, high speed and high coherence than ID19. It is used to test developments to be installed on ID19 or to accommodate in-house and industrial experiments that are not requiring the level of performances of ID19.
Four units of the Large Sample Stages have been built and commissioned to position and scan (vertical scan and rotation) the samples. The advantage of having four identical Large Sample Stages at our disposal is that the samples may be easily and quickly transported from one measuring station to the other without difficult manipulation. The specially developed control software is also identical for the four units.
Many imaging applications other than palaeontology are also foreseen in biology, cultural heritage imaging and analysis, and for the industry.

2. Design and construction
The Large Sample Stages were studied according to the mechanical specifications summarized in Table 1. In addition to these constraining specifications, the maximum sample weight is 300N, not necessarily centered on the sample stage; its dimensions are limited to a volume of Ø 400 mm x 600 mm height and the maximum off-centering of the load will be equivalent to the maximum excursions of the Sx/Sy stage, ie. ± 20 mm.
Furthermore, the space available for the installation of the Large Sample Stage is limited to a volume of (550 . 1100 . 1140) mm$^3$ (length . width . height).

| Motion                  | Travel range | Speed    | Accuracy | Minimum incremental motion (MIM) | Repeatability | Straightness | Angular error | Encoder |
|-------------------------|--------------|----------|----------|----------------------------------|---------------|--------------|----------------|---------|
| Vertical translation Z  | 600 mm       | 0 to 50 mm/s | 100 µm   | 10 µm                            | 50 µm         | In the Y direction: 10 µm | Pitch: 50 µrad Yaw: 50 µrad Roll: 100 µrad | YES     |
| Horizontal translation Y| ≥ 500 mm     | 0 to 100 mm/s | 100 µm   | 5 µm                             | 10 µm         | In the Z direction: 10 µm | Pitch: 50 µrad Yaw: 100 µrad Roll: 50 µrad | YES     |
| Rotary motion $\omega$ | Continuous multi-turn rotation | 6 rpm to 0.5 rev/hour | Angular positioning: 0.02º (350 µrad) Rotation axis Radial error: 5 µm Axial error: 5 µm Tilt error: 10 µm | 0.02º (350 µrad) | 0.02º (350 µrad) | YES |

Table 1: Main specifications for the Large Sample Stage (applying in static and dynamic modes for the $\omega$ rotary motion, and in static mode for all the other movements).

Figure 1: 3-D model of the Large Sample Stage.

Definition of Pitch, Yaw and Roll for each translation.
An exhaustive mechanical analysis [1], including a detailed Final Element Analysis, has been done on the 3-D model to predict all the deformations and the maximum displacements of the sample in the ultimate conditions.

The base of the instrument is a solid granite block weighing 250 kg. It is supported on 4 adjustable levelling feet that can be completed by air pads if the instrument is to be moved in the experimental room. The Z-stage moves on top of the Y-stage on air bearings; it mainly includes 2 vertical granite plates making a 90° angle between them. A frame supporting a standard RT250 rotary air table from Leuven Air Bearings moves vertically along the vertical granite guides, also sliding on air bearings. This rotary air table is itself supporting the standard Sx/Sy positioning stage (Huber Diffraction Techniek ref 5102.15). The total mass of the whole assembly is reaching 810 kg.

The brushless motors for the Y-, Z-, and ω-stages are controlled from SPEC via Lemo modules.

3. Measured mechanical performances and first application results

Exhaustive mechanical tests have been performed on the 4 instruments built, using an autocollimator Micro-Contrôle LAE 500 and electronic level Taylor-Hobson Talyvel 4, with and without load. The RT250 rotary air bearing has also been measured separately at the ESRF Precision Engineering Lab. Examples of the very satisfactory results are given in the tables 2 and 3 to illustrate some of the acceptance tests performed on the unit #2. The straightness and the angular deviations for all the linear motions are well conforming to the specifications or better, whilst the rotation stages over-perform with a comfortable factor of 3 to 10 for some parameters. The speed ranges and position resolutions are also conforming to the specifications or better.

Whilst the maximum rotation speed reaches 2 revolutions per second, steady rotation speeds as low as 1 revolution over 5 hours, have been successfully achieved. Some imaging data have been taken in real conditions in order to confirm the Large Sample Stage performances. An illustration is given in the following example that consists in the Computed Figure 2: Photo of the completed instrument installed at ID17.
Tomography imaging of crocodile eggs showing the embryos at different steps of their development. The data acquisitions were made in pink beam mode at energy around 100 keV, with a propagation distance (from samples to detector) of 16m, using single distance phase retrieval process [2]. The voxel size of the picture is 30 µm for eggs which largest dimensions reach 8 to 10 cm. It is not limited by the Large Sample Stage mechanical properties but rather by other instruments (mainly the detector). Up to 6 eggs were installed in a long tube to allow automatic scanning over 24 hours in a single experiment. Since their installation, these Large Sample Stages have been used for about 70% of all the tomographic experiments performed on ID19. Recent tests on BM05 demonstrated that they can even be used for scanning with sub-micron resolution (0.7 microns).

4. Conclusion

The mechanical measurements and the first experiments performed at the ESRF on the Large Sample Stages have proven that the new instruments developed in collaboration with the company Leuven Air Bearings are suitable for the new fields of applications opened after the upgrade of ID19 and also to cope with the ever increasing resolution available on the synchrotron beamlines. The precision levels and versatility reached by the instruments allow sub-micron resolutions on small to large size samples, despite their unsophisticated design based on high quality components, while remaining affordable. Many other applications of the new instruments are envisaged in various fields where high positioning precision and resolutions, large speed ranges, large movement amplitudes and rather heavy maximum loads are imposed. They will also be used to develop new acquisition geometries for both scanning and tomographic modes.

References
[1] K. Smets, Technical Calculations Report, Internal communication, 09-01-12
[2] Paganin D, Mayo SC, Gureyev TE, Miller PR, Wilkins SW. 2002. Simultaneous phase and amplitude extraction from a single defocused image of a homogeneous object. Journal of Microscopy 206: 33-40