SMOOTHING BASED ON BEST-FIT TRANSFORMATOIN

C. Yu#, BNL, Upton, NY, 11973, USA

Abstract

Smoothing is a technique to achieve accurate relative alignment of components and it's a main concern of accelerator alignment. Several smoothing techniques are reviewed in this article and the principle and application of smoothing based on best-fit transformation are introduced as there is no other paper discussing this before.

Compared with other methods, smoothing based on best-fit transformation uses design information which is more preferable in a way. It uses best-fit transformation, which is extremely easy to use, between reference and as-built group to find an optimal expression of the interested magnets or girders so that the relative alignment of them can be properly judged.

It has been used in the touch-ups of NSLS-II storage ring girders recently and also the whole storage ring re-adjustment of SSRF during 2012 shutdown. Both applications yield good alignment result. Moreover, it's expected to be used for long term maintenance of NSLS-II and have the ability to solve the potential conflict between short shutdown time and tight alignment tolerance when it is in full operation.

INTRODUCTION

Due to limitation of survey control network accuracy and slow floor movement, accelerator usually requires relatively loose global alignment tolerance (a couple of millimeter) to components. However, the relative alignment tolerance between girders is tight, usually in sub-millimeter level. For example, NSLS-II project requires ± 3 mm global tolerance and ± 0.1mm relative alignment tolerance between adjacent girders [1].

With current alignment technique, the fulfilment of both global and local tolerance is not a big issue, especially the global one. However, the local tolerance can be easily exceeded due to ground motion and the creeping of girders themselves along with the running of a machine. Different from the first time installation, the task of alignment group is to maintain relative girder alignment, instead of re-aligning all components close to a nominal zero. The technique used for this purpose is called smoothing.

The goal of smoothing is to ensure a smooth orbit with minimum amount of girder adjusted. It is vital for the storage ring of a light source due to the shortage of accessible time for survey when the machine is running.

There are several concepts and approaches to realize smoothing. For example, DESY uses cubic spline functions to perform the relative alignment of HERA [2]; SLC and APS use First Principle Component analysis to evaluate the relative alignment quality [3, 4]. Those algorithms essentially use least squares method to find one or more dimensional best-fit lines which can address the problem but somehow are a little bit far away from the daily survey and alignment technique.

This article proposes a new approach to address smoothing: compute deviations based on the best-fit transformation between reference and measured values. Simply put, the design geometry will be used to judge the alignment quality.

PRINCIPLE

As mentioned above, the global locations of key accelerator components are not a compelling consideration of smoothing. It focuses on the relative alignment quality. The best definition of relative alignment is the reference values of magnet or girder fiducials after fiducialization or girder assembly steps. When the as-built and reference values of magnets or girders fiducials agree with small amount of discrepancy, their relative alignment can be declared good.

Mathematically, best-fit transformation is used to take out the overall translation or rotation between reference and as-built coordinate systems. One can see that the goals of smoothing and best-fit transformation are coincident here: both need to check the relative relationship between two systems. Therefore, it's natural to use best-fit transformation as a way of smoothing.

Besides, best-fit transformation is a mature technique widely used in current alignment practice for varied purposes, such as bringing instrument into survey network or orienting the measurement relative to CAD model. It's easy to understand and accept.

Best-fit transformation

The formal name of best-fit transformation is Helmert transformation, also called a seven-parameter transformation. It uses two sets of points to solve a maximum of 7 parameters which includes three translations, one scale and three rotations.

In practice, there will be two point groups: one stands for reference and one for measured. The minimum amount of common points is three for a seven-parameter computation. For two-dimensional case, two points will solve four parameters.

However, it's a good practice to use as many as possible to improve the solution precision. When more than minimum points are used, least squares method will be used to minimize the sum of squares of the distance between corresponding points and finally compute the parameters and provide statistical assessment.

Any commercial software for laser tracker or articulated arm has this function. Spatial Analyzer is used in NSLS-II project and it will be explained more in the following part along with its automated script-measurement plan (MP). However, the method introduces here is independent on Spatial Analyzer and should be easily used with other software.

#cyu@bnl.gov

Basics

Assume there are two girders and each has more than 3 fiducials. According to lattice and pre-assembly data, there is a reference point group with all the fiducials which are perfect if fiducialization error is ignored. When the two girders have been aligned in tunnel and a new survey is done the as-built location of the fiducials can be obtained.

By doing best-fit transformation between the reference and as-built point groups, the relative alignment can be judged by the residuals of girder fiducials. In the following part, the storage ring girders of NSLS-II will be used to illustrate the principle.

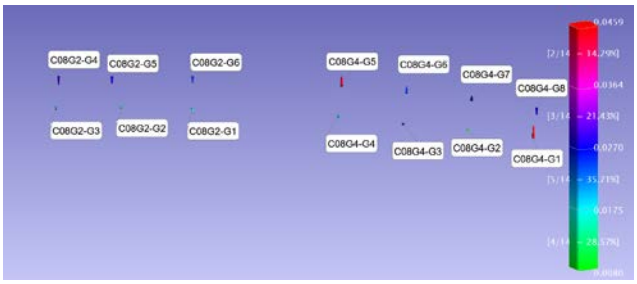


Figure 1: Layout of C08G2 and C08G4 girder fiducials and best-fit deviations.

Figure 1 shows this layout of C08G2 and C08G4 girder fiducials along with the best fit residuals in transverse direction. The maximum amplitude is 0.046 mm.

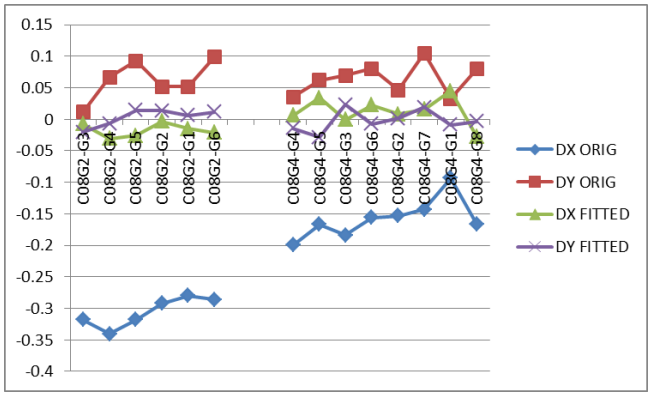


Figure 2: Comparison of C08G2 and C08G4 girder fiducials before and after best-fit transformation.

Figure 2 shows both the deviations before and after best-fit transformation. There is a large offset and slope in X direction before transformation and it's disappeared after that. What has been done by best-fit transformation is taking out of the rotations and translations of as-built values with respect to global coordinate system and showing the deviations relatively. This is what really matters when local smoothness is to be judged.

Likewise, one can check all the adjacent girders this way one by one to judge the smoothness of beam orbit. All that need to be done is doing best-fit transformation consecutively. For example, if there are 90 girders, which is the case for NSLS-II project, there will be 90 best-fit transformations to be performed.

Certain criteria, such as the relative girder alignment tolerance, can be used as a threshold of re-adjustment.

As both the reference and as-built data are handily available, it's an easy job to be accomplished. By incorporating all the best-fit transformation steps into an automated script, the solution will take only a couple of minutes.

Important notes

In the practice of NSLS-II project, 3 adjacent girders instead of 2 girders, are used to check the smoothness of alignment. The benefits of this modification are that it will yield better alignment quality with the same threshold value and that it will provide natural datum for re-adjustment. When one girder is found out of tolerance and should be re-adjusted, its upstream and downstream girders' as-built location can be used to establish survey control network.

Other issues should be noted includes:

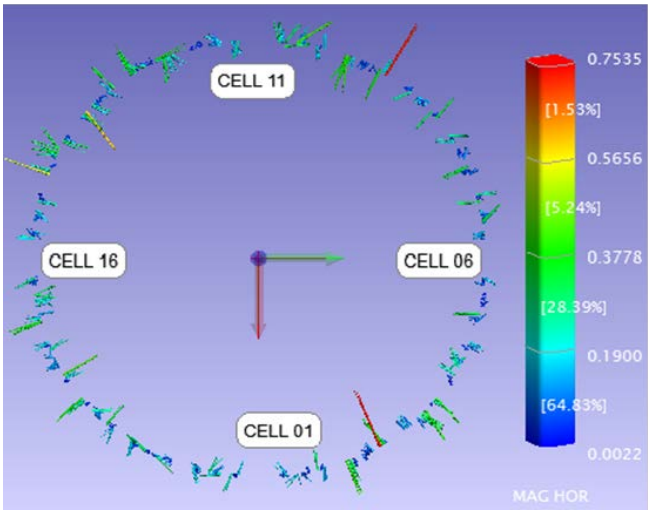
- It's important to have accurate as-built survey data as it defines the initial status of the process. Straight sections, usually much longer than any girders need more survey to intensify the connection between cells.
- It's not necessary to measure the whole machine at the same time. One can check the relative alignment cell by cell and in a couple of shutdowns all the girders will be checked and adjusted if necessary. In this manner the machine will be maintained in good alignment status and no major shutdown for a complete re-alignment is needed even after years of running.
- In order to describe the deviations clearly and make it easy to understand, local frames for each girder should be established. By this way, the impact of alignment error in beam direction, which is usually not stringent, will be excluded.
- The fiducials should be sorted in each group according to their location with respect to beam. The merit by doing this is that the relative fluctuation of girders can be shown intuitively and easy to determine whether it needs to be adjusted or not.
- The criteria of re-adjustment could be the alignment tolerance, smaller or bigger depending on the alignment quality and the location of the girders. This will be further addressed later.
- When a girder is determined to be adjusted, its upstream and downstream girders will be used to transform the as-built survey data to reference data and the control network to be used for adjustment can be easily established.

It should be pointed out that the method is not limited to circular accelerator, but also can be used in transport lines and linear accelerators.

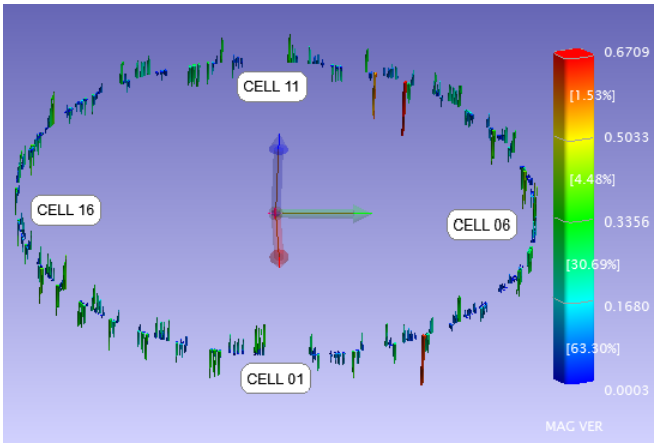
APPLICATION IN SSRF

SSRF has a storage ring with a circumference of 432m. The initial alignment of SSRF storage ring was completed at the end of 2007 and successful commissioning has been performed thereafter [5]. After ~5 years of running, a re-alignment of the storage ring was believed necessary since some of the correction strength of correctors is out of range. The best-fit transformation based smoothing technique was initialized back then.

Instead of using fiducials, all the sextupoles and quadrupoles centers were computed and hence were used during best-fit transformation process. Since the centers didn't include girder roll information, as a first step, girders were rotated based on the roll angle computed from the deviation between measured and reference information.



(a) Computed adjusted amount in horizontal direction



(b) Computed adjusted amount in vertical direction

Figure 3: Storage ring adjustment of SSRF in 2012.

Every solution includes the residual corrections to magnets within one cell and the magnets in-between cells. Multiple iterations were done to minimize the residuals and ensure good relative alignment for all the adjacent girders.

Figure 3 shows the expected adjustment amounts of magnets in both horizontal and vertical direction after smoothing computation. As can be seen in the graphs, most of the adjustment amounts are below 300 micron. Based on the smoothing result, all the girders had been adjusted accordingly. One interesting thing is that how far off the girders can drift comparing to original precise alignment.

Although it was the first attempt to apply this innovative best-fit transformation-based smoothing, the alignment quality was excellent as confirmed by the beam. Alignment group were told that the alignment was almost as good as it was when the machine was built 5 years ago.

One major issue that had been encountered was that the 7 beam lines of phase 1 had to be re-adjusted since no constraints had been provided for the beam lines during smoothing computation. Some needed to be adjusted by a couple of millimeters at the end station. In hindsight, special consideration could be taken to avoid or minimize the impact from storage ring smoothing.

APPLICATION IN NSLS-II

NSLS-II storage ring is under commissioning since the end of March, 2014 and survey group were running out of time for a complete survey for all the girders before the machine was turned on.

There was a long shutdown in May 2014 for a couple of weeks for the installation of superconducting cavity, some undulators and other components. Survey group performed a full survey to all the monuments and half of the girder fiducials (at aisle side), which we call it epoch 7 as it's the 7th round of similar survey since the project was initialized. Some girders are found out of tolerance based on the data obtained. More complicated survey was performed to those questionable girders to verify the data precision by measuring both aisle and ratchet wall side girder fiducials. Confirmed girders that were out of tolerance were adjusted accordingly.

Smoothing step

The following steps are used for smoothing:

- Perform comprehensive survey for girder of interested and its upstream and downstream ones. Girder fiducials are recommended to be surveyed 3 times in each setup to improve measurement accuracy. If there is a straight section, more setups should be added to improve accuracy.
- Compute the measured relative location of 3 girders.
- Perform a best-fit between the measured and reference coordinates to see if there are large deviations. As a rule of thumb, the fitting RMS in both X and Y direction should be below 0.05. Otherwise, it may indicate there are certain problems of the relative girder alignment.
- If the fitting result is larger than 0.05, the downstream fiducials of upstream girder and upsteam fiducials of downstream girder will be used to establish girder adjustment control network. The

nominal coordinates of those 4 fiducials will be used to best-fit and transform the measured point group. The measured point group will be used as survey control network and the reference coordinates will be used as alignment goal.

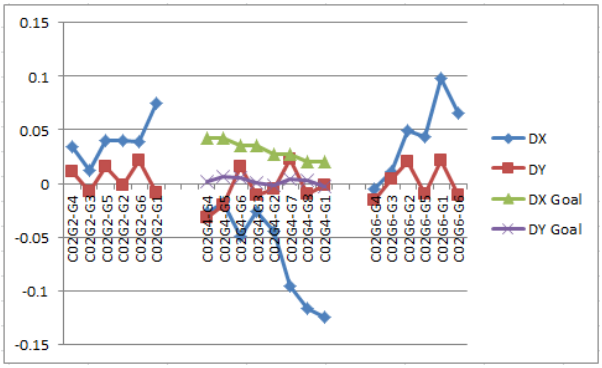


Figure 4: Relative alignment of girders in cell 2.

- The girder alignment procedure will need to be followed when girder is to be adjusted.
- Report girder location deviation.

Smoothing result

There were totally 22 girders which had been checked. Most of the check survey confirms epoch 7 within 50 micron, while C01G6 and C03G6 showed more than 100 micron discrepancy due to naming issue and bad shots in original survey. 8 girders had been adjusted according to smoothing criteria and the maximum adjustment amount is below 300 micron.

Figure 4 shows the relative alignment of girders in cell 2 after re-survey which indicates large relative deviation in X direction. “DX Goal” and “DY Goal” shows the goal of adjustment. It can be seen from the graph that the goal ensures smooth transition from upstream to downstream girder. C02G4 was adjusted accordingly.

Figure 5 shows the fitting deviations of all fiducials of all girders after adjustment. Each fiducial will be shown 3 times since it will participate in the fitting 3 times. Most of the deviations are below ±0.1mm and the RMS deviation in X and Y direction is 0.034 mm and 0.021 mm respectively, which indicates good relative girder alignment. It also should be pointed out that, if one fiducial has a problem, it might show large spikes 3 times. This is the case of the ficucials of C11G6.

Global deviation

Figure 6 shows the global deviations of all girder centers. The data is shown according to epoch 7 survey result, and dX and dY are with respect to beam direction respectively. “dX New” means the final location and “dX Old” means the location before adjustment. An “O” in transverse axis means original survey result, a “C” means it has been checked and an “A” means it has been aligned.

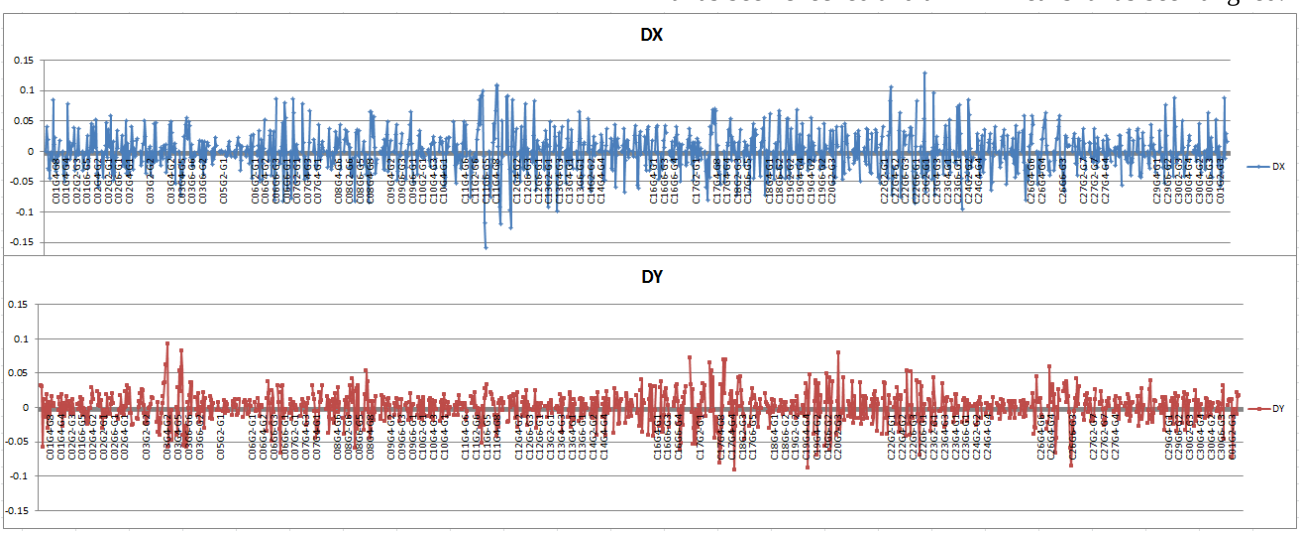


Figure 5: the fiducial deviations after best-fit transformation among all 3 adjacent girders.

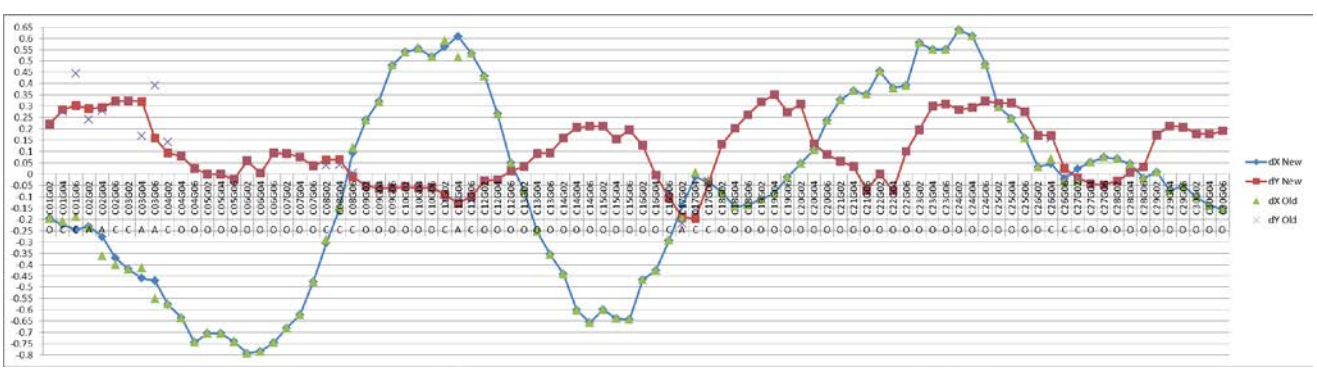


Figure 6: the girder center deviations before and after smoothing.

Although the curve looks not perfect mathematically, the relative alignment of girders is well within tolerance. This is a big difference between this approach and others, from which a very smooth curve can be generated after computation.

Lessons learned

One problem of the smoothing technique used here is that the sporadic checking of girders took a very long time since each questionable girder need comprehensive survey to both its upstream and downstream girders. As a contrast, if the girders are checked in a consecutive manner with consideration of the time available, a higher efficiency can be expected.

Most of the analysis work is done in a step-by-step manner and dedicated measurement plan (MP) will be written up to automate the process.

FURTHER DISCUSSIONS

The best-fit transformation based smoothing technique is easy to understand and use, therefore one doesn't need to learn about programming or any other special principles. Its application is successful for the partial alignment of NSLS-II project. It also yielded excellent alignment quality when it was applied in SSRF for a whole machine re-adjustment during 2012 shutdown. Therefore, it could be used by other machines as a new way to handle the smoothing requirement.

For a running light source with full of beam lines, the users may be reluctant to accept the fact of re-aligning their beam line as it will reduce usable time for experiment. Some machines, for example, NSLS, end up to no re-alignment for storage ring in decades. The best-fit transformation based smoothing technique can tackle this well by avoid moving girders around straight section unless it's absolutely necessary.

As far as the girders adjacent to straight section to be concerned, it will tolerate more alignment error compared with other girders because straight section is usually much longer and a smaller corrector strength is needed with the same alignment error. This is one of the topics that should be discussed between survey group and physicists when alignment tolerance is given out. Anyway, the best-fit transformation based smoothing technique will provide information regarding the relative alignment of girders adjacent to straight section as well and trigger an alarm when adjustment has to be done.

In a word, best-fit transformation based smoothing technique is not only suitable for complete re-adjustment of the whole storage ring, but also good for touch-ups and long term maintenance of the storage ring alignment. By surveying and adjusting the storage ring cell by cell, good storage ring alignment can be maintained. This is important for a new machine as no major shutdown will be necessary at the early stage of running due to large floor settlement.

SUMMARY

Best-fit transformation is currently a basic technique for accelerator alignment, but smoothing seems a little bit fancy as it usually associates with different language, such as Fourier function, cubic spline or Principal Curve Analysis etc. The application of best-fit transformation makes smoothing a lot easier and any surveyor can do it.

It's not only a great tool for partial and whole alignment of an accelerator at the beginning of running a machine, but also a possible solution for long term maintenance of storage ring when more constraints present.

With dedicated script, the whole smoothing process can be fully automated and high efficiency is expected.

ACKNOWLEDGEMENT

The author would like to thank all the staff who involved in the NSLS-II and SSRF alignment activities.

REFERENCES

[1] C. Yu et al. "NSLS II Girder Profiling Acitivities". in proceedings of 12th International Workshop on Accelerator Alignment. (Fermilab, Batavia, U.S.A. September 10 - 14, 2012).

[2] R. Ruland, Accelerator and Transport Line Survey and Alignment, (Stanford Linear Accelerator Center, California, SLAC Pub.-5672, 1991).

[3] H. Friedsam, W. Oren, "The Application of the First Principal Curve Analysis Technique to Smooth Beamlines,"in Proceedings of the First International Workshop on Accelerator Alignment, (Stanford Linear Accelerator Center, California, 1989).

[4] H. Friedsam, M. Penicka, S. Zhao, Beamline Smoothing of the Advanced Photon Source, Proceedings of the 1995 Particle Accelerator Conference, Dallas, USA, March 1995, pp. 2084 - 2086.

[5] C. Yu et al. "Survey and alignment of the SSRF complex" in Proceedings of 10th International Workshop on Accelerator Alignment. (KEK, Tsukuba, Japan, February 11-15, 2008).