DYNAMIC PATTERN RECOGNITION OF ACCELERATOR FACILITIES*

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ABSTRACT

In this paper, some new ideas about the dynamic situation of accelerator, dynamic pattern recognition, are briefly introduced. Some important statistical parameters about the situation description, stability evaluation and dynamic analysis of accelerator are presented from the point of a surveyor. A very useful method or procedure used to the motion analysis of the ground and the support system was creatively developed and has been used to the stability evaluation and the deformation analysis of Large Electron Positron Collider (LEP) in CERN.

1. INTRODUCTION

A particle accelerator plays a very important role in particle physic experiment. With the development of particle physics, its scale becomes larger and larger, 3 km long for a straight accelerator and 10 km of diameter for a circle accelerator. Instruments and methods of more precise alignment are required. Facing this new challenge, experts developed many special instruments and methods to keep accelerator on the necessary situation, and also they are forced to pay a special attention to its stability and study carefully the factors that can cause its instability, such as ransom displacements of the earth's crust (ground motion), vibration, floor's deformation and displacement of adjustable support system etc. Because physicists and engineers concern very much about the accelerator's situation, they expect to have a technique that can be used to describe visually and quantitatively its stability and its dynamic situation. They expect also to have a method used to analyse dynamic process and influential factors in order to control or improve its unstable situation.

Many experts did a lot of effective work on the effects of ground motion on accelerators [1]~[10]. The impacts of vibration were also much discussed [10]. Some people studied the deformation and dynamic situation of accelerators [11]~[20]. From the point of engineering deformation monitoring and analysis, the authors studied the stability of LEP in CERN [17]~[20]. Some positive results are obtained. This paper presents our work on this topic. The main purpose

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of this paper is to discuss with other colleagues and find a practical method or technique that can be used to evaluate and describe the stability of accelerators. Maybe, some useful parameters can be found to quantitatively describe their dynamic situation. Another purpose is to discuss with other colleagues how to correctly determine what leads to the instability of accelerators and how to control or avoid it so that accelerators run safely.

This paper deals with the deformation of base floor and the displacement of adjustable support system. Some parameters used to evaluate and describe the stability are proposed following our experiences from the study and application on LEP at CERN.

2. REALIGNMENT OF ACCELERATOR

The stability of accelerator depends on many factors. They can be summarized up into two kinds following its structure. One is the stability of its base and another is the support system. The former includes ground motion (random), crustal movement and deformation, displacement and deformation of man-made base. The later means the stability of adjustment device (gird) and of support bracket. From the dynamic activities of accelerator, horizontal or vertical displacement, variations of longitudinal tilt or latitudinal tilt exist in the unstable case. They can distort the geometrical form of beam line so that the energy of particles is reduced unreasonably. Maybe, accelerator could be broken in the worse case.

Fig. 1 LEP/CERN

2.1 Structural features of accelerator and realignment measurement

An Accelerator is a group of magnets well aligned along a designed axis (See Fig.1 and Fig.2). Each of them is connected through an adjustable device with a support bracket. This bracket is fixed rigidly on a man-made base (floor). Usually, this base is put on a layer (it can be absorb some micro deformation of rock base), which is located on the bedrock. There are two surveying points on each of element (magnet). It is to use those points to install all elements on their exact position through a process called “alignment”.

Generally, alignment or realignment is realized through a surveying control network points near by. The surveying control networks are divided into four categories：1. Straight traverse for straight accelerators. 2. Triangular and trilateral network for circle accelerators of a small diameter (less than 100 m). 3. Complex traverse for circle accelerators of a medium diameter (less than 2000 m) (See Fig.2). 4. Offset traverse for large circle accelerators (See Fig.1). The traverse points offer not only the horizontal coordinates but also the vertical coordinate. With the same time of precisely positioning elements, their latitudinal tilts are also precisely settled following their designed values.

2.2 Realignment and movement analysis

Fig. 2 LEP/CERN

After installation, a realignment measurement should be realized periodically. For small accelerators, radial and vertical realignments are usually carried out for checking its stability. And some of elements moved far away from their designed position should be adjusted or moved back to their designed position. For large accelerators, a relative realignment is realized and some of elements moved far away from their neighbours are considered to realign for the keeping the beam line smoothing. The realignments include the horizontal, the vertical and the latitudinal tilt. Some times one of them (e.g. vertical realignment) could be done alone following requirement. The purpose of realignment is to evaluate whether the elements moved or not, which one moved, how much it moved and how it moved. In addition, there are also much more important works with realignment measurement:

- Find some comprehensive and quantitative parameters as indexes to evaluate the stability of accelerator.
- Analyse the correlation features among displacements in time, space, area and distance. Establish a model to describe those features.
- Analysis the sources the displacements come from. Determine which are the key sources so that an effective measure can be found to control or reduce their influence on the stability.

With the work on LEP in CERN and experience on deformation monitoring, authors have been studying on these issues. Some positive results are obtained. Here do an exchange with other colleagues.

3. STABILITY ANALYSIS MODEL

There are three key problems in accelerator’s stability analysis: 1. Find the parameters, which can clearly present the geometrical situation of accelerator. 2. Establish some indexes, which can evaluate the stabilities of the entire accelerator and the part of accelerator. 3. Reduce the affect of surveying systematic errors (come from instruments and from methods) on the stability evaluation.

3.1 Description parameters of accelerator stability

Following the structural features of accelerator and the surveying method, four different parameters are adopted in the stability analysis: 1. Mean Square Error (MSE) of the coordinate difference between two alignments. 2. Mean of the absolute values of the difference of longitudinal tilts between two realignments. 3. Mean of the absolute values of the difference of deformations between two realignments. 4. Mean of the absolute values of the difference of latitudinal tilts between two realignments. Here the first three are discussed.

3.1.1 Coordinate difference between two realignments---displacement

For k^{th} and l^{th} realignments, the coordinates of the point i are $(x_i^k \ y_i^k \ z_i^k)$ and $(x_i^l \ y_i^l \ z_i^l)$. Namely, the coordinate of the point j are $(x_j^k \ y_j^k \ z_j^k)$ and $(x_j^l \ y_j^l \ z_j^l)$ (i=1, 2, …, n). The coordinate differences are $D_{x_i^{k-l}} = x_i^l - x_i^k$, $D_{y_i^{k-l}} = y_i^l - y_i^k$ and $D_{z_i^{k-l}} = z_i^l - z_i^k$. Those parameters present clearly the dynamic situation of the point i. Take MSE of those differences to describe the dynamic situation of whole accelerator:

$$\hat{\sigma}_{D_x}^2 = \frac{1}{n}\left(\sum_1^n (D_{x_i^{k-l}})^2\right) = \frac{1}{n}\left(\sum_1^n (x_i^l - x_i^k)^2\right) \tag{1}$$

$$\hat{\sigma}_{D_y}^2 = \frac{1}{n}\left(\sum_1^n (D_{y_i^{k-l}})^2\right) = \frac{1}{n}\left(\sum_1^n (y_i^l - y_i^k)^2\right) \tag{2}$$

$$\hat{\sigma}_{D_z}^2 = \frac{1}{n}\left(\sum_1^n (D_{z_i^{k-l}})^2\right) = \frac{1}{n}\left(\sum_1^n (z_i^l - z_i^k)^2\right) \tag{3}$$

Where $\hat{\sigma}_{D_x}^2$, $\hat{\sigma}_{D_y}^2$ and $\hat{\sigma}_{D_x}^2$ are respectively MSE in three different axes. Suppose their theoretical values are respectively $\sigma_{D_x}^2$, $\sigma_{D_y}^2$ and $\sigma_{D_x}^2$, we have $\hat{\sigma}_{D_x}^2 \to \sigma_{D_x}^2 \chi^2(n)$, $\hat{\sigma}_{D_y}^2 \to \sigma_{D_y}^2 \chi^2(n)$ and $\hat{\sigma}_{D_z}^2 \to \sigma_{D_z}^2 \chi^2(n)$. Therefore, through a statistical test we can determine whether the movement of accelerator along the axis is evident. This test gives us a view over whole accelerator, but it cannot present the information about a few moved points. This method can also be used for the stability evaluation of a part of accelerator flexibly.

3.1.2 Difference of longitudinal tilt   Inclination

At first, a definition of longitudinal tilt is written as:

$$I_{x_{i-j}^k} = \frac{D_{x_{j-i}^k}}{L_{i-j}} = \frac{x_j^k - x_i^k}{L_{i-j}} \tag{4}$$

$$I_{y_{i-j}^k} = \frac{D_{y_{j-i}^k}}{L_{i-j}} = \frac{y_j^k - y_i^k}{L_{i-j}} \tag{5}$$

$$I_{z_{i-j}^k} = \frac{D_{z_{j-i}^k}}{L_{i-j}} = \frac{z_j^k - z_i^k}{L_{i-j}} \tag{6}$$

Where L_{i-j} is the distance between the point i and the point j. $I_{x_{i-j}^k}$, $I_{y_{i-j}^k}$ and $I_{z_{i-j}^k}$ are the longitudinal tilts between two points at k^{th} realignment. If $I_{x_{i-j}^k} = I_{x_{i-j}^l}$, $I_{y_{i-j}^k} = I_{y_{i-j}^l}$ and $I_{z_{i-j}^k} = I_{z_{i-j}^l}$, it means there is no change on tilt. Suppose $I_{x_{i-j}^o}, I_{y_{i-j}^o}$ and $I_{z_{i-j}^o}$ be their initial values, the Inclinations (variation rate) of tilt at k^{th} realignment are defined as $\Delta I_{x_{i-j}^k} = (I_{x_{i-j}^k} - I_{x_{i-j}^o})$, $\Delta I_{y_{i-j}^k} = (I_{y_{i-j}^k} - I_{y_{i-j}^o})$ and $\Delta I_{z_{i-j}^k} = (I_{z_{i-j}^k} - I_{z_{i-j}^o})$. Their Mean of the absolute values:

$$\Delta I_{x^k} = \frac{1}{n_I}\left(\sum_1^{n_I}\left(\left|\Delta I_{x_{i-j}^k}\right|\right)\right) = \frac{1}{n_I}\left(\sum_1^{n_I}\left|(I_{x_{i-j}^k} - I_{x_{i-j}^o})\right|\right) \tag{7}$$

$$\Delta I_{y^k} = \frac{1}{n_I}\left(\sum_1^{n_I}\left(\left|\Delta I_{y_{i-j}^k}\right|\right)\right) = \frac{1}{n_I}\left(\sum_1^{n_I}\left|(I_{y_{i-j}^k} - I_{y_{i-j}^o})\right|\right) \tag{8}$$

$$\Delta I_{z^k} = \frac{1}{n_I}\left(\sum_1^{n_I}\left(\left|\Delta I_{z_{i-j}^k}\right|\right)\right) = \frac{1}{n_I}\left(\sum_1^{n_I}\left|(I_{z_{i-j}^k} - I_{z_{i-j}^o})\right|\right) \tag{9}$$

3.1.3 Angular variation　Deformation

In order to illustrate the form change of accelerator, an angle is used as an example. From Fig. 3, an angle is $\angle hij$ at k^{th} realignment and change into $\angle h'i'j'$ at j^{th} realignment. The form change can be expressed by Angle Change rate, called Deformation:

$$d_{x_i^{k-l}} = ((I_{x_{h-i}^l} - I_{x_{i-j}^l}) - (I_{x_{h-i}^k} - I_{x_{i-j}^k}))\big/L_{h-j} \tag{10}$$

$$d_{y_i^{k-l}} = ((I_{y_{h-i}^l} - I_{y_{i-j}^l}) - (I_{y_{h-i}^k} - I_{y_{i-j}^k}))\big/L_{h-j} \tag{11}$$

$$d_{z_i^{k-l}} = ((I_{z^l_{h-i}} - I_{z^l_{i-j}}) - (I_{z^k_{h-i}} - I_{z^k_{i-j}}))/L_{h-j} \tag{12}$$

If $d_{x_i^{k-o}} = 0$, $d_{y_i^{k-o}} = 0$ and $d_{z_i^{k-o}} = 0$ (o means initial), there is no deformation at all with this angle. So, it can present the form change of accelerator. Take mean of absolute values for entire accelerator:

$$d_{x^k} = \frac{1}{n_d}\left(\sum_1^{n_d}\left(\left|d_{x_i^k}\right|\right)\right) = \frac{1}{n_d}\left(\sum_1^{n_d}\left|((I_{x^k_{h-i}} - I_{x^k_{i-j}}) - (I_{x^o_{h-i}} - I_{x^o_{i-j}}))/L_{h-j}\right|\right) \tag{13}$$

$$d_{y^k} = \frac{1}{n_d}\left(\sum_1^{n_d}\left(\left|d_{y_i^k}\right|\right)\right) = \frac{1}{n_d}\left(\sum_1^{n_d}\left|((I_{y^k_{h-i}} - I_{y^k_{i-j}}) - (I_{y^o_{h-i}} - I_{y^o_{i-j}}))/L_{h-j}\right|\right) \tag{14}$$

$$d_{z^k} = \frac{1}{n_d}\left(\sum_1^{n_d}\left(\left|d_{z_i^k}\right|\right)\right) = \frac{1}{n_d}\left(\sum_1^{n_d}\left|((I_{z^k_{h-i}} - I_{z^k_{i-j}}) - (I_{z^o_{h-i}} - I_{z^o_{i-j}}))/L_{h-j}\right|\right) \tag{15}$$

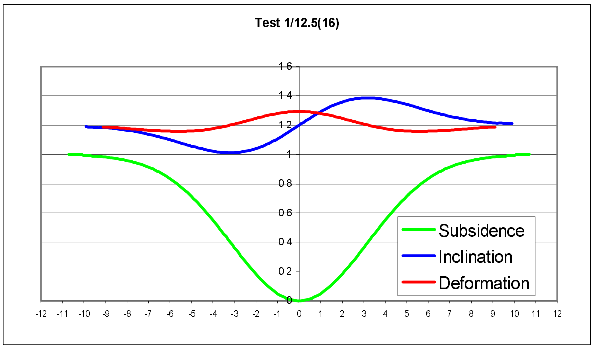

Fig. 4

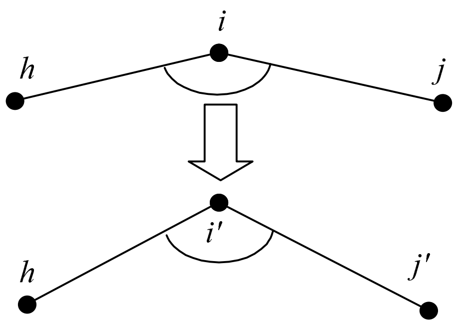

Fig. 3

Inclination and Deformation have the following features:

- Inclination describes the change of longitudinal tilt. It can be used to evaluate the stability of whole accelerator and the stability of a part of accelerator.
- Deformation describes the form change of accelerator. It can be used to evaluate the stability of whole accelerator and the stability of a part of accelerator.
- If different calculation distance L is selected, Inclination and Deformation can present the dynamic situation of accelerator from large change to small change, for example to evaluate the stability of element and the stability of the base (floor).
- It can be proved theoretically that the inclination is the differential of the displacement, the deformation is the differential of the inclination[17] (See Fig.4).
- Reduce greatly the affects of the systematic errors coming from

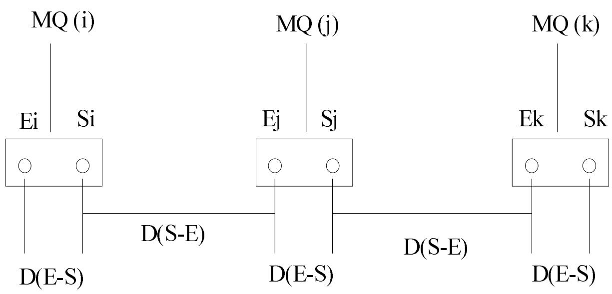

Fig. 5

surveying instruments and surveying methods so that it can more reliably present the dynamic situation.

4. EXAMPLE [17]-[22]

The method was used to LEP (CERN). Some positive results are obtained.

4.1 Vertical inclination and vertical deformation

In order to analyse the stability and dynamic feature of magnet (E-S) and of base (S-E), inclination and deformation were calculated following its structural features (Fig.5). Fig.6 shows us the situation on inclination of the element and the base. Fig.7 shows us the situation on deformation of the element and the base.

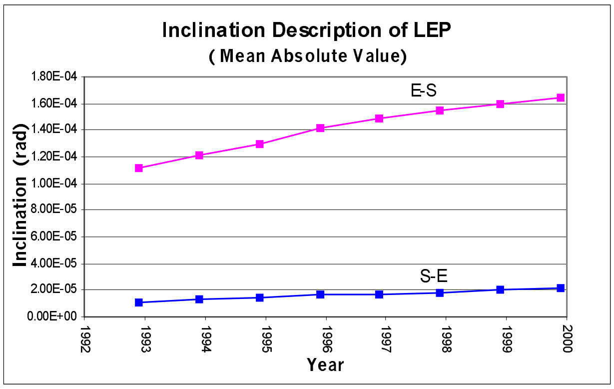

Fig. 6

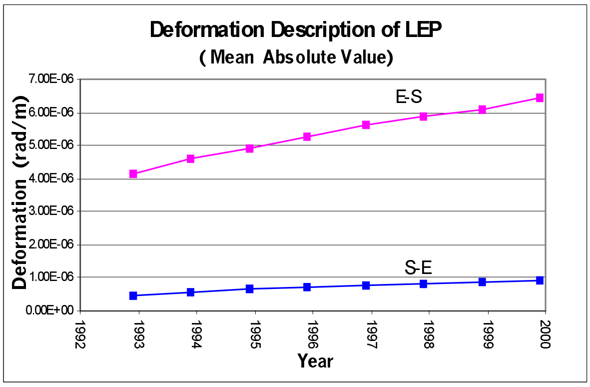

Fig. 7

Some conclusions can be derived as:

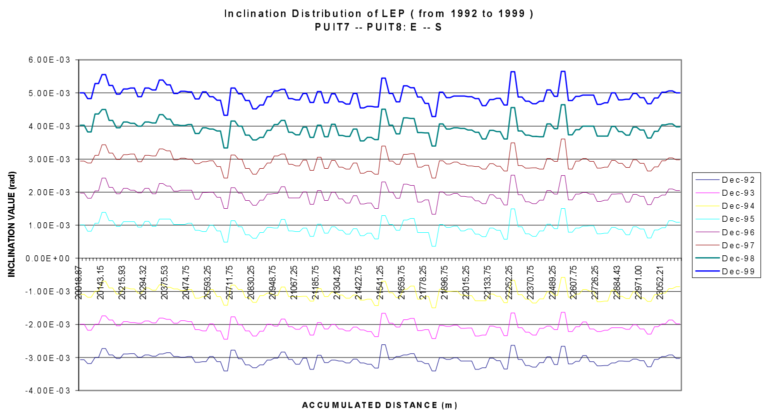

Fig. 8

- The inclination of the quadrupoles (E-S) has been increasing from 1992 to 1999 with an average speed of 0.008 mrad/year. The inclination increase direction of each quadrupole is correspondent to its inclination. This also means that a systematic movement exists on qdadrupoles(see Fig. 8).
- The inclination between two quadrupoles (S-E) has been increasing from 1992 to 1999 with an average speed of 0.0014 mrad/year. This shows a systematic movement exists on the floor of the tunnel. If we convert it into a height difference between two successive quadrupoles, it would be 0.04 mm/year.

- The deformation following the quadrupoles (E-S) has been varying from 1992 to 1999 with an average speed of 0.00018 (mrad/m)/year. The deformation increase direction is correspondent to its original deformation value.
- The deformations following the quadrupoles (S-E) has been varying from 1992 to 1999 with an average speed of 0.00006 (mrad/m)/year. The deformation increase direction is correspondent to its original deformation value.
- The analysis on actual situation of each section based on LEVELING PRECISION shows (see Fig.9 and Fig.10):
  - The inclination variation and the deformation variation existed along the whole tunnel of LEP following studying on the inclinations of S-E.
  - The sections 7 and 8 have an evident inclination variation of quadrupoles. The sections 2, 3 and 7 have evident deformation variation following studying on the inclinations of E-S.
  - The sections 2, 3, 7 and 8 are more active than others.

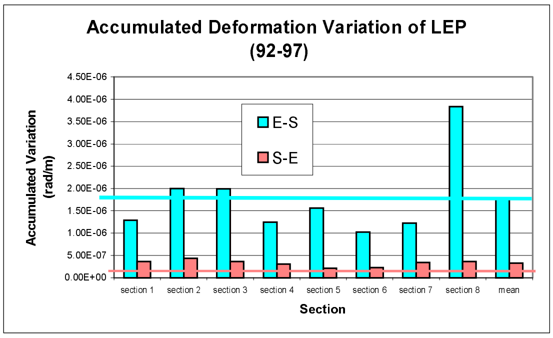

Fig. 9

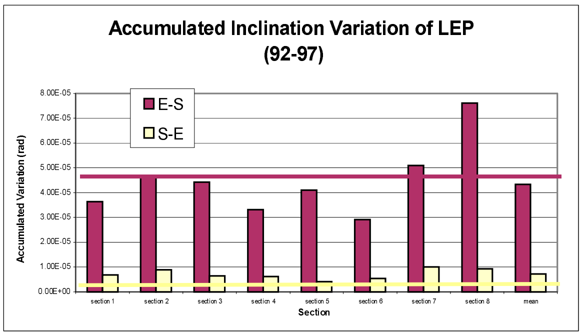

Fig. 10

4.2 Determination of deformed zone

Using the features and distribution of inclination and deformation, deformed zones can be found. Following the analysis on LEP, 7 zones were found. Fig.11~Fig.14 shows us the dynamic situation on inclination and deformation within two of the deformed zones. The dynamic situation in different date can be clearly viewed from those figures.

5. CONCLUSIONS

- Means of Absolute Values of inclination and deformation are good parameters to describe the dynamic situation for linear/curvilinear objects. They can be used to evaluate stability of those objects on combination of surveying precision (tolerance). With the help of their functional relationships, the dynamic features can be analysed and correctly find the deformed zones.
- This method can be used the stability evaluation of linear equipment and structural engineering (railway, high way, bridge, tunnel and accelerator). The deformation

analysis of different magnitude can be realized by change the calculation distance. It can be used to evaluate the stabilities of the whole or part accelerator.

- It can be used to evaluate the stability of element itself and the stability of the support system using those measurements of the points on the elements. It can be used to analyse the deformation and displacement of element itself and the deformation and displacement of the support system using those measurements of the points on the elements.

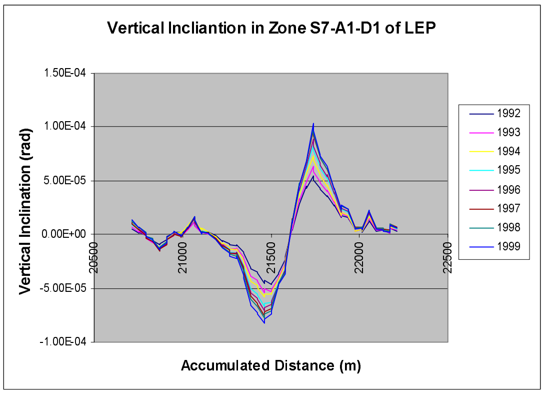

Fig. 11

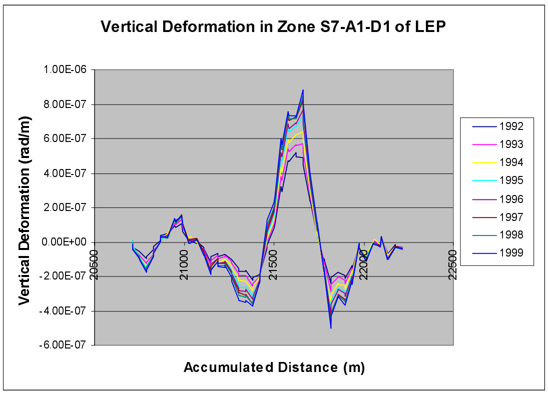

Fig. 12

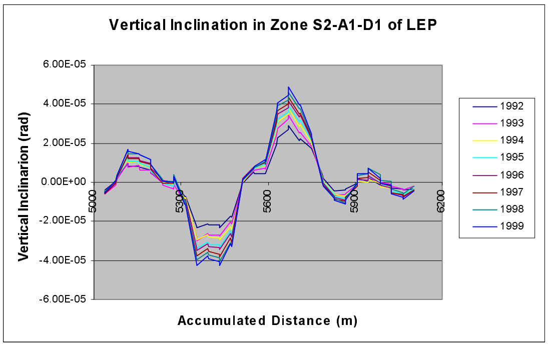

Fig. 13

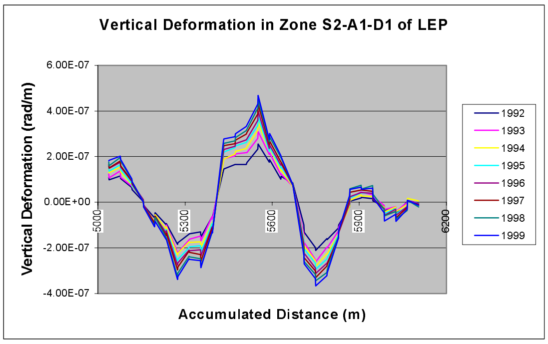

Fig. 14

6. REFERENCES

[1] G.E.Fisher and M.Mayoud, *Some Thoughts on Linear Collider Alignment and Mechanical Stability,* CLIC note 61, CERN, Geneva, 1988.

[2] Vladimir Shiltsev, *Space-Time Ground Diffusion: The ATL Law for Accelerators*. Reports at the Fourth International Workshop on Accelerator Alignment, IWAA 95, Tsukuba, Nov. 14-17, 1995, PP40-69.

[3] Shigeru Takeda et al, *Slow Ground Motion and Large Future Accelerator*, EPAC'96, Sitges, 1996,KEK Preprint 96-38.

[4] A. Sery, *Ground Motion Studies with Respect to Linac Performance*, Proc. LINAC96, CERN96-07

[5] Bruno Esparon, *Nivellement et "Lissage" des Grands Accelerateurs-Analysis des Movements*, Memoire Juin 1997.

[6] Shigeru Takeda et al, *Ground Motion Studies for Large Future Linear Colliders,* PAC'97, Vancouver, 1997, KEK Preprint 97-53.

[7] A. Verdier, *About the "ATL Law"*. Beam Physics Note 30, June 1999.

[8] Shigeru Takeda et al, *Compensation for Incoherent Ground Motion,* IWAA'99, Grenoble, 1999, KEK Preprint 99-135.

[9] Shigeru Takeda et al, *Inherent Ground Motion*, KEK,1-1 Oho, Tsukuba-shi, Ibaragi-ken, 305-0801,Japan.

[10] *Proceedings of The 22nd Advanced ICFA Beam Dynamics Workshop on Ground Motion in Future Accelerators,* November 6 - 9, 2000, SLAC, San Francisco, USA.

[11] Fred Linker, *Estimate of Maximum Expected Rate of Vertical Movement of the SLC Arc Tunnel Floor,* Single Pass Collider Memo CN-212, 1982.

[12] J-P.Quesnel, *Stabilité Vertical des Tunnels du SPS,* LEP/SU/Int, 890s, CERN, 1988.

[13] Rainer Pitthan, *Re-alignment: It is the Tunnel Floor which Moves, isn't it ?*, 4th International Workshop on Accelerator Alignment. Tsukuba, Japan, 1995.

[14] Horst Friedsam, M. Penicka, and J. Error. *Status Report on the Long-term Stability of the Advanced Photon Source*, 5th International Workshop on Accelerator Alignment, Argonne, USA, 1997.

[15] S. Takeda, A. Akiyama, K. Kudo, H. Nakanishi and N. Yamamoto, *Slow Drift and Frequency Spectra on Ground Motion,* 3nd International Workshop on Accelerator Alignment, Annecy, France, 1993.

[16] V.V. Parkhomchuk, V.D. Shiltsev, and G.V. Stupakov, *Slow Ground Motion and Operation of Large Collders,* Part, Accel.46, pp 241-258, 1994.

[17] Fengxiang JIN, *Deformation and Movement Analysis of LEP*, Post-Doctoral Thesis, SUST&SU/CERN. Oct. 1999.

[18] Fengxiang JIN, Michel MAYOUD and Jean-Pierre QUESNEL, *Situation Analysis and Stability Evaluation of Large Electron Positron Collider in CERN*, AVN, No.2, 2002.

[19] Fengxiang JIN, Michel MAYOUD and Jean-Pierre QUESNEL, *Vertical Deformation Analysis of LEP in CERN*, AVN, No.4, 2002.

[20] Fengxiang JIN and Michel MAYOUD etc., *Deformation Analysis of LEP's Tunnel,* 6th IWAA (International Workshop of Accelerator Alignment), 18 Oct 1999, Grenoble, France.

[21] Fengxiang JIN, Michel MAYOUD and Jean-Pierre QUESNEL, *The Statistic Features of A Linear Model and Their Application on Data Processing*. Surveying Review, No.1, 2001.

[22] Fengxiang JIN and Michel MAYOUD, *Data Perturbation Analysis of A Linear Model*, The Chinese Journal of Nonferrous Metals (English Version), No.2, 2000.

[23] Fengxiang JIN, *Pattern Recognition on Surveying Information of Surveying Data,* Chinese Journal of Nonferrous Metals, No.2, 1999.

[24] Fengxiang JIN, *Pattern Recognition Problem in Deformation Monitoring and Analysis,* Chinese Journal of Nonferrous Metals, No.3, 1997.

[25] Fengxiang JIN and Bin XU, *Geometrical Features and Statistical Tests of GM Model*, Chinese Journal of Nonferrous Metals, No.2, 1996.

[26] Michel MAYOUD, *Méthodes d'évaluation statistique de la qualité des résultats topométriques*, XYZ, No.5. 1980.

[27] Amanda MASON, *Vertical Control of LEP Quadrupoles 1993-1994*. Semp. 1994.

[28] Bruno ESPARON, *Nivellement et "Lissage" des Grands Accelerateurs-Analysis des Movements*, Memoire Juin 1997.

[29] Fengxiang JIN, *Statistical Diagnostics and Deformation Monitoring Theory,* Agricultural Scientific and Technical Press of China. Sept.1995.