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CONTROL OF THE CLOSED ORBIT
IN SYNCHROTRONS BY DISPLACEMENT OF MAGNETS

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At the 1965 Conference in Frascati, results of Lambertson and Laslett[1] were reported concerning the adjustment of a closed orbit through use of information obtained from electrodes that detect the location of the synchrotron beam within the vacuum chamber. Such a technique would be useful for compensating errors that develop in the magnet ring, and also would be helpful in repositioning the beam for various research applications. The actual adjustment of the beam position could be effected by magnetic corrections, by positional adjustment of the magnetic elements of the ring, or by a combination of these methods -- and in practice magnetic corrections might best be used to influence the orbit early in the acceleration cycle. The work to be described in the present report concerns further study of the effectiveness of positional adjustments for compensating positional errors of the magnet-ring structure.

As in the work previously reported,[1] we have employed as an example a magnet structure containing a large number of moveable support points (276),[2] that exceeds the number of locations at which it would be practicable to provide beam-control sensors. A correction system therefore does not, under these circumstances, provide a unique means of annulling the orbit displacements at the pickup stations.

* Work done under the auspices of the U.S. Atomic Energy Commission.

Accordingly it is expedient to combine the possible corrective support movements into a limited number of groups, each involving the movement of 10 to 11 neighboring supports to provide a smooth bell-shaped hump (or slump), and to correct or realign the magnet structure by movements of various magnitudes for these individual groups. With this grouping restriction, the movements to produce a desired repositioning of the closed orbit at the detector locations are essentially unique; it is desirable, however -- in the interest of avoiding unproductive movements and in suppressing undesired beam excursions at azimuths not monitored by detector units -- to eliminate from the correction certain "eigenvector movements" that would introduce spatial variations of either very high or very low frequency or, generally, for which a nominal amplitude of movement has very little effect on the beam.[1]

The computational work presented previously[1] concerned the adjustment of 72 support groups, to reposition 276 individual supports, on the basis of information derived from detectors at 72 locations around the orbit (≈ 4.3 sensors per betatron wavelength). We now wish to contrast these results with similar data obtained by use of data from 144 detector locations, corresponding to approximately 8.6 sensors per betatron wavelength (Table I). In each case, a certain number (19 and 23, respectively) of the relatively unproductive eigenvector movements have been suppressed. Judged by the maximum orbit displacement after application of the proposed correction, significantly improved alignment is seen to result by the use of information from 144 sensors in those cases for which the short range nature of the initial misalignment makes it difficult to provide effective compensation.

The effectiveness of the proposed control or correction system, as we have conceived it, appears to be highly insensitive to moderate errors in one's knowledge of the true dynamical transfer matrix of the

accelerator (Table IIA). Thus if the actual "tune", Q, of the accelerator differs from that of the design machine (but does not become closer to an integer than about one-eighth of a unit), the recommended corrections are almost as effective as they would be for an ideal machine, and after several iterations of the correction procedure would give results that converge exactly to these expected ideally. Similarly, if the distinction between the conceptual accelerator (on the basis of which the recommended corrections are computed) and the actual machine lies only in the difference of means for obtaining an actual measured Q, the effect of the recommended corrections immediately is virtually identical with the effect obtained ideally (Table IIB).

In Table III are given the effects of "noise" that will occur in (a) the information derived from the beam sensors and (b) in the corrective movements that actually are applied to the ring-element supports. The presence of such sources of error (sensor- or support-noise, respectively) degrades somewhat the effectiveness of the highly complete compensation achieved in the case of the longer wave length smooth initial distortions, but does not markedly degrade the correction for the more difficult short-wavelength errors. The effect of sensor noise, moreover, "levels off" upon repeated use of the corrective procedure, since errors introduced because of this noise are intrinsically removable. Errors that result from incorrect adjustments of the supports, on the other hand, will gradually accumulate, since such errors in principle cannot be completely removed or compensated by use of the grouped supports that are visualized for application of the proposed correction system. Uncorrectable errors that gradually accumulate from this and other sources of disturbance must ultimately be suppressed by a re-survey of the ring, but such re-surveys should be required much less frequently and would need to meet less stringent accuracy requirements when used just for initial alignment and

subsequently in connection with a closed-orbit control system. Thus, it appears that reasonably realistic noise levels in the survey and the control system components are tolerable.

Finally, one might note that the beam-sensor information affords the opportunity of judging whether the significant readjustments need be made only locally, so that there would be less effort involved in making these readjustments and also a reduction of the support-noise errors that necessarily are associated with putting the recommended readjustments into effect. In computational examples for a 144-sensor system, with a certain amount of sensor noise present (R.M.S. = 0.010 unit), we have found that localized disturbed regions that generate 1 unit of closed-orbit displacement can be identified in the presence of a modest background of misalignments around the ring (R.M.S. misalignment of supports = 0.014 unit) by noting the regions wherein the closed-orbit excursions differ significantly from the free-oscillation waveform. By restricting the corrective movements to those support groups within and bordering such identified regions, a localized correction can be prescribed. In many cases this less general procedure will be found to provide an acceptable and efficient correction.

As implied above, further investigation of orbit-control systems should include the use of magnetic corrective elements as well as provisions for readjustment of the physical support structure. The effectiveness of such a system should be studied both for the accommodation of physical movements and for the ability to compensate magnetic errors in the accelerator ring. From our results obtained up to the present we are encouraged to believe that an orbit-control system employing the concepts we have outlined here would be a highly useful adjunct to a large accelerator facility, for which reliability of performance is especially important, and more specific work directed to the design of such a system would be warranted when the specific configuration and parameters of such an accelerator become definite.

REFERENCES

(1) G. R. Lambertson and L. Jackson Laslett, "Derivation of Corrections to Control the Closed Orbit in an Alternating-Gradient Synchrotron," Proceedings, V International Conference on High Energy Accelerators, Frascati, 1965 (C.N.E.N., Rome, 1966), pp. 26-33.

(2) Lawrence Radiation Laboratory Report UCRL-16000 (1965).

TABLE I

RATIO OF FINAL TO INITIAL MAXIMUM ORBIT DISPLACEMENT *

INITIAL MISALIGNMENT	(S2) Single Support Point	Biased-Cosine Movement, Length: (S6) 5L = 77.7 m	(S7) 9L = 140 m	(S8) 13L = 202 m	(S9) 17L = 264 m
72 Sensors Exclude 19 Eigenvectors	0.734	0.402	0.138	0.0515	0.0580
144 Sensors Exclude 23 Eigenvectors	0.505	0.0367	0.0415	0.0476	0.0614

* Displacements measured relative to the magnet structure and sampled computationally at 288 locations around the magnet ring.

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TABLE II

EFFECT OF CORRECTION PROCEDURE APPLIED TO AN ACCELERATOR
WITH FOCUSING CHARACTERISTICS DIFFERING FROM THE DESIGN MACHINE

Length of initial misalignment: 13 L = 202 m. (S8)
72 Sensors
19 Eigenvectors excluded

A. Actual Q differs from Design Value

Q, Design	16.725	16.725	16.725	16.725	16.725
Q, Actual	16.525	16.625	16.725 (Design Machine)	16.825	16.925
Ratio: Max. Orbit Displ., Initial* / Max. Orbit Displ., Final*					
After First Application	0.3467	0.2167	0.0515	0.8176	8.9806
After 4 Applications	0.0585	0.0535	"	0.1561	↓ Divergent
After 8 Applications	0.0524	0.0518	"	0.0613	

B. Actual Q Restored to Design Value by Tuning Adjustments

Q, Design			16.725	16.725	16.725
Q, Actual (before restoration)			16.725 (Design Machine)	16.825	16.925
Ratio: Max. Orbit Displ., Initial* / Max. Orbit Displ., Final*					
After First Application			0.0515	0.0489	0.0506
After 4 Applications			"	0.0515	0.0512
After 8 Applications			"	0.0515	0.0512

* Sampled computationally at 288 locations around the magnet ring.

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TABLE III

R.M.S. CLOSED-ORBIT DISPLACEMENT

RESULTING FROM CORRECTION PROCEDURE WITH NOISE PRESENT

		72 Sensors 19 Eigenvectors Excluded	144 Sensors 23 Eigenvectors Excluded
A. SENSOR NOISE:	R.M.S. Noise Value = ϵ_b		
	R.M.S. Orbit Deviation:*	$0.83\ \epsilon_b$	$0.86\ \epsilon_b$
B. SUPPORT NOISE:	R.M.S. Noise Value = ϵ_h ‡		
	R.M.S. Orbit Deviation*		
	From a single correction	$5\ \epsilon_h$	$5\ \epsilon_h$
	From n previous corrections	$1.3\ \sqrt{n}\ \epsilon_h$	$0.9\ \sqrt{n}\ \epsilon_h$
	Uncorrectable fraction of the Support Noise:	≈26%	≈18%

* Sampled computationally at 288 locations around the magnet ring, midway between F and D magnet units.

‡ Support noise introduced into 276 supports at each correction.

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