DAMPING COHERENT OSCILLATIONS IN THE AGS*

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Summary. In order to further study the vertical instability in the Brookhaven AGS[1] a narrow band feedback damping system has been developed. The damping force is obtained from a pair of 6 ft long coils located in one of the straight sections. The damping signal is provided by a pair of pickup electrodes at an angle $\theta = 10.7^{o}$ upstream from the coils. Since $\nu_v \cong 8.8$, $\nu\theta \cong \pi/2$. The damping is proportional to $\sin[n\theta - (n-\nu)\, 2\pi\, f_o T]$ where n is the mode number, fo the rotation frequency and T the time delay between the pickup and damping elements. The system is designed to work over a range in fo from 200 kc to 370 kc. In this range, with T = .14 μsec, and for n = 7-11, the angle in brackets varies ± 19° from $\pi/2$ if ν changes about ± 1%. With a simple filter in the feedback loop it is possible to provide damping for the lower order modes n = 9,8,10, without exciting those for n = 7,11 etc. under normal operating conditions.

Introduction

The general design requirements for feedback systems that will damp coherent betatron oscillations in an accelerator have been developed by F.E. Mills[2]. If θ is the azimuthal angle between the point where the beam position is measured and where the damping force is applied, T the signal time delay between these elements, ν the betatron wave number and ω_o the beam angular frequency then the force will be proportional to the displacement and $\sin[n\theta - (n-\nu)\, \omega_o T]$. Here n is the mode number of the oscillation which in the AGS can be less than ν, as well as larger than ν. One can make the damping independent of n by choosing θ and T such that $\omega_o T = 2\pi N + \theta$ where N is an integer[2]. This requires that T vary inversely with ω. If one wishes to damp a large number of modes or, as can occur in a machine with several bunches, to damp modes where the bunches are not in phase then wide band electronics must also be employed. For in the latter case the signal obtained from an individual bunch displacement must be applied to that bunch, which also puts tight requirements on the variation of T with ω. Optimum damping using the Mills scheme is obtained if one can make $\sin \nu\theta$ (or $\sin \nu\omega T$) = ± 1 i.e. the damping signal is applied to the beam after an odd number of a quarter betatron wave lengths have occurred. Such a system is in operation at the Argonne ZGS[3].

The possibility of using a narrow band feedback system to damp the vertical instability in the Brookhaven AGS is suggested by the following. When the oscillations occur the modes observed n = 9,8,10, always begin with all twelve bunches in phase, at least for intensities up to 1.6×10^{12} protons per pulse. Thus if only the lower order modes are to be damped the circuits employed can be relatively narrow band with the requirement that the gain fall off rapidly enough so that the higher order modes are not strongly anti-damped. This would then permit the use of an existing pair of 6-ft long five-turn coils, located at the sides of the useful aperture in one of the AGS 10-ft straight sections, to provide the damping force. These coils were originally employed to measure vertical ν values by rf excitation of coherent betatron oscillations.

The need for a variable delay (T) is obviated by two facts. First, the range of ω_∞ = 371 kc i.e., about 1.8:1. Most important however is the presence of a standard pair of vertical position electrodes at an azimuthal angle of $\theta = 10.7^{o}$ upstream from the above mentioned 10-ft straight section. Thus if one uses .86c propagation velocity cable T ≅ .094 μsec plus any nominal delay present in electronics. The changes in $(n-\nu)\omega_o T$ with n, ν, ω_o for fixed T are therefore not overwhelming for the lower order modes. Furthermore, because $\nu = 8.8 \pm 1\%$, $\nu\theta \cong \pi/2$ and near optimum damping is possible for the lowest order modes i.e., $\sin[n\theta - (n-\nu)\, \omega_o T] \cong 1$. Table 1 shows the variations in this angle for different n's over the normal range of ν_v and ω.

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Design Considerations

System Gain

It can be shown[2] that if λ is the growth rate of the instability that one wishes to damp it is necessary to have

$$\left| \frac{\Delta p}{p} \frac{v}{4\pi\, \nu_y} \frac{\sin[n\theta - (n-\nu)\, \omega_o T]}{y_o\ (t-T)} \right| > \lambda$$

where v is the beam velocity, p its momentum, Δp the transverse momentum imparted by the beam by the damping coils, and y_o (t-T) the beam displacement as measured by the pickup electrodes. The term in brackets is the damping rate of the feedback system. Now $\Delta p = Ky_o$ where K depends upon the pickup electrode position sensitivity, the beam intensity and the gain of the associated electronics, including the damping coils. The sign of $K \sin \varphi$ is chosen to damp the lowest frequency mode present in the machine. We can rewrite the above criterion as

$$|K| > \frac{4\pi\, \beta\gamma\, m_o c \nu_y \lambda}{v} = \frac{4\pi\, \gamma\, m_o\, \lambda}{\omega_\infty\, \bar{\beta}}$$

where $\bar{\beta} = \frac{R}{\nu_x}$,[6] R = the synchrotron radius and $\nu_x \cong \nu_y$.

In the AGS $\bar{\beta} \cong 12{,}850\ \text{cm}/8.7 = 14.8\times10^{2}$ cm. $\omega_\infty = 2\pi \times 371$ kc and one has observed for the early coherence (obtained by flat topping the AGS magnet at about four times injection field) we must have

$$|K| > \frac{1.7 \; .938 \frac{\text{Bev}}{c} \; 2}{371\text{x}10^{3}\text{x}14.8\text{x}10^{2}\,\text{cm}} \; \frac{28}{\text{sec}} = 16.2\text{x}10^{-8} \; \frac{\text{Bev}}{\text{c cm}}$$

to damp the observed n = 9 mode.

The theory of the resistive wall instability[5,6] predicts that the growth rate should vary as $\frac{1}{\gamma}$ which indicates that K should be independent or momentum ($\beta \simeq 1$). However, at higher energies $\approx$ 18 Bev ($\gamma \cong 19$) growth rates for the n=9 mode of 30 sec^{-1} have been observed at intensities of $1.3\text{x}10^{12}$ protons per pulse in the AGS.[1] Thus a value of $K > 180 \times 10^{-8} \frac{\text{Bev}}{C}$ would be necessary to damp this instability. Since the growth rate is ~N the number of particles per pulse, K must also increase with N.

Now the two five-turn damping coils are driven in parallel in order to raise the resonant frequency of the system. The field along the central axis is such that $\Delta p = .75\text{x}10^{-5} \left(\frac{\text{Bev}}{C}\right) \frac{1}{\text{amp}}$ for this connection. Thus for damping the low energy coherence we need

$$|K'| = \frac{|K|}{.75\text{x}10^{-5} \frac{\text{Bev}}{C}} \text{amps} > .022 \; \frac{\text{amps}}{\text{cm.}}$$

as the gain from the pickup probes to the damping coils. The pickup electrode position sensitivity is 16% per cm. and the overall output for $1.3\text{x}10^{12}$ protons with input cathode followers driving 180Ω line, is 65 mv/cm. A differential to single ended gain of

$$\rho > \frac{.022 \; \frac{\text{amps}}{\text{cm}}}{.065\text{v/cm}} = .34 \; \frac{\text{amps}}{\text{volt}}$$

is then required to damp the low energy coherence or 3.8 $\frac{\text{amps}}{\text{volt}}$ for the high energy coherence.

This relatively modest gain requirement is one of the reasons for choosing to extract the low frequency coherent wave information directly from the pickup electrode signal with a filter. The amplitude is then proportional to the intensity and the beam displacement. It is possible to use a detector to extract this information in which case a gain proportional to the bunching factor is obtained. However, some additional wideband amplification would be required and as discussed below eventual filtering of the resulting signal is still necessary.

Damping Coil Driver

It is evident from Table 1 that all the modes listed could be satisfactorily damped if the necessary amplification introduced negligible phase shift up to say 1 mc. However, it was not possible to achieve this in the original design for two reasons. The two existing five-turn coils (6-1/2 ft x 3-3/4-in.) when connected in parallel have a self-resonant frequency of $\approx$2 Mc. They are driven by a two-stage amplifier with both interstage and output transformers, a design which was dictated by the desire to have a high current (up to 1 amp peak) capability so that this part of the system could still be used to excite coherence at high energy. The resulting system after some sacrifice of output current capability still produces 90° of phase shift at 1.5 Mc with a 12% peak in the output. At/Mc the phase shift is 53° and at 350 kc 19°. The low frequency response is 3db down at $\approx$ 15 kc. With a 3:1 step-down in the output transformer the overall gain is 275 ma/volt push-pull input to single ended output. Thus the minimum gain required between the output of the pickup electrode cathode followers and the driver input is 340/275 = 1.24.

Filter

The primary purpose of the filter is to provide sufficient attenuation above the frequency at which (arg K + φ)>π so that the higher order modes will not be strongly excited. Thus at most a simple single time constant filter, producing $\pi/2$ phase shift can be used. If the elements providing the damping force behaved as a pure L or C over the entire frequency range of interest the driving stage could be designed to provide the necessary rolloff. This is not possible with the existing components for reasons outlined above. In fact the phase shift, without loss of gain, present in the coil and driver made it questionable that a satisfactory compromise between gain and bandwidth could be obtained.

Because the n=8 mode, when it occurs, has been observed to have a growth rate about one half that of the n=9 mode and the n=10 mode has never been seen to grow appreciably it was felt that the 3 db. point of the filter could be $\cong$ 300 kc. It would then also serve to remove most of the bunch frequency ($12f_0$ in the AGS) and its harmonics from the beam position signal. A series RC was used and its location chosen to make maximum use of this feature. Thus 33 KΩ resistors were placed in series with the outputs of the pickup electrodes so that the input capacity of the cathode follower preamplifier could provide the necessary time constant. This reduces the dynamic range, due to the bunched beam, which these circuits have to handle and hence provide for linear operation over a larger range of beam intensities. Similarly the following amplifier stages are less likely to be over driven by the individual bunch signals. The possibility of this is one argument against filtering in the output stage as suggested above. The amount of this type of signal arising from a vertical bump in the equilibrium orbit at the observation station is minimized by trimming the pickup electrode capacities to balance out any offset present.

The overall response of the filter and driver is such that at $\cong$550 kc arg K=$\pi/2$, and $|K|$=.5, but since the damping force is ~ $|K|\sin(\varphi+\arg K)$ significant antidamping will occur at somewhat higher frequencies. At about 60 Kc, arg K becomes negative but $-\pi/2$ is reached below 10 Kc which is a safe margin from the lowest frequency coherence mode of interest ($\approx$24 Kc).

Difference Amplifier

For all initial tests of the system a Tektronix "G" preamplifier and P-132 power supply has been used for the difference amplifier. A maximum push-pull gain into 180Ω of 20 is available from this unit thus affording a comfortable margin for damping the low energy coherence. Over the frequency range of interest here (up to 2 Mc) this combination acts like a constant time delay of about 46 nsec. and hence its effect on the system response is included by adding this delay to T as shown in Table 1. It is planned to replace this amplifier with one that has twice the gain and less than half its effective phase shift at 1 Mc.

System Performance

Figure 1 is a block diagram of the complete system. The switches are coaxial relays that make it possible to open the control loop and externally excite the beam. There can be several milliseconds jitter in their action and eventual replacement with solid state switches is planned.

Under normal operating conditions the vertical instability is not present in the AGS[1] up to intensities of 1.7×10^{12} protons/pulse. In order to study the effectiveness of the damping system rf excitation is used to stimulate the high energy coherence while it occurs spontaneously at low energies ($\gamma \geq 1.5$) if one flat tops the magnet power supply early in the cycle. Growth of the high energy coherence can be traced to the fact that $\partial\nu_y/\partial r$ changes sign late in the cycle (around 17 BeV) and remains near zero for many tens of milliseconds. On an early flat top $\partial\nu_y/\partial r \cong 0$ also, and as a result the spread in betatron frequencies over the beam is very small. The effect of Landau damping is thus greatly reduced and any instability present can be expected to show itself or be easily stimulated.[4,5] The performance of the damping system in these circumstances will then give a true picture of its characteristics.

Figures 2,3 and 4 show the operation of the system on an early flat top ($\gamma \cong 1.7$). The upper trace is a vertical sum signal and the lower a vertical difference signal. The gradual loss seen on the sum signal is due to gas scattering while the early notch occurs when the machine goes into the flat top. In the first photo, taken with an earlier and narrower band version of the driver using series coil connections, the loop was closed when the flat top started and the system gain was about twice the 16.2×10^{-8} BeV/c cm. calculated above. The coherence is seen to grow to an amplitude of .15 cm. peak to peak in the n=9 mode $(n-\nu)f_0 \cong 55$ kc, while with the damper off amplitudes of 1 cm. p.p. were observed for the 1.3×10^{12} protons/pulse intensity obtained on this day.

Antidamping of a higher order mode can occur later on during the flat top at a time depending upon the loop gain, beam intensity, and whether the damper is turned on early or late. This is not always a pure mode, i.e. all bunches in phase with each other, but it is still possible to identify the predominant frequency by observing the pickup electrode signal or the current in the damping coils. In Fig. 2 the n=7 mode is the one excited $|n-\nu|f_0 \cong 525$ Kc, the low frequency being a result of the narrower bandwidth. The next two photographs were taken with the present system operated at a gain of almost sixteen times the 16.2×10^{-8} BeV/C cm. value. Fig. 3 shows the loop being closed after the coherence has grown spontaneously and gives a good measure of its growth rate ($\cong 40$ sec^{-1}) for the $1.4^{+}\times10^{12}$ proton/pulse available for this run. One can see also how rapid the damping rate is at eight and sixteen times the calculated value; for in this case one of the coaxial relays closed several milliseconds after the other. This is the reason for the change in slope of the damping envelope near the end. In Fig. 4 the damping system was turned on early and hence only the antidamped mode eventually appears. It is an n=12 mode with a frequency $(n-\nu)f_0 \cong 960$ Kc although the n=6, 11 modes are also antidamped. However, this result can be explained by the previous remarks concerning the magnitude of $|K| \sin(\varphi + \arg K)$. When the loop gain is reduced to $4\times16.2\times10^{-8}$ BeV/C cm. (normalized to 1.3×10^{12} protons/pulse) no higher order mode appears and the coherence is reduced to .025 cm p.p. amplitude.

Some damping of a stimulated n=9 mode at high energy ($\gamma \cong 19$) has been obtained with a gain of about 500×10^{-8} BeV/C cm. and an intensity of 1.4×10^{12} protons/pulse. Occasional later growth of a n=6 mode (≈ 1.06 Mc) was observed. At twice this gain complete damping was obtained but at the expense of always stimulating the higher order mode. In both cases this mode disappears when the initial excitation is removed.

Thus the present system can adequately damp the low energy coherence even in the absence of significant Landau damping which is present under normal operating conditions, but is marginal for the high energy instability where normally Landau damping is minimal. For it is not evident that if the gain is made large enough to suppress completely the spontaneous growth of the lower order modes, n=9,8 one of the antidamped modes will not appear. It is possible to provide some Landau damping by programming the sextupoles in the AGS[1] which would then reduce the gain requirement put on the damping loop. However, it is felt that an additional improvement in the bandwidth i.e., the frequency at which $\arg K = \pi/2$ will permit satisfactory operation at high fields. This will be achieved by using a separate two-turn coil driven by lower current but much higher g_m tubes. It will be possible to maintain the same gain and increase the resonant frequency of the output stage to beyond 5 Mc. Thus up to 1 Mc and beyond the principal phase shift in K will come from the filter which is limited to $\pi/2$. In this manner it seems possible that at least a factor of two increase in bandwidth will be obtained.

Even with this improvement however, the use of the narrow band system will eventually become limited as the AGS intensity is increased. For the loop gain will have to increase linearly with beam intensity and while the lower modes are still damped the strength of the antidamping as well as the growth rates of the antidamped modes will be increasing. Thus if the loop response is not changed there will be some intensity at which the system will always oscillate. It is expected that this will occur at high energies first since with the present system the stability is marginal as discussed above. However, before this limitation sets in the other basic limitation of a narrow band system may render it ineffective. For it is quite possible that at higher intensities coherent modes where the bunches are not in phase will start to appear[5] even though the lower order "collective"[5] modes are damped. Since individual bunch motion is not detected satisfactory damping of these modes cannot occur. It will still be interesting to observe the action of the system on such an instability if it arises.

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References

1. E.C. Raka, Bull. Amer. Phys.Soc. 11,469 (1966)
2. C.H. Pruett, R.A. Otte, F.E. Mills, Proc. V International Conference on High Energy Accelerators, 343, 1965.
3. J.H. Martin, R.A. Winge,R.Hilden, F.E. Mills, Ibid. 347
4. L.J. Laslett, V.K.Neil and A.M. Sessler, R.S.I. 36, 426, (1965).
5. E.D. Courant, A.M. Sesslet, R.S.I. 37,1579(1966).
6. E.D. Courant, H.S. Snyder, Annals of Physics 3, 1, (1958).

TABLE I

$T = .14\mu sec$

ν	n	f_0	$n\theta$	$-(n-\nu)\omega_0 T$	φ	$(n-\nu)f_0$
8.88	7	200 kc	74.8°	+19°	93.8°	376 K
	8		85.5°	+8.9°	94.4°	176 kc
	9		96.1°	-1.2°	94.9°	24 kc
	10		107°	-11.3°	95.7°	224 kc
	11		117.7°	-21.4°	96.3°	424 kc
8.72	7	371 kc(f_∞)	74.8°	+34.2°	109°	638 kc
	8		85.50	+14.3°	99.8o	267 kc
	9		96.1°	- 5.6°	90.5o	104 kc
	10		107°	-25.4°	81.6°	475 kc
	11		117.7°	-45.2°	72.5°	846 kc

Ideally $T = \frac{\theta}{.86\omega_\infty}$ and one can write $\varphi = [n\theta - (n-\nu)\omega_0 T] = n\theta\left[1 - 1.16\frac{\omega_0}{\omega_\infty}\right] + \nu\theta\frac{1.16\omega_0}{\omega_\infty}$ which shows the significance of $\theta\nu \cong \pi/2$.

The additional .046 μsec. delay, some of which can be eliminated, comes from the difference amplifier used in early tests.

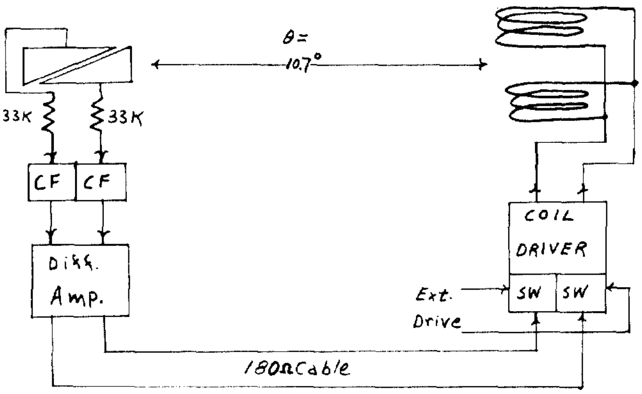

Fig. 1. Block Diagram of Damping System.

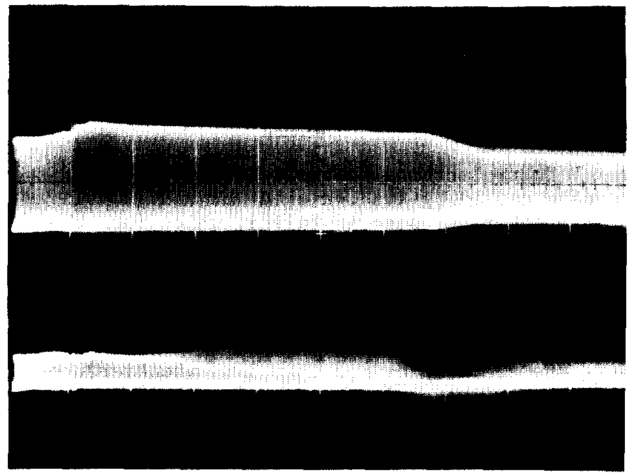

Fig. 2. Vertical Pickup Signals; 20 milliseconds/cm.

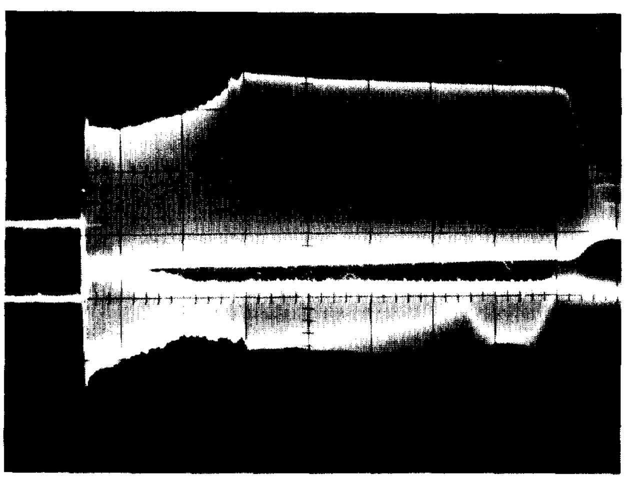

Fig. 3. Vertical Pickup Signals; 20 milliseconds/cm.

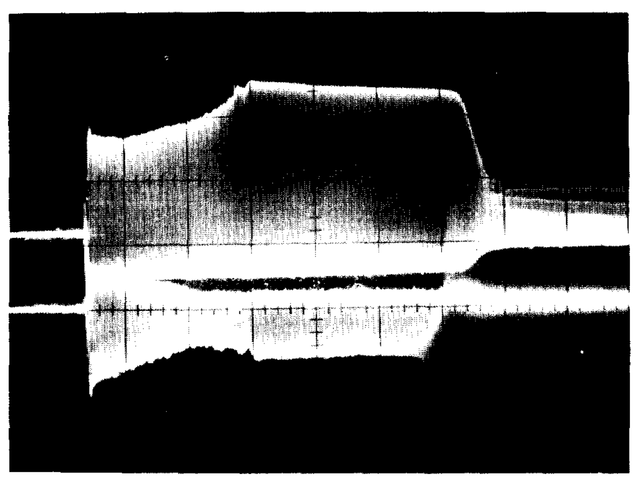

Fig. 4. Vertical Pickup Signals; 20 milliseconds/cm.