AUTOMATIC STABILIZATION OF UNDERWATER ACOUSTIC BEAMS WITHOUT MECHANICAL MOTION OF THE TRANSDUCER

by D. G. TUCKER and J. G. HENDERSON
Electrical Engineering Department,
University of Birmingham, England

Note on Authors

David Gordon TUCKER holds the degrees of B. Sc., D. Sc., and Ph. D. of the University of London, all in Engineering. He is a Member of the *Institution of Electrical Engineers* and of the *British Institution of Radio Engineers.*

Since 1955 he has been Professor of Electrical Engineering and Head of the Department of Electrical Engineering, University of Birmingham, England.

John Gibb HENDERSON holds the degree of B. Sc. of the University of Durham in Electrical Engineering, and is an Associate Member of the *Institution of Electrical Engineers.*

Since 1949 he has been a Lecturer in Electrical Engineering at the University of Birmingham, England.

Summary

A method of electronic stabilization of beam direction in an echo sounder or asdic (or *sonar*) system is described; there are no moving parts at all, except in the gyro equipment, and the cost of the electronic equipment and its maintenance is probably much less than that of corresponding mechanical arrangements. The principle involved is to transmit the acoustic energy over a wide angle covering the expected range of the ship's motion, but to receive the echo with a narrower beam which is maintained in its required direction by deflecting it electronically from the normal axis of the transducer by the amount of the error in the ship's position due to roll or yaw. The method of beam deflection used is to transform the received signals from the three or more sections of the transducer to a variable frequency controlled by the position error and then to connect the sectional outputs together via phase-shifting networks whose phase shift varies with frequency.

INTRODUCTION

In various applications of underwater acoustic echo-ranging, advantages would accrue from the stabilization of the acoustic beam against undesired ship's motion. For example, in an echo sounder, where the beam is nominally vertical and the depth of water under the ship is measured, the rolling motion of the ship swings the beam from side to side; and if the angle of roll exceeds half the beamwidth of the beam, then the dominant echoes received at the limit of roll do not come from the bottom underneath the ship but from a more distant part of the bottom. This means that the apparent depth indicated on the recorder varies from the true depth while the ship is passing through the vertical position to a greater depth when the ship is rolled over to one side — contributing to the well-known wavy echo trace. If the beam were kept always vertical, the trace would be much smoother, since then only the vertical bodily displacement of the ship would be shown on the trace; in shallow water (say 20 fathoms) the improvement might be small if the sea were very rough, but in depths of say 50 fathoms or more, the improvement could be very marked. To overcome the difficulty merely by increasing the beamwidth of the system would seriously reduce the value of the equipment for survey purposes, and would, in any case, always pose the question as to whether the indicated depth is really the depth below the ship or is the slant depth of a shallower region to one side of the track. Geometrical considerations of this type have been discussed in a paper by SCHÜLER (1) * and the improvement in performance produced by stabilization of a directional echo sounder has been commented on by HERDMAN (2).

The advantages of stabilization of a vertical beam would be even greater in fish location by means of an echo sounder, for then it is important to keep looking at the same place on the bottom, otherwise the information regarding the fish will be erratic, unreliable and difficult to interpret.

Stabilization against rolling motion may be important, too, in a *fixed-beam* surveying asdic (3), where the beam is directed at right angles to the ship's fore-and-aft axis in an almost horizontal position. If the vertical beamwidth is large, it might at first be thought that stabilization would be unimportant; but since the secondary lobes of the vertical directivity pattern can be used to give important information (3), it is still desirable to provide stabilization. It is also often desirable to avoid reverberation (or back-scattering) from the sea surface and to avoid multiple-path transmission involving reflection at the surface, and it is then arranged that the beam axis is tilted down so that the horizontal direction corresponds to a zero of the directivity pattern; it is obvious that this is ineffective unless the beam has stabilization against roll.

Again, if such a surveying asdic has a very narrow beamwidth in the horizontal plane, it may well be found that yawing of the ship swings the beam sufficiently to spoil the record, and then stabilization against yaw would be worth while. Most small ships yaw a few degrees, so that if beamwidths of the order of 1° are used, the problem is almost certain to be encountered. This applies, too, in a horizontal-beam search-type asdic, where difficulty may be experienced in holding the beam on to a *target* when a narrow beam is used to give accurate location or to improve the echo/reverberation ratio.

* These numbers refer to the references listed at the end of the article.

Stabilization is rarely provided in echo sounders and commercial asdic equipment because of the prohibitive cost of the mechanical arrangements normally thought necessary. Echo-sounder transducers, for instance, are usually fixed rigidly to the hull, and to provide mechanical motion for stabilization would require pivots and driving shafts which would greatly increase the cost of installation and maintenance.

It is possible, however, to provide stabilization against roll and yaw by purely electronic means, involving no additional mechanical arrangements for the transducer apart from more wires in the cable connecting it to the equipment in the ship. The initial cost of the additional electronics is unlikely to exceed that of the mechanical arrangements otherwise necessary, and in most cases it is likely to be very much lower; maintenance is quick and easy and is done from inside the ship — at sea, if necessary — and requires no docking. The principle involved is discussed in the next section, but briefly it consists of the following :

(*a*) the transmitted pulse is sent from a smaller transducer (or a part of

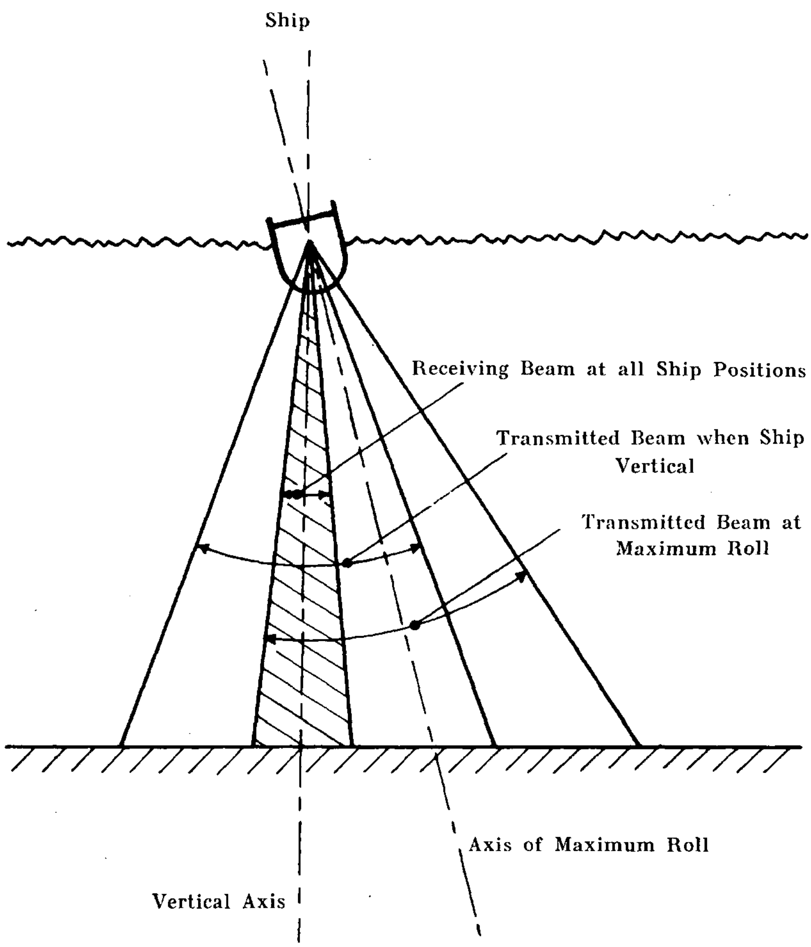

FIG. 1. — Showing Stabilization of Receiving Beam and required Width of Transmitted Beam in an Echo Sounding System.

the receiving transducer) so that the sound energy is transmitted into an angular sector in the plane of stabilization which is equal to the angle which would be swept by the receiving beam if it were unstabilized,

(*b*) the receiving transducer has its direction of peak response (i.e. axis of *beam*) deflected electronically under the control of a signal proportional to the error between the ship's instantaneous position and its mean or desired position. Therefore, provided the equipment is correctly set up, the receiving beam lies always in the desired direction.

Fig. 1 illustrates the principle for an echo-sounding system. The beams have, of course, been idealized by showing definite boundaries to them; but these lines may be regarded, if desired, as the angular positions at which the response of each beam is 3 db below that at the centre of the beam.

It is technically possible to deflect the transmitted beam electronically, so that it, too, can be narrow. But the cost of doing this is not justified by the slight improvement of performance so obtained.

BEAM DEFLECTION BY PHASE-SHIFT NETWORKS AND FREQUENCY CHANGERS

The principle of beam deflection used for the receiving beam is basically the well-known one of varying the phase relationships between the signal outputs from the various parts of the transducer by means of phase-shifting networks. The transducer is divided into several equal sections in the plane in which the beam is to be swung. The output signals from each part of the transducer are connected together as shown in fig. 2, where the transducer has been divided into only three parts, for simplicity. In the absence of the phase-shifting networks, the outputs of the three sections will be in phase when the received signal comes from the direction normal to the face of the transducer; and the maximum output is produced for this direction, the response falling for directions at each side of the normal according to the familiar directivity curve of fig. 4 (*b*). Now this curve may be regarded as the product of two curves as shown in fig. 4 (*a*). These two curves are

(*i*) the diffraction pattern of three point sources or receivers,

and

(*ii*) the directivity curve of one of the sections of the transducer.

Whatever the number of sections into which the transducer is divided, the product of the diffraction pattern and directivity curve of one section must and will always come to the same overall curve, with the first zero at an angle from the normal of $\sin^{-1}\left(\frac{\lambda}{l}\right)$ radians, where λ = wavelength of sound in water and l = length of transducer.

With phase-shifting networks inserted as in fig. 2, the outputs of the sections are not in phase for a received signal direction normal to the transducer face, but at some other angle; consequently the beam may be regarded as deflected to one side of the normal. The phase networks in fact shift the diffraction pattern (*i*) to one side or the other of the angular origin, but they do not, of course, affect the directivity (*ii*) of the individual sec-

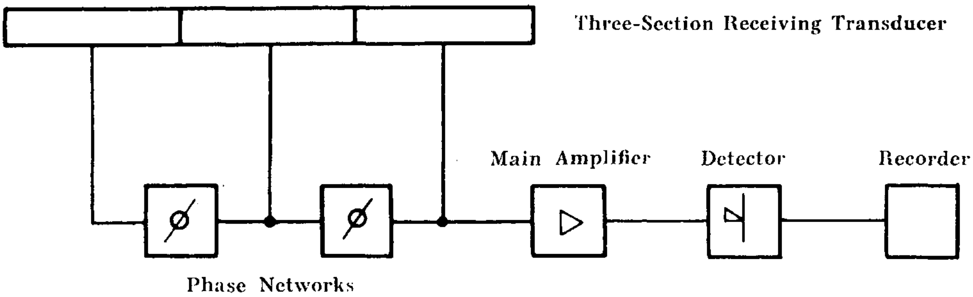

FIG. 2. — Schematic of Arrangement for Beam Deflection by a Fixed Amount.

tions. Thus the resultant directivity curve is the product of curve (*i*) deflected and curve (*ii*) unchanged, as shown in fig 4 (*c*) for an angle of deflection of $\sin^{-1}\left(\frac{\lambda}{3d}\right)$ or $\sin^{-1}\left(\frac{\lambda}{l}\right)$. It can be seen that at this comparatively large deflection, the directivity curve is very distorted. If the phase shifts were increased to increase the deflection further, it would be found that at a deflection of $\sin^{-1}\left(\frac{\lambda}{2d}\right)$ the main peak and the *diffraction secondary* would be of equal height, and thereafter the role of the two peaks would be interchanged. In other words, deflection beyond an angle of $\sin^{-1}\left(\frac{\lambda}{2d}\right)$ is not possible, and to avoid trouble from the diffraction secondary, deflection beyond $\sin^{-1}\left(\frac{\lambda}{3d}\right)$ is not advisable, and in some applications even less can be accepted. Inspection of the curves in detail will show that the maximum sector which can be covered by electronic deflection, measured between the 3- db response points, is approximately four times the 3- db beamwidth.

Subdivision of the transducer into more than three sections increases the maximum possible angle of deflection since the diffraction secondary peak is removed further from the normal. In general, with n sections, the maximum sector is approximately $(n + 1)$ times the 3- db beamwidth. The proportion of the maximum sector which is usable depends on the purpose of the equipment, but the distortion of the pattern for a given angle of deflection is always decreased by increasing the number of sections.

Now for a beam-stabilization system, the receiving beam deflection must be variable and under the control of a signal derived from the angular error of ship's position and desired position. The variation might, of course, be obtained by providing variable components in the phase networks, ganging them all together, and driving them by a small motor controlled by the position-error signal. But this would be a clumsy way of doing the job, would be expensive, and not readily lined up. A method of obtaining the variation without any moving parts is described below, and is thought to be preferable.

Fig. 3 shows the recommended method. The phase networks are now separated from the transducer sections by frequency changers, and the local oscillator which feeds a signal to all of them has its frequency controlled by a d.c. voltage representing the position error. The phase networks have negligible attenuation in the working frequency-band and have a phase shift which varies with frequency, either from negative through zero to positive values, or, while being entirely positive, varies from less than 2π radians to more than 2π radians. The former corresponds to a band-pass filter formation and the latter to a low-pass filter formation. The phase is zero or 2π respectively at the frequency which corresponds to zero

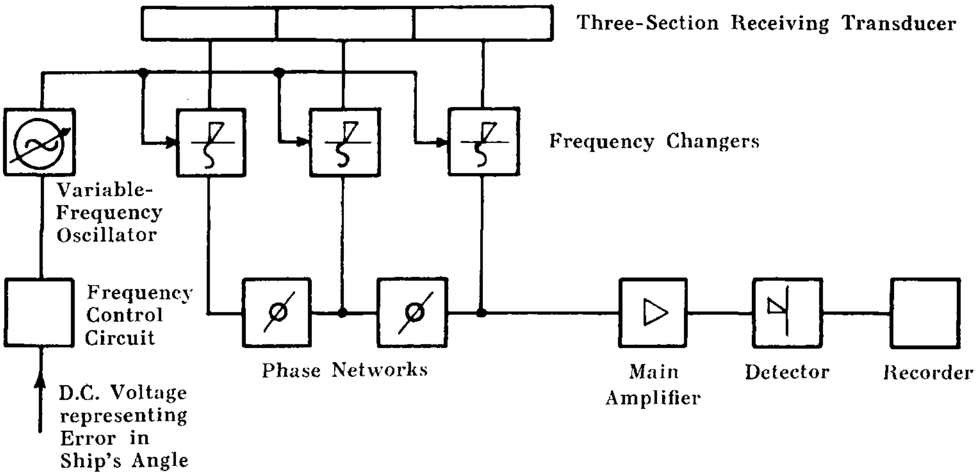

Fig. 3. — Schematic of Arrangement for Variable Beam Deflection

position error, and at this frequency, therefore, the beam is undeflected. For negative position errors the frequency is reduced, giving algebraically reduced phase shifts and negative deflection of the beam; for positive position errors the frequency is increased, giving increased phase shifts and positive deflection of the beam. Thus if the d.c. control voltage is correctly adjusted, and the relation between beam direction and position error is linear, then complete stabilization of the beam is achieved.

It will usually prove most convenient to make the local oscillator have a frequency range above the acoustic signal frequency, and to take the difference frequency from the frequency changers. It should be noted that while the signal phase angles are faithfully preserved in the frequency-changing process (which uses a modulator plus a filter of suitable design), yet when the difference frequency is chosen, the phase angles are all reversed in sign; therefore the beam deflections are reversed, and this must beam deflection correct the error due to the ship's position.

The choice of the number of sections into which the transducer should be divided is evidently determined by the expected angular range of roll or yaw in relation to the beamwidth, and by the permissible distortion of the directivity pattern. The design of the remainder of the beam-swinging electronics follows quite readily; the relationship between oscillator frequency variation and the phase/frequency response of the phase networks is obvious, and the range of frequency variation should be as large as convenient in order to minimize errors due to inherent instability of fre-

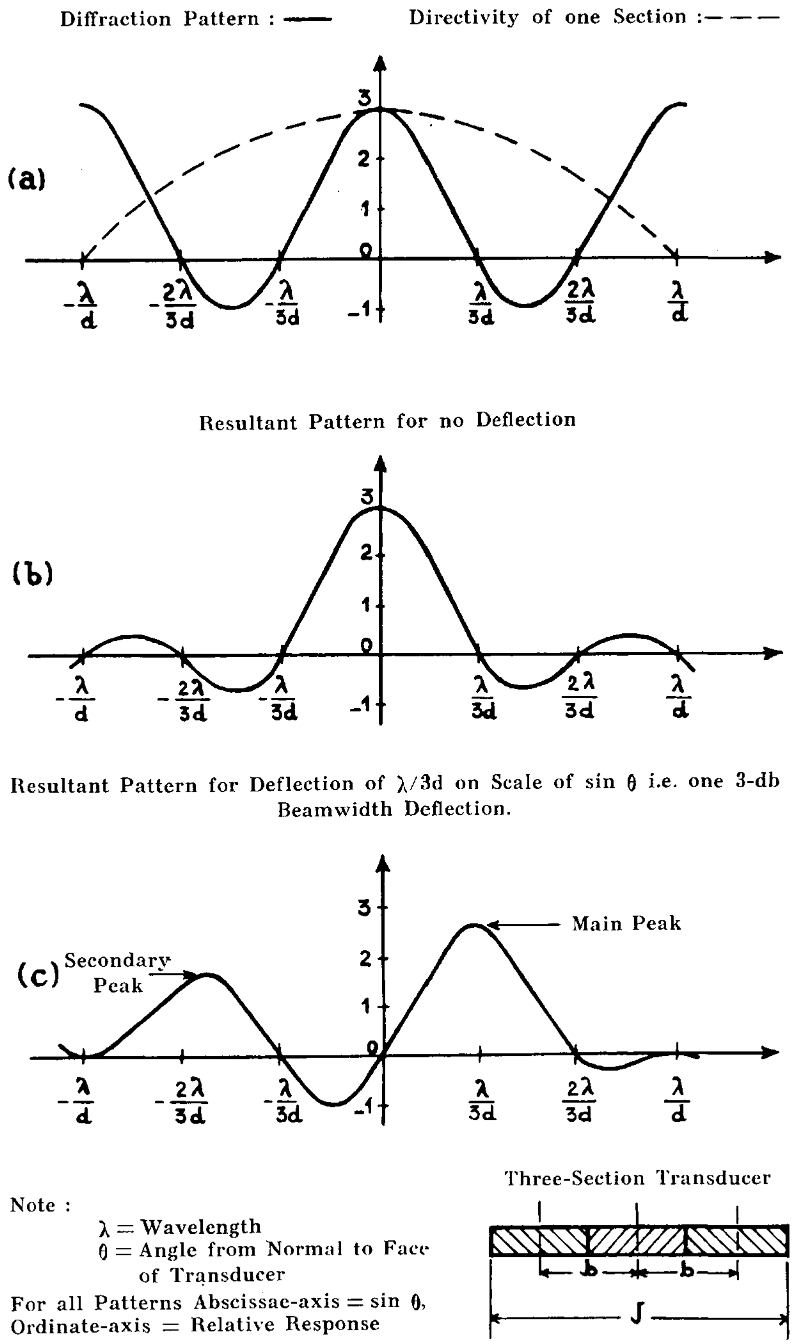

FIG. 4. — Directional Patterns.

quency at any given d.c. control voltage, but the larger the frequency range, the wider must be the bandwidth of the main amplifier. With the relatively slow rates of swing involved, there are unlikely to be any other complications. The circuit design of the frequency changers and oscillator is conventional; the former are most suitably made from rectifier modulators as these have a fairly stable conversion loss, and the latter is conveniently of the resistance-capacitance-tuned type in which at least one of the resistances is formed by a valve circuit whose resistance value is easily changed by a change of steady grid voltage.

OBTAINING THE CONTROL SIGNAL FROM A GYRO SYSTEM

A signal for controlling the direction of the receiving beam whilst the ship is rolling can be obtained quite simply from a *roll-gyro* in conjunction with the scheme shown in fig. 5. A roll-gyro has its spin-axis vertical and

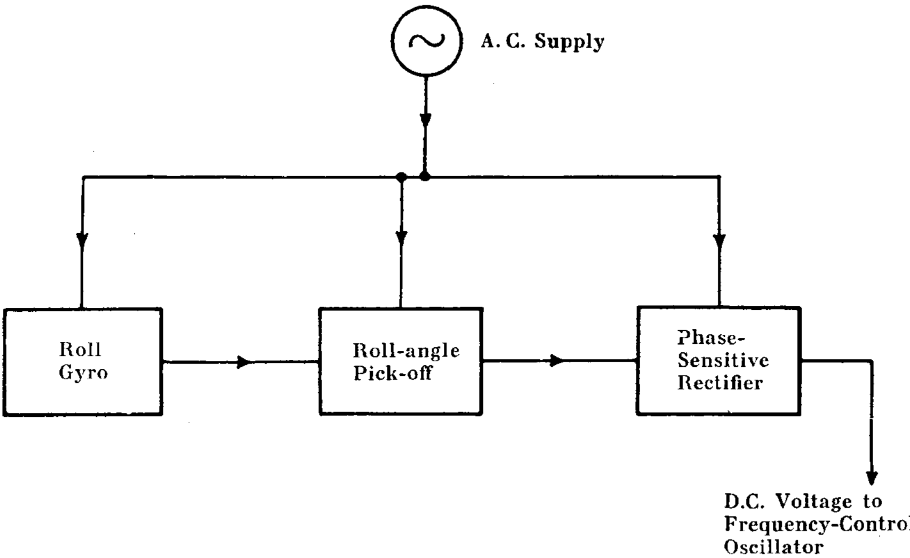

FIG. 5. — Scheme for Providing a Control-Voltage Proportional to Roll Angle

is bottom heavy, so that it gives a vertical datum. The roll angle can be measured with respect to this datum by means of an electrical position pick-off which has its rotor attached to the horizontal-gimbal axis whilst its stator is attached to the gyro base and hence to the ship. Such a position pick-off gives an alternating output voltage, the amplitude of which is proportional to the roll angle and the phase of which reverses with the direction of roll. This voltage is converted into the d.c. voltage that is required for the control of the directivity of the receiving beam by passing it through a phase-sensitive rectifier which then gives a d.c. voltage proportional to the roll angle and the sign of which corresponds to the direction of roll.

The rolling motion of a ship has a low characteristic frequency of the order of 0.1 c/s and on this account it is quite possible to operate the position pick-off and phase-sensitive rectifier from a frequency as low as 50 c/s and still be able to filter out the a.c. component of the rectifier output voltage without impairing the low-frequency roll-signal, which is used to control the directivity of the receiving beam. Thus no special electrical supplies are needed for this part of the system.

With such a scheme it would be possible to stabilize the receiving beam against roll to within $\pm \frac{1}{4}^{\circ}$, which is the order of wander of a roll-gyro.

An Asdic system with a forward-directed beam can be stabilized against the yawing of a ship in a similar way by substituting a yaw-gyro for the roll-gyro. A yaw-gyro has its spin axis in the horizontal plane, and acts as a directional gyro which is arranged to measure the deviation between the ship's instantaneous course and the ship's heading. However, such a gyro would drift with respect to the ship's heading on account of the friction torques of the gimbals and any minute lack of balance in the gyro. But as stabilization against the transient yawing motion is all that is required, it is permissible to monitor the gyro position and constrain it so that the average deviation of the gyro with respect to the ship's fore-and-aft axis is zero. This can be achieved by feeding back a fraction of the d.c. voltage which controls the receiving beam, to a torque motor which is coupled to one of the gimbal axes. In this way the gyro is subjected to a small precessional torque proportional to the yaw angle and whenever the average yaw angle deviates from zero the gyro will be precessed so as to minimize the average deviation. This additional control system has a long time-constant so that although it is effective in correcting errors due to gyro drift it has no significant effect on the voltage which is used for the stabilization of the receiving beam against the transient yawing of the ship.

The time-constant of the yaw-gyro feedback system, which has been described, would however be too long to provide a satisfactory automatic correction to the direction of the acoustic beam during rapid changes of the ship's course. To meet this situation it would be expedient to fit an overriding relay-type of control system which would apply a much larger, constant torque to the gyro whenever the average yaw angle lay outside the limits of say $\pm 2^{\circ}$. Thus if the ship were to make a 180°-turn the yaw-gyro would be forcibly precessed so as to remain within 2° of the ship's fore-and-aft axis and then when the ship had steadied on the new course the relay control would cease to function and the gyro would be restored slowly to the condition of zero average yaw angle by the drift-correcting control system.

CONCLUSIONS

The system described could readily be engineered to be reliable and successful. The authors have not had the opportunity of trying it out as a whole, but they have had extensive experience of beam deflection by the frequency-changing method described and also of gyro systems; they are therefore confident that the principles are perfectly sound. The system proposed is not a feedback system, i.e. there is no feedback of a signal proportional to the error between the actual beam axis and the desired axis position. It is not considered that feedback is necessary, since the accuracy of stabilization does not generally need to be high. But it is interesting to observe that a feedback system is feasible, since the receiving beam position relative to the transducer axis can be measured by either

(*a*) the phase angle produced in the frequency-dependent phase-shifting networks, or

(*b*) the frequency applied to the frequency changers.

It should not be difficult to devise circuit arrangements for measuring and using these quantities as the basis of a feedback signal, but it is most unlikely that the expense would be worth while.

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