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MASTER

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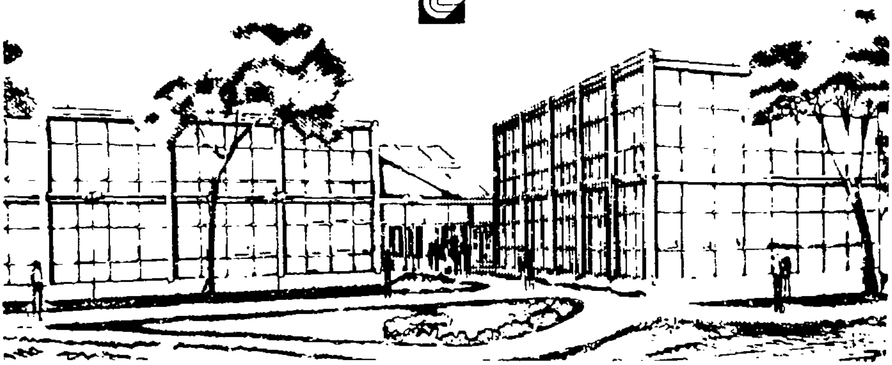

DESIGN OF A HIGH SPEED ROTATING MECHANICAL SHUTTER*

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ABSTRACT

We have designed a high-speed rotating shutter to operate in a 10^{-6} Torr vacuum at the optical focus of a laser spatial filter. The shutter is basically a wheel with a single 3x10-mm slot at the perimeter, which rotates with a peripheral speed of 1 [illegible]/s. The motor to drive the rotating wheel is magnetically suspended and synchronously wound. The wheel achieves a 4 μs opening time and a timing accuracy of better than 0.[illegible] μs.

Twenty similar motors will be used on Nova, the laser fusion test facility being constructed at the Lawrence Livermore Laboratory, to prevent the amplified spontaneous emissions of light, preceding the main pulse, from reaching the fusion target. The synchronization system incorporates a digital phase controller. Slot location is sensed optically and compared to a reference signal; the difference is then used to change the phase of the motor input frequency, driving the error to zero. Timing between the 20 synchro- [illegible] the laser is accomplished by computer control of the reference signal for the [illegible]. The magnetically suspended motor will [illegible] disk, [illegible] rpm.

We are considering the use of a beryllium alloy, titanium alloy or an epoxy-fiber glass wheel, configured to produce uniform radial and tangential stresses throughout the wheel.

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INTRODUCTION

High pulsed power laser systems spontaneously emit light before their main stimulated light pulse. This spontaneous light, referred to as amplified spontaneous emission (ASE), is amplified by all subsequent active optical components in the laser chain, and may reach sufficient intensity to damage laser fusion targets before the arrival of the main stimulated emission pulse. This light may be blocked by the use of an electrooptical shutter, such as a Pockels' cell or purely mechanically by a high speed rotating shutter or chopper wheel.[6]

To be effective, the window time of the shutter should be extremely short and as close to the desired laser pulse length as possible. Electrooptical switches can be quite fast ([illegible] s); but as the optical beam size increases, the optically active element must also increase along with cost. Usually the cost is proportional to at least the beam diameter squared. Another approach is to place a high speed rotating disk with a very small slot at or near the focus of a spatial filter. At this location even the largest beam apertures reduce to less than a millimeter (diffraction limited spot size is [illegible] for a [illegible]). If a wheel with a 1 mm [illegible] opening [illegible] were placed at the spatial filter focus, then microsecond opening times could be obtained; i.e., [illegible] speeds approaching conventional electrooptical shutters.

This paper discusses the preliminary design of such a high speed mechanical shutter system including the wheel design, motor requirements and the all important motor speed and synchronization controls.

Electrical synchronization is particularly difficult because on the Nova laser system twenty beams must be switched concurrently but not quite simultaneously. That is, because of differences in individual shutter to target distances and shutter to master oscillator distances, each shutter wheel must open at a slightly different time. This problem has been solved by the use of synchronous motors (constant speed) driven by individual phase controllable power supplies which are in turn synchronized to a master oscillator.

The physical location of the wheel, at the center of an evacuated spatial filter, presents some interesting mechanical problems concerning bearing design for ultra high speed vacuum environments. A magnetically levitated motor armature was eventually selected and is further explained in the paper.

Rotating Wheel Design

If a high speed shutter wheel were to operate in air and still achieve maximum speed, it would be limited to slightly under sonic velocity or [illegible] cm/s. By operating in a vacuum this speed range can be extended to that limited only by the density and strength of the wheel material. To achieve still faster opening times, two counter rotating wheels could be used, but this is more an implementation and economic decision than a structural decision.

[illegible] of wheel designs[1,2,3] indicates that [illegible] has a significant effect on [illegible] profiles [illegible] flat disk with a center hole [illegible] the Stodola[1,i] or uniform stress profile. The Stodola wheel distributes the mass such that radial and tangential stress components are equal throughout the wheel. Since all portions of the wheel are equally stressed, the wheel achieves minimum weight and maximum peripheral speed for any given stress level. The radial and tangential stress [illegible] is given by

$$\sigma = \frac{\rho(\omega r)^2}{2\ln(\frac{t_0}{t})}$$

where is the material density, r. the peripheral speed, and t_0/t the center to edge thickness ratio. A plot of the edge to center thickness ratio for several materials (each at a constant stress level) operating at various peripheral speeds is shown in Figure 1. Each curve represents a different material evaluated at an optimum design stress as listed in Table 1. The operating stress level was selected based on consideration of each materials fatigue endurance strength, a confidence level for the material properties, correction factors for surface roughness and stress concentration, and an adjustment to take advantage of the fact that the stress level never cycles into compression during normal cyclic start-stop operation.

Since the internal stress is uniform and depends only on peripheral speed, density, and thickness ratio, the curves in Figure 1 lead to an interesting conclusion. At edge speeds less than 0.1 mm/s (225 mi/hr), the choice of material is entirely arbitrary and speeds exceeding 1 mm/s are nearly impossible with any combination of profile or material.

Certainly carbon filament epoxies perform better than even titanium alloys but by only a small margin. This indicates that properties other than strength and density be given equal consideration during material selection. For use with a magnetic bearing motor, low wheel weight is desirable as it minimizes bearing electronics and power requirements. Low weight will also allow a smaller motor to be specified while maintaining a constant start-up time. The epoxy composite material also has the advantage of lower stored energy at any given peripheral speed. This combined with the delamination of the material during explosion compared to lethal shrapnel released by a metallic wheel at a similar speed led us to choose the composite wheel.

On the other hand, far less is known concerning the fatigue endurance strength of composite materials as compared to say titanium alloys. This can be compensated for by using a larger factor of safety. Epoxy materials will also outgas substantially more than metals thereby increasing the vacuum pumping load over metallic wheels. A recently measured epoxy resin outgassed at a rate of 1×10^{-5} Torr-l/s cm^2 as compared to electropolished stainless steel at only 4×10^{-9} Torr-l/s cm^2.

Little is also known concerning the deformation and cracking that will occur in a filament epoxy wheel resulting from a stress concentration at the perimeter where the shutter wheel slot must be placed. A metallic wheel would benefit from a keyhole type slot to reduce the stress concentration at the bottom of the slot, but this technique, when applied to fiberous materials, would simply expose more filament ends. Kulkarni[5] has proposed placing a glass-filament epoxy reinforcing band around the outer perimeter of the wheel to lower the stress level. This appears to be a viable solution but has not yet been tested.

For comparison with the uniform stress profile wheel, the maximum peripheral speed obtainable with a flat disk containing a small central hole is also shown in Figure 1. A flat wheel is limited to approximately 5% of the speed of the uniform stress wheel because of its inability to support a radial stress at the center.

Motor and Bearings

In designing a shutter wheel motor-bearing support system to operate in an evacuated spatial filter, consideration was given to 1) a dry lubricated mechanical bearing motor submersed in the vacuum, 2) a wet ball bearing motor driving a vacuum feedthrough shaft, 3) a dry bearing motor with vacuum submersed rotor and externally mounted stator winding, and 4) a totally vacuum submersed motor with magnetic bearings. Only the latter magnetic bearing motor was determined to be totally satisfactory.

Because of space limitations, the wheel size was limited to 300 mm diameter, which at a peripheral speed of 1 mm/μs corresponds to 64,000 rpm. This relatively high rotational speed resulted in the elimination of most of the potential bearing schemes.

Dry lubricated ball bearings have been used successfully at speeds up to approximately 8,000 rpm in spacecraft applications. These are special bearings with teflon ball retainers and proprietary graphite surface treatments. Higher speeds cause galling and rapid failure of the balls in the vacuum environment. The bearings are also relatively small and cannot support radial loads exceeding approximately 13 N (3 lb).

A magnetic fluid seal on a vacuum wall feedthrough has the potential of approaching the necessary rotational speed but no documented high-speed vacuum systems could be found. The shaft size necessary to support a 2 kg wheel also leads to shaft peripheral speeds that exceed present magnetic fluid design standards.

Consideration was also given to a motor with an in-vacuum rotor and a magnetically permeable vacuum wall located between the rotor and stator. This places the potentially high outgassing motor stator outside of the vacuum enclosure. Unfortunately the design still leaves the shaft bearings inside of the vacuum chamber.

Magnetic bearings have several potential advantages that easily make them the first choice for supporting a high speed wheel in a vacuum. Magnetic bearing stiffness may approach the stiffness of conventional mechanical ball bearings (100 N/μm) but in most cases this may not be necessary as absolute shaft location accuracy is not necessary. A ball bearing mounted shaft and wheel combination, for instance, must be carefully balanced to minimize rotating masses and the forces they can generate on structures; whereas a soft magnetic suspension will allow the shaft-wheel combination to rotate about its inertial axis even if this does not correspond to the geometric center of the shaft.

Resonant frequencies are still to be considered a problem but since the bearing stiffness and damping can be dynamically varied, as with certain active suspension systems described later, operation near a resonance or passing through resonant frequencies during start-up are easily handled.

Power failure can also be easily handled by battery back-up systems which could easily operate most support systems for several minutes to an hour sufficient time to bring the wheel to a stop before lowering the shaft onto the magnetic faces. Servo-loop failure is harder to preclude, but can be designed against by having conventional ball bearings back-up the magnetic bearings and come into contact with the shaft only if the magnetic bearings fail.

The magnetic bearing suspension systems themselves can be divided into electronically controlled "active" systems or "passive" permanent magnet or fixed current electromagnetic systems. Active systems use electromagnets exclusively and up to ten servo loops. Passive systems use several fixed field permanent magnets and several low power balancing electromagnets. Fully passive systems are unstable as first deduced in 1842.[7]

Inductive or Hall effect sensors are used to sense the position of the shaft and to close to servo loop. Active systems have the ability to incorporate damping into the control loop. This may be taken advantage of when passing through resonance frequencies to prevent excessive shaft deflections. The bibliography lists several articles [8,9,10,11] covering the field of magnetic bearing design.

Several companies are now designing magnetic bearing systems for special applications. Cambridge Thermionic Corp. Inc., Cambridge, Mass. has extensive experience in small passive bearing systems and holds several exclusive patents. They have been building aerospace components for NASA since early 1960. SKF, King of Prussia, Penn. in cooperation with Societe de Mechanique Magnetique (S2M) in Vernon, France have concentrated on large bearing-shaft applications. S2M and its predecessor Societe Europeene de Propulsion (SEP) have been building fully active suspension systems since 1969. Spin & Space in Phoenix, Arizona is a recently formed company specializing in aerospace and satellite components. Unfortunately there are no production magnetic bearings available off-the-shelf, and consequently any design tends to be customized to the users application. Development of a single prototype motor for this shutter wheel application will cost approximately 100 K$.

ASE Shutter Wheel Control System

The control task for synchronization of several rotating shutters is two-fold. First, all the wheels must be synchronized to each other; and second, the wheels must be timed to the laser pulse arrival time.

A hysteresis synchronous motor was selected because it is necessary to do phase control to synchronize the wheels. It is inadequate to just control the speed of the wheels. The wheels must first be running all at the same speed and then adjusted in phase to allow the laser beams to pass through all the slots at the correct time. By using a synchronous type motor, the speed problem is eliminated. A hysteresis type motor was chosen because this type of motor needs no slip rings or brushes.

The major drawback of hysteresis type motors is their inefficiency· not only do they require a larger frame size per horsepower but also their power factor is poor requiring a large power supply. This drawback may be overcome by using a permanent magnet synchronous motor; however present construction techniques for permanent magnet motors limit the speed of these devices. The hysteresis motor because of its rotor construction can be subjected to higher mechanical stresses and therefore reach the higher speeds required in this application.

A control strategy which accomplishes this task is block diagrammed in Figure 2. To synchronize the individual wheels to each other, each motor-wheel combination has its own digital, closed loop, phase control network. The phase control networks are referenced to a common timing signal. This timing signal originates from a master oscillator and is adjusted in time with the laser pulse switchout by a computer controlled phase shifter. The same computer that controls the phase shift also controls the switchout, thereby timing the wheels to the switchout.

The computer controlled phase shifter is constructed using counters in a countdown mode. The counters are preloaded to the desired phase shift by the computer. The output is a 400 Hz reference.

The closed loop phase synchronization system has been prototyped using off the shelf hardware. The motor is a two phase 110 V, 0.1 hp, 8000 RPM, 400 Hz hysteresis synchronous motor made by Ashland Electric. The wheel is a flat aluminum disk 200 mm in diameter, 3 mm thick, with two 1.5 mm wide by 4 mm long slots milled 180° apart. At 8000 rpm these slots provided a 20 μs window. The motor is driven by an in-house designed two phase power supply. The feedback sensor is a discrete LED and photo transistor pair.

The phase control network shown in Figure 3 consists primarily of two counters and a comparator. The free running counter takes a high frequency signal and divides by 2^{15} to obtain the motor's input frequency of 400 Hz. An up/down counter provides a phase shift. The up/down counter contains a value proportional to the phase error between the sensor and reference signal and is incremented or decremented depending upon whether the sensor leads or lags the reference signal. The comparator outputs a pulse whenever the value of the bits A_0 - A_{13} are equal to the value of the bits B_0 - B_{13}. Since bits A_{14} and B_{14} are not compared, the frequency of A=B is 800 Hz. This signal A=B in conjunction with a D-type flip flop provides a phase shifted 400 Hz signal. The amount of phase shift equals the value contained in the phase shift counter multiplied by the period of the 13.107 MHz clock. The resolution is plus or minus one count or 76.2 ns. Operation of the controller consists of determining a leading or lagging condition, thereby increasing or decreasing the value contained in the phase shifting counter.

The rate at which the error is corrected depends upon the clock frequency of the up/down counter. Due to the highly underdamped phase characteristic of the motor, it was found a two clock rate correction technique works much better than a single fixed rate. When the error is "large" the clock rate is high, f_1 = 819.2 kHz; as the motor approaches synchronization, the clock rate is decreased to a low value, f_2 - 23.25 Hz. The slow clock rate is kept much less than the sampling rate of the sensor to insure stability.

The decision between large or small errors is made by an additional counter and comparator. The counter contains the magnitude of the phase error; and when the magnitude is less than a preset value determined by the comparaior, the clock is switched from its high to low rate. The best results were obtained when the clock rate was switched at an error magnitude of about 20 μs.

The prototype control system is capable of maintaining phase synchronization with a jitter of 2 μs with a 20 μs window. This last remaining jitter source was determined to be the circuitry which converts the 400 Hz digital signal to a sine wave as needed by the power supply driving the motor.

Conclusions

A design study has been completed on the use of a very high speed rotating wheel as a shutter to block light preceding the main laser pulse from reaching a laser fusion target. Wheel peripheral speed is limited with the best carbon fiber epoxy materials to approximately 1 mm/μs; consistent with long wheel life, safe operation, and reasonable system reliability. A uniform stress profile wheel with a 10:1 center to edge thickness ratio is proposed. With a millimeter wide slot at the perimeter, submicrosecond opening times may be achieved. The slot is reinforced against cracking by using a circumferential wrapping of glass or carbon filaments in epoxy.

The wheel, motor and shaft will be suspended by a series of magnetic bearings allowing virtually frictionless operation at 10^{-6} Torr vacuum. The motor and bearing thermal losses will be removed by incorporating a liquid cooling jacket within the motor stator. Excessive heating is detrimental in that it can increase the outgassing of the motor substantially and require excessive vacuum pumping.

An all digital wheel synchronization control system has been designed and prototyped. It will synchronize all wheels in the laser system to each other and to the laser pulse switchout system. Synchronization has been demonstrated at better than 2 μs with full expectation of reaching 0.2 μs.

As laser aperture sizes increase, high speed mechanical shutter wheels positioned near the focus of a spatial filter can compete very favorably with electroptical shutters such as Pockels cells. They also have the potential for lower cost when compared to large aperture Pockels cell or Faraday rotators.

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Appendix I

Manufacturers of Mechanical Bearing Hysteresis Synchronous
Motors for Vacuum or Space Environments

IMC Magnetics Corp.
Eastern Division
570 Main St.
Westbury, L.I., New York 11591

Schaeffer Magnetics
20416 Corisco St.
Chatsworth, CA 91311

American Electric
1600 East Valencia Drive
Fullerton, CA 92631

Appendix II

Manufacturers or Suppliers of Mechanical Bearings for Vacuum and Space Environments

Ball
Aerospace Systems Division
P. O. Box 1062
Boulder, Colorado 80306
(303) 441-4000

Barton Bearings
Danbury, Conn.

Appendix III

Manufacturers or Suppliers of Magnetic Bearing Motors

Spin & Space Systems
11001 North 24th Ave.
Suite 605
Phoenix, Arizona 85029
(602) 997-9514

SKF Technology Service Center
P. O. Box 515
1100 1st Ave.
King of Prussia, PA 19406
(215) 265-1900

Cambion, Cambridge Thermionics Corp.
455 Concord Ave.
Cambridge, Mass. 02138
(617) 492-7082

Societe de Mechanique Magnetique (S2M)
Vernon, France
(contact through SKF)

Table 1

Comparative specifications of materials selected for high speed shutter wheel use. The last column labeled yield strength to operating stress level represents the overall factor of safety. The operating stress was selected based upon consideration of factors affecting metal fatigue, reliability, the effect of stress concentrations, surface finish and the probability of cracks.

Material Type	Typical Designation	Specific Gravity	Tensile Yield Strength MPa(kpsi)	Selected Operating Stress MPa(kpsi)	Yield Strength / Operating Stress
Carbon Filament Epoxy	Celion 6000/5213	1.55	510 (73.9)	255 (37)	2.0
Magnesium Alloy	AZ31B-H24	1.74	138 (20.0)	91.7 (13.3)	1.5
Beryllium Alloy	HIP-50	1.84	345 (50.0)	178 (25.9)	1.93
Aluminum Alloy	7075-T6	2.79	503 (73.0)	225 (32.6)	2.24
Titanium Alloy	6Al-4V	4.54	827 (120.)	353 (51.2)	2.35
Maraging Steel	18Ni-300	7.70	1380 (200.)	676 (98.0)	2.04

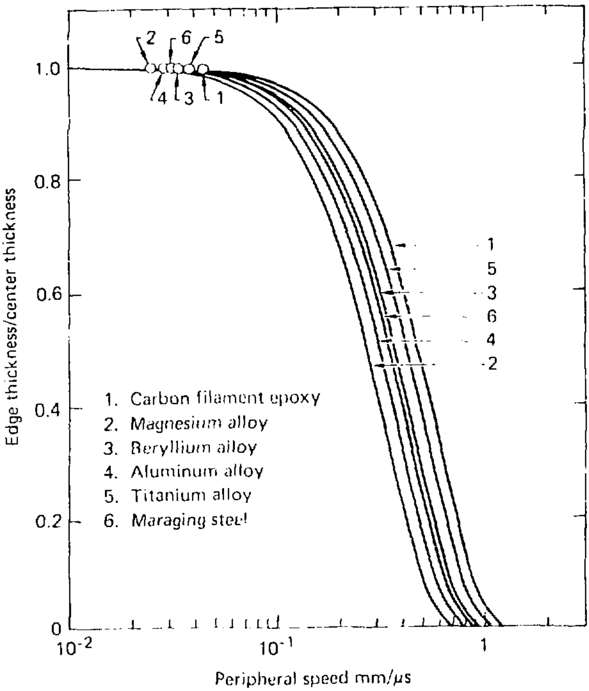

Figure 1. Edge to center thickness ratio for a Stodola or uniform stress flywheel, necessary to maintain the operating stress level given in Tabel 1 at various peripheral speeds. The circled (o) data points represent the maximum peripheral speed obtainable with a flat wheel (constant thickness) containing a small central hole and operating at the stress levels given in Table 1.

BLOCK DIAGRAM OF ASE SHUTTER CONTROLS

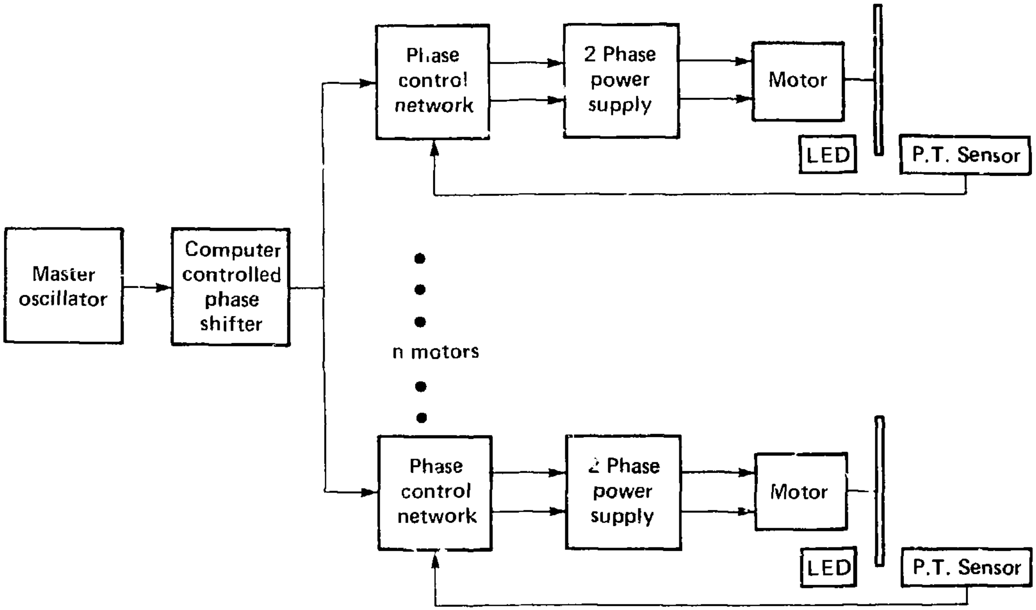

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Figure 2. Block diagram of shutter wheel control system.

ASE SHUTTER PHASE CONTROL NETWORK

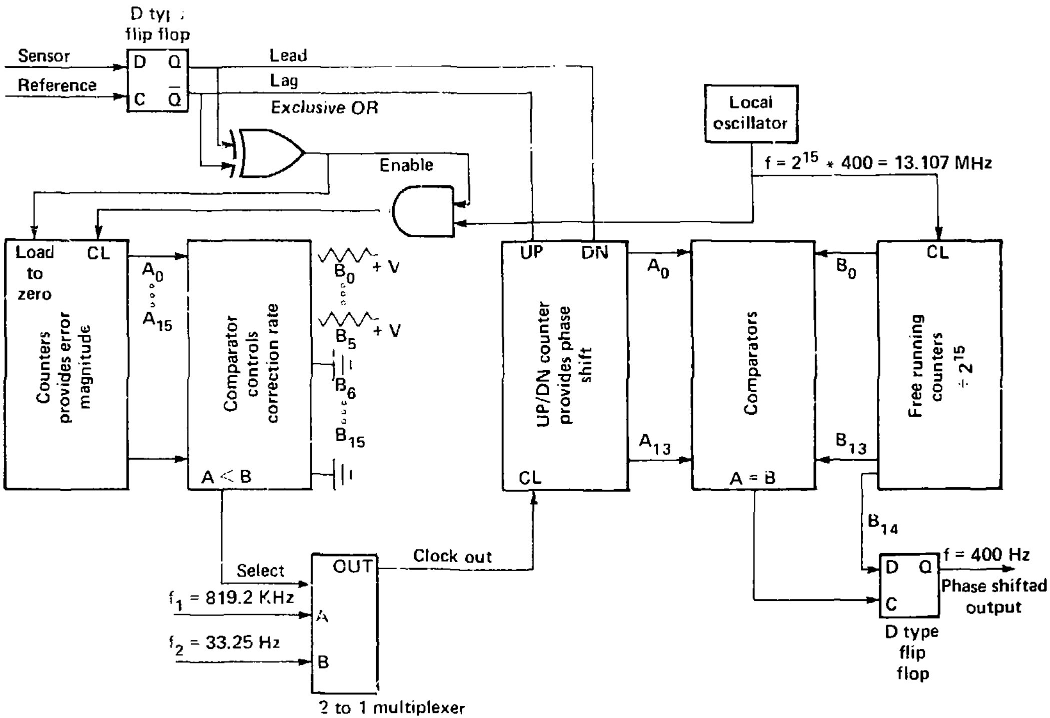

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Figure 3. Shutter wheel phase control network shown in Figure 2.