AMERICAN CONSULTING ENGINEERS COUNCIL'S

HEAVY MOVABLE STRUCTURES
MOVABLE BRIDGES AFFILIATE

3RD BIENNIAL SYMPOSIUM

NOVEMBER 12TH - 15TH, 1990

ST. PETERSBURG HILTON & TOWERS
ST. PETERSBURG, FLORIDA

SESSION
WORKSHOP NOTES

Session (5-9)
"State Of The Art Mechanical Gear Systems" R.L. Cragg, Engineering Consultant, Maple Glen, Pa.

In the introduction to Volume II of his book, "MOVABLE BRIDGES", Otis Hovey, Assistant Chief Engineer of American Bridge Co. at the time, has outlined the desireable characteristics of the machinery to move the span. Among other things he points out :

- the machinery should be laid out in the simplest possible way.
- the machinery should be such that the number of parts is small.
- each part should be of the simplest construction to do the work.
- the first cost and maintenance should be minimum.

Although these instructions were written over sixty years ago they are surely just as true today as they were in 1927.

Once movable bridges advanced beyond the stage of a log positioned across a gully, or a platform crossing the moat surrounding a castle and the quaint, manually lifted spans so popular across the canals of the Netherlands it is logical the Engineers and Designers selected gears as the heart of the machinery systems to move the spans.

After all, gears are one of Man's oldest mechanical devices, they have served Mankind for over 5000 years, they are one of the most basic machinery elements. Indeed, in Charlie Chaplin's movie, "Modern Times" were symbolized with gears and pinions: Rube Goldberg's offspring, the recently popular children's game "Mousetrap" included a type of gears; even the service organization Rotary International is identified by a gear symbol; many advertisements include gear meshes and outstanding corporations such as XEROX include gears in their corporate publicity to convey the assurance of successful entities working together.

Gears are certainly one of the most recognized machine elements and create impressions of positive action, coordinated movement, repeated accuracy and efficiency in the public mind.

They have instilled respect and confidence in reliable performance and integrity of operation. It is no wonder Engineers chose them to move the massive spans of the highway and railroad bridges in their crossings of navigable waterways throughout the United States and the World.

Today we are going to look at gear driven movable bridge operating machinery systems and find out just what a State of The Art System looks and sounds like, what components it includes and what maintenance it requires.

Basically the operating machinery is a simple , straight forward system that converts a moderate rotational speed, low torque input to a low speed, high torque output. It consists of :

1. A prime mover such as an electric motor, internal combustion engine, steam engine or even animal or human power that introduces rotary motion to

2. A series of pinions, gears and shafts that reduce the speed and increase the torque to a final member which introduces motion to the span.

Such a system is shown schematically in Fig. 1. Of course, here we also see the associated components of bearings to support the shafts on which the gears and pinions are mounted, couplings to join the shaft ends together and a brake. This basic system permits easy modification to meet the needs of various design and operating requirements. For instance, when two pinions are necessary, it is easily accomplished by merely adding another shaft extension with the required gears, shafts and bearings; and when load sharing is required a gear type differential is incorporated. (Fig. 2)

Notice the basic system is suitable for use on any type of bridge - swing, bascule or vertical lift . Of course a vertical lift would not incorporate a differential; but, as has been pointed out, this does not change the basic system.

The following characteristics and benefits of gear drives are recognized to be of prime importance to movable bridge operating machinery :

1. They are rugged and dependable.
2. They are forgiving and can sustain substantial abuse without catastrophic failure.
3. They require little maintenance and what maintenance is required can be done without the aid of highly trained technicians.
4. They are capable of handling shock loads well in excess of their design capacity without failure or even permanent damage.
5. Once the ratios are set they do not change so that motions and registrations will repeat themselves time after time after time.
6. The components lend themselves to shop assembly into common frames and onto platforms so that accurate alignment is possible under shop conditions which also simplifies field installation.

There are few records concerning machinery on many of the early movable bridges in this country; therefore, I'm not certain just when the first gear set found a home on one of these structures. However, as the railroads pushed westward, as electrical power became available and was distributed and as the use of the electric motor became feasible so was the popular application of gears to movable bridges advanced.

As a result, many bridges designed and completed in the 1880's and 1890's were equipped with gear drive systems.

Some of these were rim-bearing swing spans - and many are still in use today. A typical design would house the motors and controls together with the primary gear reductions in the machinery house, located in the middle of the span above track level. Two, or more drive pinions were normally used so that a differential mechanism was included in the system. Transverse shafts extended from the differential output shafts to bevel gear sets, frequently miter boxes, that translated the rotation from horizontal shafts to vertical shafts. Additional gear reductions were included, if required, in continuing the drive to the rack pinion shafts. (Fig. 3)

At this time gears were exposed and the shafts supported on cast iron or Babbitt bearings, axial location was maintained by thrust faces on the bearings and gear hubs or shaft shoulders. It was common to offer some protection to the upper ends of vertical pinions by providing a cover, or shroud, to help keep junk from entering the mesh. OSHA was not in business at the time so no protective gear guards were required around the open gearing, couplings and other rotating equipment. Gear type couplings were some time away in the future so shaft ends were joined by rigid flange, sleeve or jaw type couplings.

A swing bridge of this period is the Chicago, Central & Pacific Railroad bridge across the Missouri River between Council Bluffs, Iowa and East Omaha, Nebraska. In addition to the fact it is old - erected in 1893 and still operating until June, 1988, when a tornado caused the destruction of several rack and track sections rendering it inoperable - it is an interesting installation since the crossing consisted of two swing spans, each with its pivot pier on the river bank and having a common rest pier in the middle of the river.

The East span is operated by two separate electric motors driving gears on a common shaft. The second reduction bull gear incorporates a two pinion, bevel gear differential whose two output shafts each drive a set of miter gears immediately followed by another vertical shaft spur gear set driving a vertical shaft to a pinion which is meshed with two gears on the rack pinion shafts. Thus there are four rack pinions driving the span. Load sharing between each set of two pinions is achieved by the differential in the machinery house, but no load sharing is provided between the two rack pinions at one location.

Now remember, these photos show equipment - gears, bearings, shafts, couplings - that have rendered nearly 100 years of service. Machinery exposed to the elements - rain, snow, dirt, pigeon droppings - bearings having years of accumulated dirt and contaminated grease piled high on their working surfaces. The fact this machinery has continued to work under such adverse conditions is a tribute to the engineers for designing such rugged equipment, a commendation to those who built and installed the equipment for the quality and integrity of their workmanship and a testimony to the reliability and soundness of the gear drive system.

With the materials handling equipment and the tools of the period it was a remarkable feat just to get the machinery in place. This was a cumbersome installation; each gear and pinion had to be individually aligned, each bearing positioned and shimmed properly and all mounting bolt holes drilled and reamed in the field to assure correct fits with the mounting bolts. The number of pieces was great and installation time considerable.

Maintenance costs, other than occasional lubrication, have been minimal; yet the machinery continued to do its job until outside forces interrupted its operation.

Similar open gear drives were used on bascule and vertical lift bridges.

As time went on someone got the idea to incorporate the gears, shafts and bearings into an enclosed housing and - Lo!, a Speed Reducer; Babbitt bearings yielded to bronze bushings and they to self-aligning, sealed, anti-friction bearings and rigid couplings disappeared in favor of flexible grid and gear couplings. Inaccurate cast tooth racks and composite tooth form gears were replaced by gears having accurate, generated involute profile teeth; shafting materials have improved and the mechanical machinery systems now have even more reliability than those of a century ago.

Today's State of the Art Gear Drive System basically is not substantially different from earlier mechanical systems; however, it is superior since it includes : improved materials; more accurate manufacturing and quality assurance; advanced design considerations; a better understanding of the operating requirements and specific features especially included to satisfy the needs of the job at hand.

Rather than re-inventing the wheel, gear drive systems have profited from the experiences of thousands of mechanical, heavy movable structures, machinery installations. These systems recognize that the object is to move the structure from one position to another - open or close the span - in the easiest, most reliable manner possible without the aid of complicated, sophisticated, sensitive equipment better suited to lunar landings or submarine excursions.

Machinery systems should be designed with several goals in mind:

1. Simple, uncomplicated design.
2. High overall system efficiency.
3. Easily installed.
4. Readily maintained.
5. High reliability.
6. Economy of over-all cost.

With these goals highlighted let's take a look at today's mechanical, gear drive system. The prevailing Standard Specifications of both AASHTO (2.5.1) and A.R.E.A. (6.5.6) set the stage for our considerations, for they state: "The machinery shall be simple and of substantial construction."

For our investigation we shall use a representative drive as shown in Fig. 4. The overall ratio of 438.6:1 is accomplished in one, differential, quadruple reducer. Two 20 HP drive motors are coupled directly to the input shaft, brakes are also located on the high speed shaft and the output shafts are coupled to floating shafts which connect directly to the rack pinions. Spherical Roller Bearing Pillow Blocks support the two rack pinion shafts.

Simple, Uncomplicated Design

This system is certainly very simple, for what could be more direct and basic. Notice that the only open or exposed gears are at the rack/rack pinion interface; connecting shafts are "floating", thus eliminating the need for additional bearings and supports; flexible couplings unite the shaft ends so that precise alignment is not beyond reasonable amounts achievable in the field. Indeed a simple, pragmatic approach.

High Overall System Efficiency

The machinery is designed and sized to move the span against frictional resistances, inertia, and unbalanced conditions including various wind, snow and ice loadings. Certain of the frictional considerations are outside the equipment that causes the span to move (i.e. The losses developed by trunnion bearings, center bearings, balance wheels, rim rollers, the bending of wire rope around drums, flat and curved track plates, etc.) and are present no matter what type drive is used. However, the friction introduced by the members of the drive system vary depending upon the equipment selected. Desirably the engineer will select components to maintain the maximum overall system efficiency.

A.R.E.A. and AASHTO give certain coefficients for the bearings and gears to be used in determining the machinery losses; sleeve bearings - 0.05, anti-friction bearings - 0.01 and open gear sets - 0.02.

The efficiency of this machinery, as an open gear type drive, would be calculated at about 56% following A.R.E.A. and AASHTO values. However, by using speed reducers and mounting the shafts on anti-friction bearings the losses are now only 1% per reduction, and the overall efficiency is now about 90%.

Easily Installed

Field installation of today's machinery is eased considerably since shop assemblies are made of the major components and field work is held to a minimum.

In this case the reducer, motors, brakes and electrical control devices are mounted on a common platform. The pinion bearings are secured to the structure after aligning the rack and pinion. Alignment of the main machinery frame is then made with the pinion shafts and the frame grouted and bolted to the pier.

Installation of the rack pinion bearings has been made easier on Highway Bridges since AASHTO now recommends providing slotted bolt holes in the housing feet of anti-friction bearing pillow blocks and the use of chocks for installation and adjustment (2.6.4).

It is not necessary to place all four reductions in one reducer. Depending upon the available room, and other considerations, one primary and two secondary reducers could be used without decreasing the overall efficiency (Fig. 5). Installation procedures would be similar, except that the secondary reducers would be aligned with the pinion shafts first and then the primary reducer assembly aligned and installed.

Other features may be included in the speed reducer to reduce the number of parts that must be put together in the field. For example, an emergency drive shaft can be provided at little additional cost. This shaft is suitable for hand operation, driving with a portable pneumatic or hydraulic motor or an electric drill. When this feature is incorporated a safety interlock switch is supplied on the shaft end cover to prevent accidental starting of the main drive motors when the emergency drive shaft is in use.

Readily Maintained

Maintaining an enclosed drive such as this is pretty much relegated to periodic audio-visual surveillance, lubrication of the bearings, couplings, speed reducers and rack/rack pinions as designated by the manufacturer and, of course, housekeeping.

No specialized equipment, gages or instruments nor technically trained personnel are necessary to competently maintain the equipment.

Bearings and couplings must be observed visually to assure the seals are retaining the grease and that the fasteners are tight and not deteriorating through corrosion. And, of course, they must be lubricated periodically.

The gears in speed reducers are automatically lubricated by either a splash or circulating system. In most cases the bearings are lubricated in the same way. However, some times this is not possible and separate grease fittings are provided to lubricate the bearings. The lubricating oil in the reducer requires periodic changing, just like the oil in one's car.

Over a period of time it becomes diluted, accumulates foreign materials and looses its ability to effectively perform its job. Also, where the ambient temperatures vary widely from summer to winter one grade of oil is not suitable.

Observing the oil level in a speed reducer is normally done by minding the sight level gage or using a dip-stick; however, it can be monitored at the Operator's Console by locating an oil level sensor in the reducer casing that will send a signal when the level is low.

High Reliability

Gear drive systems have already established their reliability through the many years of service they have fulfilled. Today that reliability is increased for several reasons:

1. Better Design and Evaluation Techniques.

Both AASHTO and A.R.E.A. require speed reducers to be designed in conformance with American Gear Manufacturers Association Standards. AASHTO goes one step further and imposes this same requirement on open gearing also. The two appropriate standards concerning spur and helical gears are ANSI/AGMA 2001-B88 (a revision of AGMA 218.01), for evaluation of open gearing, and AGMA 420.04, for speed reducers.

These standards represent an advancement over the modified Lewis Formula used for determining the allowable loads on gear teeth per AASHTO 2.6.12 and A.R.E.A. 6.5.19. They take into account the Geometry Factors, Dynamic Factors, Load Distribution Factors and other conditions that influence satisfactory gear set performance in rating each reduction for Surface Durability (Pitting Resistance), Bending Strength and Yield Strength Horsepower. In most cases on movable bridges the Surface Durability Rating is the critical consideration.

Additionally, most speed reducer manufacturers make ample provision to handle instantaneous overloads without damage to the unit. AGMA Standard 420.04, Section 4.7 suggests a maximum momentary or starting load of 200% rated load. However, the speed reducers produced by most manufacturers will permit much higher loads without destroying or rendering the unit inoperable.

Anti-friction bearings used in the speed reducers as well as those supporting the various shafts are selected with a minimum life expectancy of 40,000 hours. Now, a 40,000 hour minimum life translates to about 100 years for a span opening 1000 times a month.

In a similar manner the shafts and couplings are designed to accommodate the loads developed at 150% full rated motor torque.

Certainly, high reliability is assured.

2. Improved Materials, Metallurgy and Manufacturing.

The availability of a greater variety of not only raw materials but also improved commercial products has provided the engineer much greater flexibility in design. This is particularly evident in the steels used for gears, pinions and their supporting shafts.

Proper selection of steels with suitable response to heat treatment assists in obtaining fulfillment of the required specifications. In speed reducers this is especially important since the allowable stresses are a function of the material hardness and it is essential that those hardnesses be achieved.

The same is true of shafts, couplings and bearings. In the case of bearings the very high reliability anti-friction units achieve contributes significantly to increasing the integrity of the system since they do not "wear" - that is, increase their internal, or running, clearances - as sleeve bearings do. Accordingly, anti-friction bearings will maintain the correct center distances in gear sets and assist in reducing accelerated tooth wear.

Manufacturing procedures have also been refined so that surface finishes, tolerances and quality not found in early equipment is not only achievable but standard practice today. For instance, large diameter, coarse pitch rack teeth the were previously inaccurate, "as cast" teeth are now precise, generated or form-cut teeth holding AGMA, Quality 6 or better tolerances.

The bottom line on all these considerations is longer, more trouble-free life and higher reliability.

Economy of Over-all Cost

At first glance it might appear that a gear drive system is more costly than a hydraulic system sized for the same operating conditions.

We all agree the original price of the hardware is probably less for hydraulic equipment. How much less becomes somewhat of a problem to identify due to the manner in which the bid items are defined. For instance, many times the operating machinery is lumped together with the trunnion assemblies, lock machinery and installation costs. Thus the actual hardware cost of the machinery is combined with other related and non-related costs.

Additionally, hydraulic and mechanical require different structural attachments as well as pier designs that don't even show up in the machinery package costs. Together with this are the anticipated maintenance costs - historically they are known for mechanical drive systems but they are just now being accumulated for the few hydraulic systems in operation.

Paramount in determining maintenance costs is personnel expense. Are our present people able to do the job? Will they require special training? Will additional people with other skills be required?

Other costs that can be significant include those associated with maintenance of traffic in the event of a serious breakdown. Past experience indicates it is a rare possibility that such an event will occur on a mechanical system. The track record on hydraulics is not yet established.

Useful life of the machinery also has a part in its cost. Every day traffic is going over and under movable bridges that have been in service 50, 60 , 70 or more years and are still operating with the original machinery with few, if any, replacement parts and even scant maintenance. Today's systems will serve even longer.

The fact of the matter is the true costs of a system consist of many elements: the costs of - original hardware, structural attachments, maintenance, repair and replacement, public inconvenience and useful life expectancy.

In summary, the present day gear drive system offers the owner comfort in the fact that it is simple, assures high system efficiency, is easily installed, readily maintained, very reliable and most economical in over-all cost.

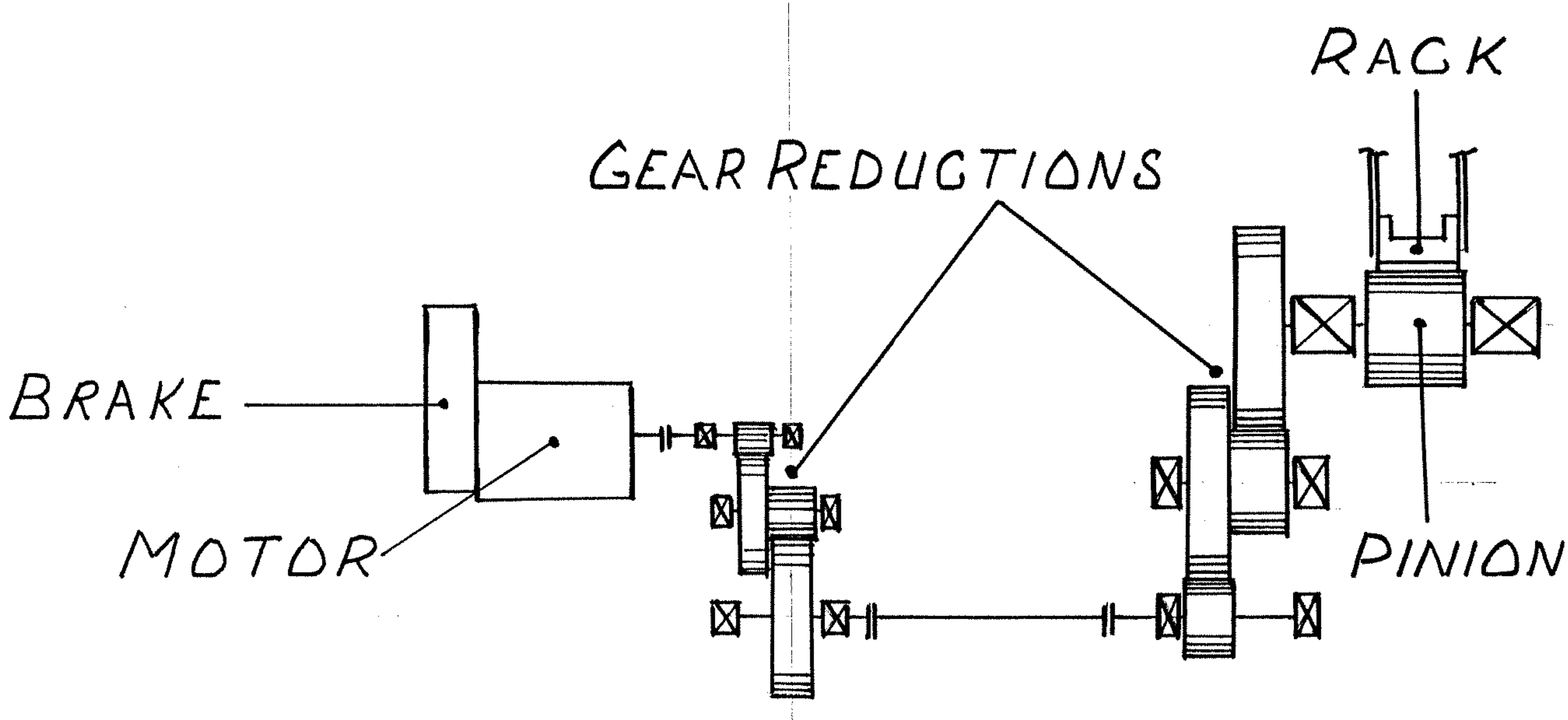

FIG. 1

BASIC DRIVE SYSTEM

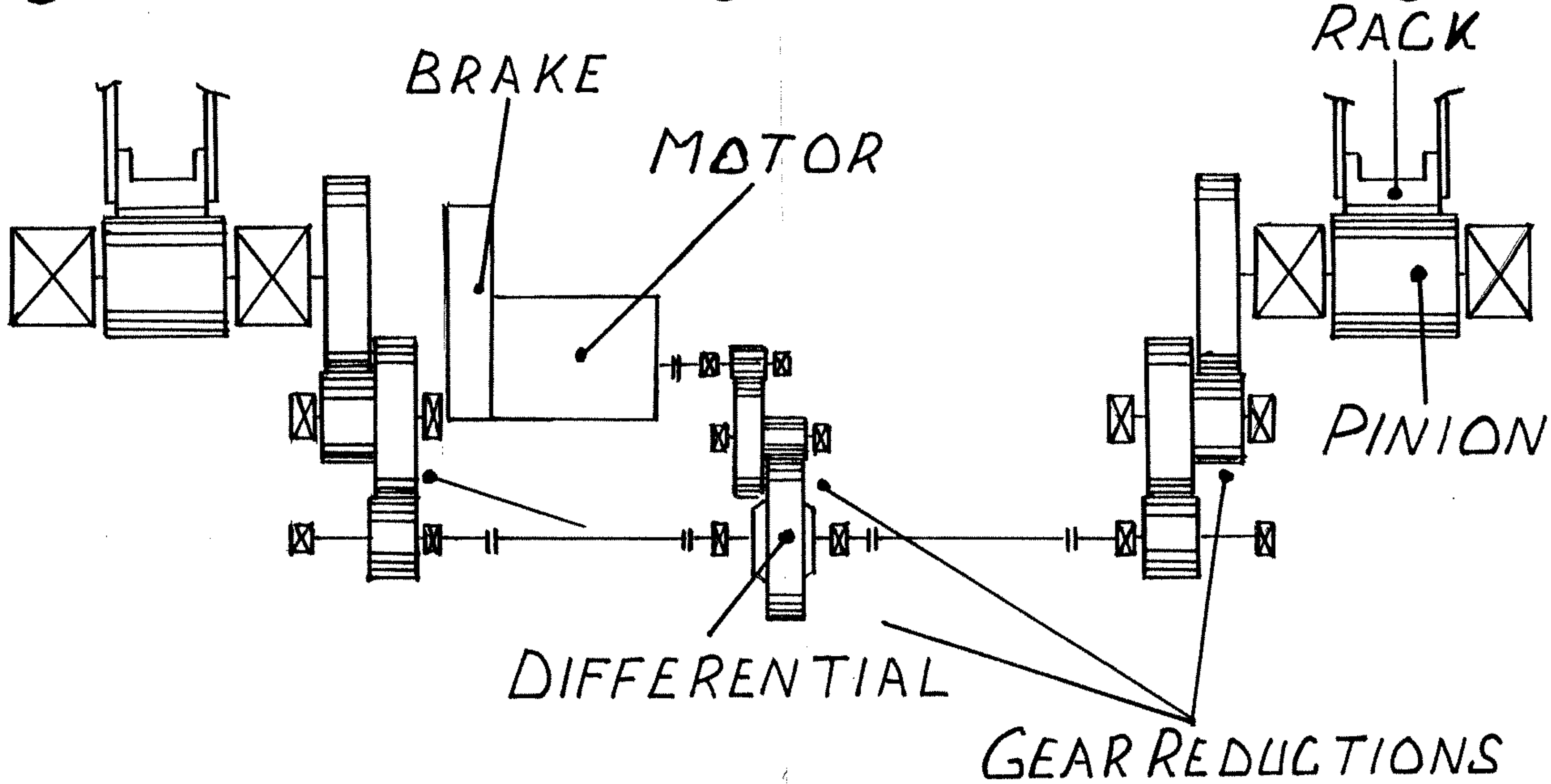

FIG. 2
TWO PINION DRIVE
WITH
DIFFERENTIAL

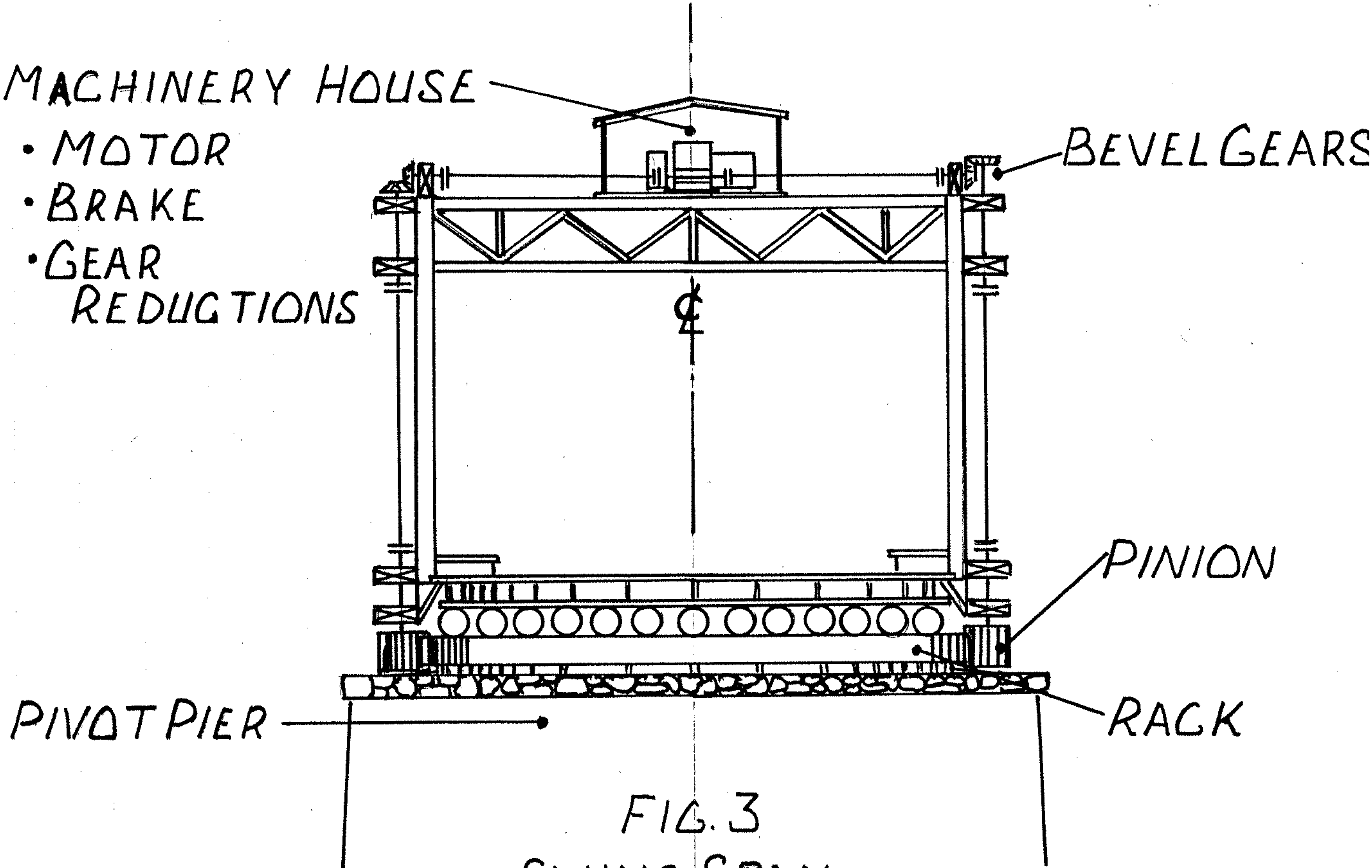

FIG. 3
SWING SPAN MACHINERY

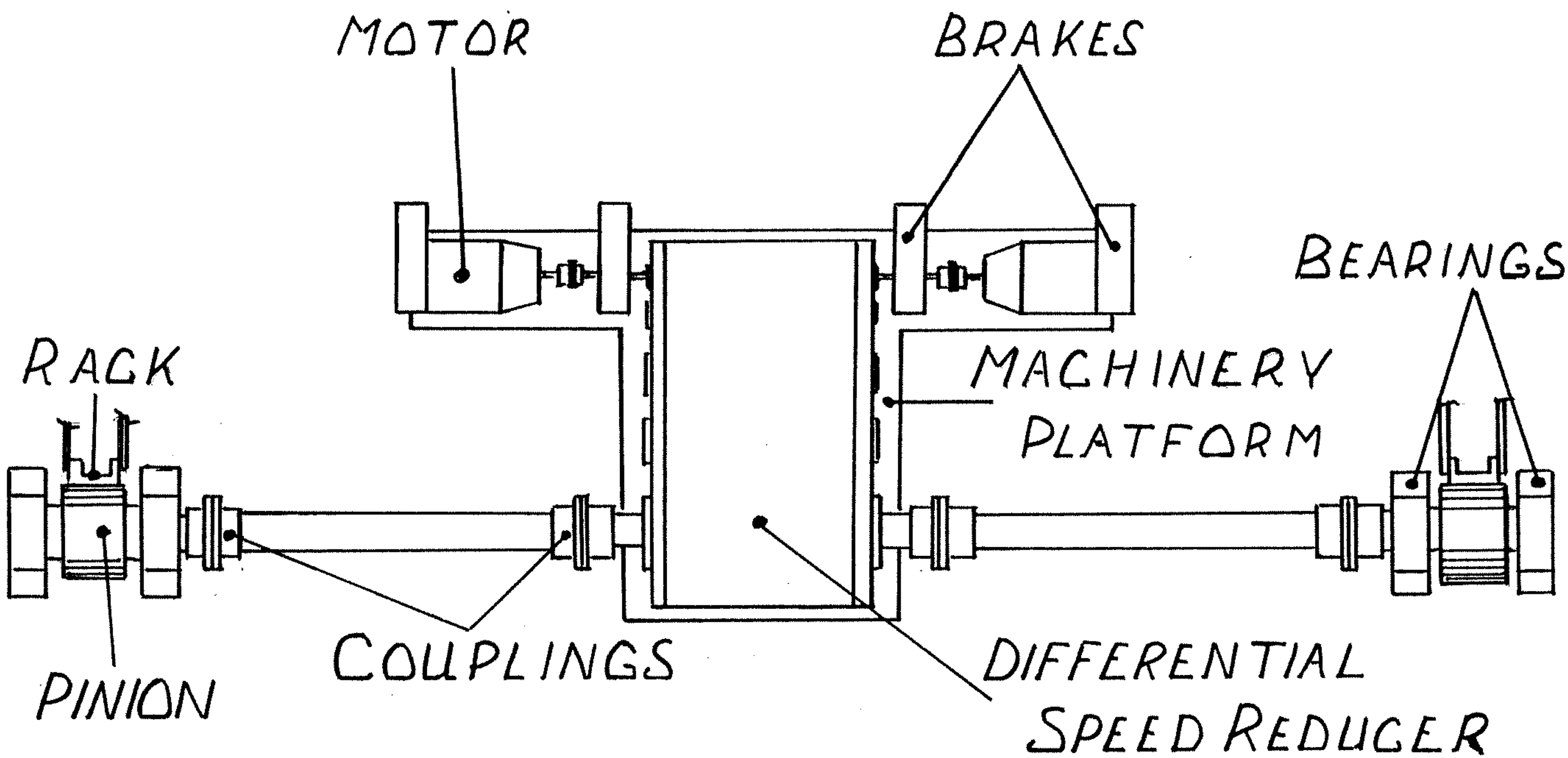

FIG. 4
ENCLOSED GEAR DRIVE SYSTEM

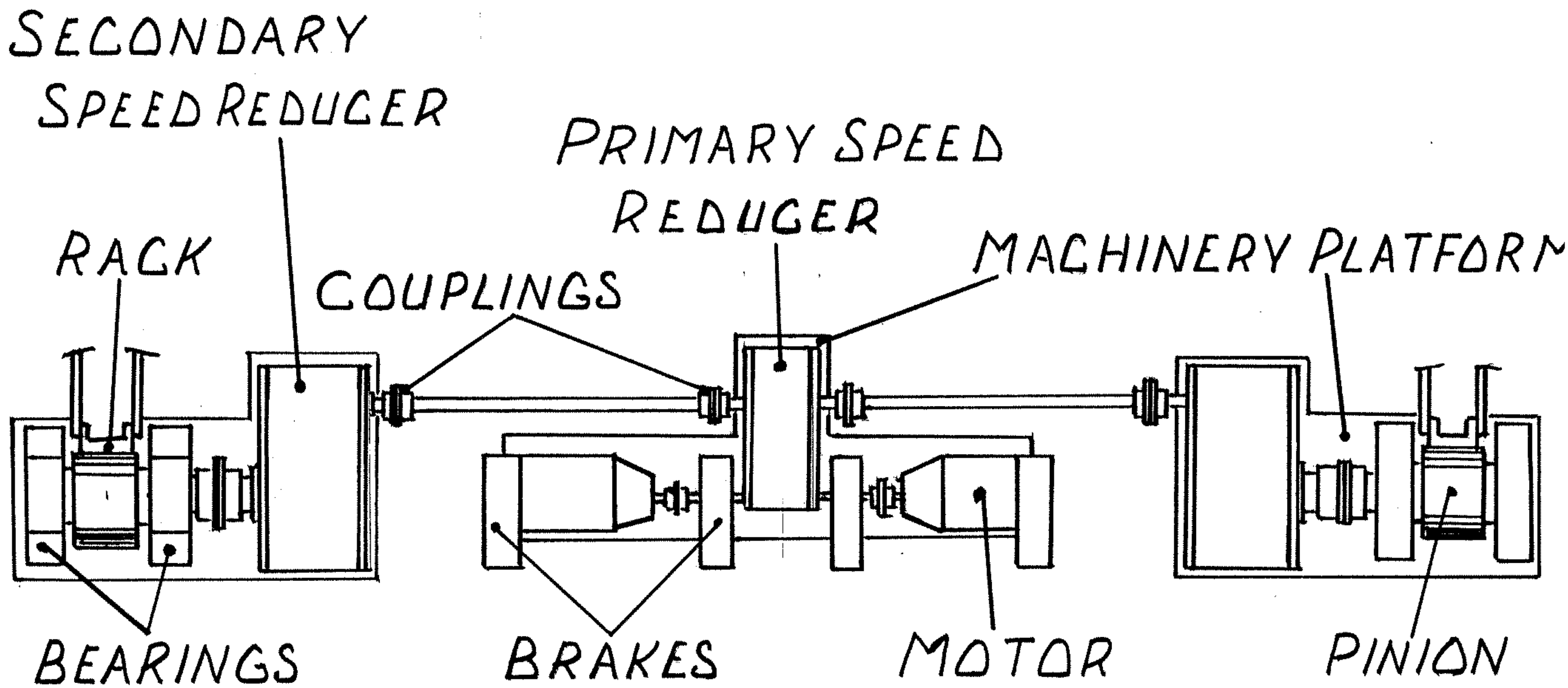

FIG. 5
ENCLOSED GEAR DRIVE SYSTEM