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"CONSIDERATIONS ON THE DESIGN OF SPEED REDUCERS FOR MOVABLE BRIDGES"

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ABSTRACT

The future new construction and rehabilitation of many of our country's moveable bridges will continue to give strong consideration to the fully enclosed speed reducer. As each new or rehabilitated moveable bridge project is examined, there is a significant likelihood that the long term benefits associated with the enclosed drive will yield the most economical life cycle approach.

Considering the fact that each moveable bridge is site specific, that is, affected by the unique combinations of location, space, environment and use, each will require special machinery system design considerations.

Far too often, it has been observed that the procurement specifications, which have been used to address the scope of the speed reducer, have been of a purely functionally type, often times leaving the door open for the bidder/supplier to furnish equipment which may not be suitable or optimized for the application.

The objective, therefore, is to incorporate a machinery specification that is primarily functional, yet one which will address the considerations specifically unique to the particular moveable bridge application.

The following considerations will be covered with regard to enclosed drives and related machinery:

1) Adaptability of the enclosed drive to various machinery arrangements.

2) Design and configuration of drives to suit machinery space limitations.

3) Appropriate considerations for the rating of gear drives.

4) Selection and types of bearings.

5) Designing for extreme operational conditions.

6) Coupling Considerations.

7) Lubrication options.

8) Design Features.

9) Installation

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INTRODUCTION

As many of our country's existing moveable bridges undergo rehabilitation or machinery replacement, many of the original machinery arrangements will be necessarily re-evaluated, giving way to the incorporation of a lifting mechanism which will utilize today's technology. In some cases, where the environment and convertibility suits, hydraulic cylinders will be considered. In many other cases, a mechanical system incorporating enclosed geardrives will be the likely choice. Although the first cost of a mechanical system is somewhat higher than hydraulics, the enclosed drive has proven to be a reliable, low maintenance solution for bridge machinery applications for the last 50 years. Over this time, there have been instances where the performance of the geared system did not live up to expectations. In some cases, the specifications for procurement were not definitive enough to give the equipment supplier a clear understanding of the machinery requirements, while in other cases, the equipment supplier did not provide a product which met the intent of the specifications.

In today's marketplace, competitive pressures are greater than ever before. This has given rise to situations where specification ambiguity has led to the procurement of drives which may not be suitable for the application, but do meet the specification **as written**. The reference to AASHTO specifications is not sufficient enough, as they are general in some areas and leave the potential for the misapplication of equipment.

1. ADAPTABILITY OF ENCLOSED DRIVES

Enclosed drives allow the machinery system designer the ability to develop many possible machinery arrangements to suit almost any machinery space. Some of the attributes associated with the use of an enclosed drive in moveable bridge machinery are:

- The wide range of ratios and multiple reduction possibilities allow the speeds for the motor drivers and accessories such as brakes, clutches, encoders, tachometer transmitters, etc. to be optimized.

- Enclosed drive configurations and multiple unit combinations enable the machinery to be arranged to best suit existing bridge structural supports.

- Enclosed drives can be supplied with an oil bath type lubrication to minimize maintenance.

- Mechanical drive packages can be designed to be off-site assembled, then delivered for installation with minimal work.

- Enclosed drive systems can be designed to incorporate various accessories, auxiliary drive inputs, clutches and brakes.

- The reliable, low maintenance, long service life of an enclosed drive has a positive impact on bridge machinery life cycle operating and maintenance costs.

2. DESIGN AND CONFIGURATION OF GEAR DRIVE SYSTEMS

There are wide arrays of geardrive arrangements possible to offer the bridge machinery designer great flexibility in establishing an arrangement to suit any particular moveable bridge installation. This also enables accessory components to be optimized for their best performance, configuration and location.

In some rack and pinion shaft arrangements, a shaft mounted reducer can offer a cost effective solution by simplifying installation and alignment. It would also eliminate the foundation work necessary to support the geardrives. In other arrangements, the drive can support and locate one end of the rack pinion shaft.

When replacing old, open gearsets on existing moveable bridges with new enclosed drives, it is often possible to fabricate machinery skids which can interface with the existing available structure to help minimize foundation modifications and ease installation. This approach must take into consideration the effect of the drive system reaction loads on the supporting structure.

Where foundation space is limited, the use of right angle gearsets within the geardrive configuration can shift the machinery layout, to suit installation constraints.

An important consideration relative to gearbox configurations which are sidewall mounted, shaft mounted, or mounted on the moving structure is to be certain that suitable design provisions are incorporated to enable the drive to perform satisfactorily during all phases of operation. This includes providing suitable internal lubrication to all components and the preclusion of lubricant leakage from any seal, breather, housing joint, attached accessory or housing connection.

3. GEARSET SELECTION AND RATINGS

Gear rating and design is an applied art. Gear success or failure is based on many system factors, only one of which is the gearing calculated rating per a published standard. Gear rating standards are basically a tool for experienced designers. Real ratings vary from company to company based on the way gears are made, installed, and applied. The purpose of AGMA Standards is to establish a common basis for rating various types of gears for differing applications with the maximum degree of uniformity and consistency between rating practices in the industry. AGMA Standard 6010-C88 offers the designer options on methods of calculating gear capacity. **(See typical example of a gearset selection using the current AGMA rating practice at the conclusion of this paper).** The choice of calculation method employed is dependent upon sufficient knowledge and experience from previous applications and an assessment of the risks and uncertainties in loading. It is only when uncertainties in design, materials, manufacturing, and loading become defined that the value of a service factor can be more accurately determined. In the absence of definitive information, employment of conservative design practices are the most prudent approach.

The application of the enclosed drive requires that its' capacity or "**unit rating**" be defined by the overall mechanical power rating of all static and rotating elements within the drive. These elements include: gears, shafts, bearings, housings keys, and fasteners. The unit rating must include allowances for uncertainties in design analysis, material characteristics, and manufacturing quality as well as consideration for human safety risk and the economic consequences of failure. The greater the uncertainties and/or consequences, the higher the rating should be.

The required unit rating of an enclosed drive is a function of the application and an assessment of the variables that can affect the overall unit rating. Among these considerations are: variables in material, machining tolerances, environmental conditions, severity of service, life requirements, loading, etc. It is critical that the designer makes allowances for these variables when establishing the design.

When an enclosed drive is subjected to a momentary overload, stall conditions, and low cycle fatigue, the conditions must be evaluated to assure that the yield strength of any component is not exceeded. Additionally, shaft, bearing, and housing deflections from extreme conditions can have a significant effect on gearmesh alignment. The enclosed drive must be evaluated to assure that the gearmesh alignment integrity is maintained to prevent localized high stress concentration and/or permanent deformation.

4. BEARINGS

The basic function of the bearings within an enclosed drive is to reduce friction while transmitting the gearmesh reaction loads to the supporting structure or housing. The bearings typically employed for this purpose may be either of the rolling element type, which contain balls or rollers interposed between the housing and shaft, or of the journal bearing type which utilize an oil film cushion to transmit the reaction loads.

Most commercial gearboxes produced today incorporate some form of rolling element bearing due to industry standardization, widespread availability, low operating power loss, and economical cost. The life of a rolling element bearing is affected by the quantity and quality of lubricant, bearing fits and running clearances, load intensity, temperature, speed alignment, system vibrations, and corrosion.

Journal type bearings, (also known as plain or sliding bearings) offer advantages in that they are not susceptible to false brinelling from structural vibrations, have a greater resistance to corrosion from moisture (assuming use of bronze types), have a high stiffness, have the capacity for high specific loads and the ability to run with marginal lubricants. Journal bearings typically have higher power loss than rolling element types, and are normally custom manufactured for the specific application.

Regardless of which type of bearing is utilized, they are all influenced by lubrication. Suitable design considerations must be taken to ensure that all bearings are lubricated at all times regardless of mounting and bridge structure movements.

5. DESIGNING FOR UNUSUAL OR EXTREME OPERATING CONDITIONS

Enclosed drives which are utilized for moveable bridge applications are subject to some unusual conditions which must be addressed in the design phase. These conditions include: exposure to environmental conditions, extreme overloads from weather related conditions, the need to operate in the event of loss of power to the main motor driver, change in stationary and operating orientation when mounted on the moveable span and vibrations transmitted by traffic over the moveable structure.

Environmental Conditions:

Most enclosed drives used in moveable bridges are located over waterways which makes them susceptible to high humidity and, at times, salt air corrosion. Additionally, changes in temperature can also produce moisture internally. The operating duty cycle on bridge machinery is short; therefore, the enclosed drive will never reach an operative temperature where water, which has built up within the drive, will dissipate.

Some solutions to counteract these conditions and their adverse effects would be to apply suitable, long-term anti-corrosive finishes on the internal and external surfaces, to utilize hygroscopic breathers to limit moisture intake, utilize heaters in the oil sump, and raise the oil level on the enclosed drive to just cover the gear elements (in order to consider raised oil levels, suitable provisions must be made to the design to preclude oil leakage).

Extreme Overloads:

The type of overload that would be expected in a moveable bridge drive train would typically be weather related, caused by extreme conditions of wind, or rain/snow which would significantly increase predicted loads. Additionally, the frequency of operation and the motor starting torques also have an impact on the loading of the internal elements.

The rating methods employed in AGMA standard 6010 for enclosed drives typically provide for a minimum of 200% momentary or starting load. Higher overload capacity is possible by altering materials and heat treatment, however, the strength capacity of the gearset and shafts (combined transmitted power and overload) should not exceed 80% of the yield strength of the material used.

Emergency Operation:

The enclosed drive system used in moveable bridge applications must be suitable to operate in the auxiliary drive mode, often operating at a reduced speed. This warrants the use of a positive lubrication method without the use of external lube pumps which may not be operational in the auxiliary mode.

Change in Operating Orientation:

Often times, moveable bridge machinery will be mounted on the moveable span itself. This is critical in Bascule bridge applications where the span will sweep through an arc from the horizontal to near vertical position, shifting the lubricant position within the drive. Appropriate design considerations must be taken in order to ensure that lubricant reaches all necessary components and that the change in altitude does not cause leakage out of the breather, dipstick, oil seals, or any other gearcase connection. This will often mandate the relocation of certain connections and the incorporation of shaft extension "stuffing boxes" to prevent shaft seal leakage.

Structural Vibrations:

The nature of a bridge structure is such that vibrations are ever present from the movement of traffic across the span. The degree to which the mechanical drive system is subjected to these vibrations is dependent on equipment mounting location and the dampening characteristics of the surface to which the equipment is mounted. Vibration may also be transferred through the drive train into the enclosed drive. This is sometimes negated by the backlash in the rack and pinion. Where machinery arrangements do not adequately isolate the geartrain, vibration can lead to destructive fretting of the rolling element bearings. This can be avoided through the use of oil film bearings within the drive or a resilient coupling connection between the drive and the connected machinery.

6. COUPLING CONSIDERATIONS

In most moveable bridge machinery systems, which utilize mechanical power transmission equipment, the shaft couplings play an important role in transmitting the required torque from the reducers to the outboard rack pinions. In some cases, the type of flexible couplings used has been the mechanical joint type, such as the gear toothed coupling, where flexibility is accomplished by sliding and rolling action. In other cases, a combined mechanical and material coupling has been used, such as the metallic spring grid type, or the resilient material couplings which use elastomers or steel springs such as steel disc and diaphragm couplings. The combined mechanical material and the resilient material couplings offer a torsional dampening quality due to their reduced torsional stiffness.

The decision as to the type of coupling which should be used is based on careful consideration of the following:

1) Torque and speed
2) Requirement for non lubricated type couplings
3) Minimum backlash requirement
4) Operating speed range

5) Misalignment capability
6) Axial positioning requirement
7) Axial displacement/movement
8) Floating shaft or separation requirement
9) Fail safe requirement
10) Shock protection requirement
11) Vibration dampening requirement
12) Failure mode considerations
13) Environmental restriction on materials
14) Overload protection requirement

The system choice for a coupling selection should strive to utilize a double engagement coupling assembly (using tandem flexible elements) which will serve to minimize the cyclic forces and moments on the system shafts and bearings. Additionally, the portion of the coupling assembly weight which is supported by the speed reducer must be checked against the overhung load capacity of the speed reducer. This is especially critical where floating shaft type coupling assemblies are used to ensure that the overhung load does not adversely affect reducer bearing life.

For gear type double engagement couplings, the reducer shaft length must be adequate to allow retraction of the outer coupling sleeves so that alignment readings can be taken.

Drive systems which have substantial axial shaft displacement from the movements of connected machinery can utilize sliding type gear couplings (with extended hub/sleeve spline length). Sliding type coupling assemblies can also readily accommodate axial adjustment/positioning of the floating shaft assembly in the field.

Where "fail safe" considerations are desired, dual load path coupling arrangements can be used to permit limited operation when the coupling main load carrying torque path has failed, thus avoiding catastrophic failure.

Standard "straight toothed" couplings will allow misalignment angles of up to 1/2 degree. Beyond this point, special coupling design considerations are necessary to minimize bending moments and radial forces transmitted to connected machinery.

For vertically oriented couplings and floating shaft assemblies, attention to lubrication is important to ensure that grease lubricated flex elements retain their lubricant. An alternative approach would be to utilize a non lubricated flexible disc type coupling thereby eliminating the lubrication requirement.

Some machinery arrangements utilize auxiliary drive inputs which are linked by the use of a disconnect coupling. Auxiliary drives operate at lower speeds and torques. Additionally, the auxiliary drive system is intended for occasional or emergency use. It is therefore desirable to use a disconnect coupling which completely disconnects, allowing the outer sleeve to completely separate from the driven equipment in order to address the differential in speed when not in use.

7. LUBRICATION OPTIONS

The type of oils most commonly used in enclosed drives applied to moveable bridge applications are petroleum based mineral oils. These oils are often compounded with chemical additives to improve specific properties such as improving resistance to rust and oxidation or maintaining a protective oil film under high ger tooth loads.

In general, mineral oils have been found to excel as lubricants for almost every situation. The choice of lubricant and the appropriate additive is determined by the manufacturer's assessment of the environmental and operating conditions for the application along with the loadings and materials utilized within the drive. Caution should be exercised relative to the effect that certain additives may have on the elastomeric, and/or textile fiber materials within the drive. The oils should be high grade, well refined, neutral in reaction, and not corrosive to gears, bearings and seals.

On occasion, synthetic lubricants are used in applications where the enclosed drive experiences extreme temperatures or frequent overloads. Synthetic lubricants can be advantageous as opposed to mineral oils in that they are generally more stable, have a longer service life, and operate over a wider temperature range. They are also considerably more expensive than mineral oils.

Grease lubrication of bearings, and on occasion, some smaller gear drives is generally reserved for instances where oil lubrication is impractical. An example would be an installation where the drive changes its orientation due to movements of the span, thereby shifting the oil level away from components needing lubrication.

Improper lubrication is a leading cause of enclosed drive failures. The accumulation of impurities or moisture in the lubricant, degradation of the oil, or reduction in oil level can damage the equipment. A regular scheduled program of oil sampling or oil changing, along with proper oil level maintenance is critical to the longevity of the enclosed drive.

8. <u>DESIGN FEATURES</u>

When the enclosed drive is used in a moveable bridge application, it should be practically fitted with features which suit the minimum realistic needs for long term reliability and maintainability. Some design features that fit this category are:

Breathers:

Since lubrication is the lifeblood of the enclosed drive, oil quality has a direct impact on the reducer longevity. Contamination of the oil sump from the influx of moisture through the breather during periods of inactivity will reduce oil service life and cause rust forming condensation on the gear elements. The use of a breather with a hygroscopic agent will help keep dry air in the system. Proper attention to desiccant service life and desiccant replacement will be important to ensure long term benefits to the equipment.

Lubrication Systems:

It is possible to provide oil bath type splash lubrication to most reducer configurations (provided proper consideration is given to oil sealing). Reducer arrangements which utilize external lubrication systems should be avoided where possible. Drives which utilize external lubrication pumps could be deprived of needed lubricant if the pump becomes inoperable or if span vibrations loosen piping joints which could drain the sump of lubricant.

Auxiliary Power Take Offs:

Most enclosed drives used in moveable bridge applications have multiple reductions which could readily accommodate the interface with tachometer transmitters, encoders, brakes, auxiliary drives, etc. by the simple extension of an unused shaft.

Fasteners:

Fasteners which require regular removal or adjustments such as those on inspection cover openings, drain and fill plugs, and packing gland adjustment screws should be made of a material like stainless steel which will be compatible with a constant high humidity or salt air environment.

Seals:

In enclosed drive configurations where oil levels may be raised above the housing split, oil levels may shift due to bridge span movements, or where reducer mounting arrangements may place a head of oil on the housing splits or oil seals, suitable considerations must be taken to seal against oil leakage. These include the use of seal, packing, and gasket materials which are compatible with the gearbox oil and its specific additives. "Stuffing Box" type packing gland seal arrangements must include suitable length shafts extensions which will practically enable full access for seal and packing replacement without removing shaft couplings, as well as the availability of replacement split seals and packings.

Oil Sump Heater Provisions:

In cold weather environments which require a means of heating the oil sump to achieve a reasonable oil viscosity for safe gearbox operation, rod type sump heaters are often considered. It would be ideal to place the heaters in oil-tight tubes which would allow removal without draining the oil sump and also prevent "coking" of the oil on the heater rods. An alternative to the use of sump heaters in cold weather environments would be to consider the use of synthetic lubricants which can generally operate over a wider temperature range.

9. INSTALLATION

The enclosed drive is generally shipped from the factory completely assembled. Mating gears and pinions are carefully assembled at the factory to provide proper tooth contact. Bearing settings are normally set to yield the proper running clearances. Nothing should be done to disturb these settings.

Solid Foundation:

The reducer foundation should be rigid enough to maintain correct alignment with connected machinery. The foundation should have a flat mounting surface in order to assure uniform support for the unit. **If the unit is mounted on a surface which is other than horizontal, consult factory to ensure that design provides for proper tooth contact, adequate lubrication and suitable oil sealing considerations.**

Design of fabricated pedestals or baseplates for mounting speed reducers should be carefully analyzed to determine that they are sufficiently rigid to withstand operating vibration. Vibration dampening materials may be used under the baseplate to minimize the effect of vibration.

When mounting a drive on structural steel, the use of a rigid baseplate is strongly recommended. Consideration should be given to bolting unit and baseplate securely to steel supports with proper shimming to ensure a level surface.

If a drive is mounted on a concrete foundation, allow the concrete to set firmly before bolting down the unit. For the best mounting, structural steel mounting pads should be grouted into the concrete base, rather than grouting the gear unit directly into the concrete.

Leveling:

If shims are employed to level or align the unit, they should be distributed evenly around the gear drive base under all mounting pads to equalize the support load and to avoid distortion of the housing and highly localized stresses. All pads must be squarely supported to prevent distortion of the housing when the unit is bolted down.

Alignment:

If equipment is received mounted on a bedplate, it has been aligned at the factory. However, it may have become misaligned in transit. During field mounting of the complete assembly, it is always necessary to check alignment by breaking the coupling connection and shimming the bedplate under the mounting pads until the equipment is properly aligned. All bolting to the bedplate and foundation must be properly tightened. After satisfactory alignment is obtained, all couplings should be properly reconnected.

Couplings:

Drive shafts should be connected using flexible couplings. The couplings should be aligned in accordance with the manufacturer's instructions.

Alignment and Bolting:

The gear unit, together with the prime mover and the driven machinery, should be correctly aligned. After precise alignment, each member must be securely bolted and dowelled in place. Coupling alignment instructions should be carefully followed. It is essential that the enclosed drive be securely bolted to it's foundation utilizing bolts of the proper diameter to match housing mounting holes. Bolts should be SAE grade 5 or equivalent. Shear blocks are recommended at locations where there is an overhung load in a direction that would subject mounting bolts to shear forces. Sidewall mounted equipment or span movements which place the equipment in vertical positions, are typical applications which should employ shear blocks.

SUMMARY

The advantages of the enclosed drive for use in moveable bridge applications have been well established over the past 50 years. Proper considerations regarding the unique aspects of their application will guarantee continued reliable and cost effective long term bridge machinery service life.

TYPICAL EXAMPLE

GEAR REDUCER SIZING FOR BRIDGE DRIVE SYSTEMS

1. **Typical Load Condition:**

	OUTPUT TORQUE at 1.3 RPM	**% TIME**
Normal Operating with wind load:	641520 in-lb	25%
Normal wind load plus ice load:	879120 in-lb	40%
Heavy wind load plus ice load:	997920 in-lb	35%
		100%

2. **Motor Horsepower:** Assuming 80% total efficiency.
997920 * 1.3 RPM / 63025 * .8 effy) = 25.7 HP at maximum output torque

Motor Horsepower:
25.7 * 1.2 (SF on applied load) = 30.9 HP, use 30 HP motor.

3. **Brake Torque:**

Brake set torque : $1.4X10^6$ in-lb (Maximum torque x 1.4 SF)

Brake maximum torque: $1.75X10^6$ in-lb (1.4 x 1.25 brake torque tol.)

4. **Gear Box rating, Design Torque and Horsepower:**

4.1 Gear Size:

Gearing should be sized for a minimum service factor of 1.0 at motor horsepower and 40,000 hrs gear life.

In addition, gear tooth bending should not be stressed above 75% of material yield strength at motor stall torque or brake maximum torque.

4.2 Resulting actual service factor for gearing:

Use Miner's Rule to determine effective torque per operating load cycle.

Durability: a = .046 (SN curve slope for durability in power rather than stress)

$(.25 * 641520^{1/.046} + .40 * 879120^{1/.046} + .35 * 997920^{1/.046})^{.046}$
= 953949 in-lb effective torque for durability.

Strength: a = .0153 (SN curve slope for strength)

$(.25 * 641520^{1/.0153} + .40 * 879120^{1/.0153} + .35 * 997920^{1/.0153})^{.0153}$
= 982024 in-lb effective torque for strength

Effective Horsepower at 1.3 RPM, at 80% assumed total system efficiency:

DURABILITY INPUT POWER = 953949 * 1.3 RPM / (63025 * .8 effy) = 24.5 HP
STRENGTH INPUT POWER = 982024 * 1.3 RPM / (63025 * .8 effy) = 25.2 HP

Actual service factor $= \dfrac{\text{GEAR RATED POWER}}{\text{EFFECTIVE POWER}}$

Therefore: Durability Service Factor $= \dfrac{30}{24.5} = 1.22$ MINIMUM

*Strength Service Factor $= \dfrac{30}{25.2} = 1.18$ MINIMUM

Component Design:

All components should be designed within AGMA allowable stress levels for the motor HP rating. Stresses also should not exceed 75% of material yield at maximum brake torque or motor stall torque or at 200% of motor torque.

*Pitch, pressure angle and tooth profile modification can generally be optimized in order to achieve higher gear tooth strength without increasing the gear size. In normal design criteria, the gear strength rating would be 130% of the gear durability rating.

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