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RATIONAL SPECIFICATIONS FOR SPEED REDUCERS ON MOVABLE BRIDGES

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In 1916, the pre-eminent bridge engineer Dr. J. A. L. Waddell made the following observation about bridge specifications in his comprehensive treatise, *Bridge Engineering*: "There are no bridge specifications yet written, and probably never will be, which will enable an engineer to make a complete design without using his judgment to settle many points which the specifications do not thoroughly cover; or, as Theodore Cooper puts it: 'The most perfect system of rules to ensure success must be interpreted upon the broad grounds of professional intelligence and common sense.' " Now, nearly 100 years later, I imagine Waddell is ensconced in the proverbial destination, looking at today's bridge specifications and the dilemmas faced by engineers, probably chuckling to himself and thinking, "I told you so."

Contemporary specifications on just the machinery required for movable highway bridges have increased exponentially in the past twenty years. For instance the AASHTO Standard Specifications of 1988, with interims, was a pamphlet of 65 pages—a mere bump in the road compared to the 286 pages included in the 2008, 2nd Edition of the LRFD Movable Bridge Specifications. Add to this similar increases in the volumes of owner's standard specifications together with the special provisions prepared by the engineer for each project, as well as industry standards for proprietary products and it's a daunting task just to review and understand the specifications, let alone intelligently estimate the job to include all the stated and implied conditions to say nothing about covering the unknown contingencies arising during manufacture resulting from inconsistencies, redundancies and interpretations of the myriad specifications. It is understood and agreed that discrete specifications are necessary to cover all the machinery elements. Those specifications must be valid, achievable and distinctly described so that the owner's objectives are fulfilled, the engineer's designs are satisfied and the completed project accomplishes its goals. This paper will briefly investigate and review current specifications of AASHTO, AREMA, AGMA and various other general and special provisions developed by movable bridge owners and consultants that are placed upon gear-type speed reducers for service on movable bridges. The intent is to identify some of the inconsistencies, areas of conflict and other adverse influences that promote excessive costs, delays in completion of the project, inconvenience to the traveling public as well as an adversarial environment between the owner and contractor. Another purpose is to offer suggestions to remove such obstacles from the specifications without altering the design and performance requirements or serviceability of the units furnished.

Nearly all agencies and bridge owners include a variety of specifications in their construction contract documents, as well as a governing order in cases of discrepancy. Typically the included documents and priority order is:

1. Special Provisions
2. Technical Special Provisions
3. Plans
4. Supplemental Specifications
5. Standard Specifications

The agencies also make it clear that all are an integral part of the contract and a requirement in one is as binding as though occurring in all. Herein lies a probable glitch in the system because of inconsistencies among the documents.

Let's take a look at the speed reducer specifications. First, it should be recognized that the specifications are not those of any specific state or other owner, or any specific engineer or consultant, but are generic and typical of most contract provisions. In order of priority, then, the applicable documents are:

1. Special Provisions

   The General Provisions Section usually invoke AASHTO or AREMA Movable Bridge Specifications that require speed reducers to be manufactured in accordance with current AGMA standards, except that rolling element bearings shall have an L-10 life of 40,000 hours.

2. Technical Provisions

   The Technical Provisions will include a section describing the performance requirements and features desired in the speed reducers. Performance requirements include the horsepower, input speed, ratio and service factor(s), rated in accordance with current AGMA Standards. Features include such things as: restrictions on input/output shaft center distances, type of lubricating system, breathers, oil level indicators and sampling cocks, locations of external mounting bolt holes and diameter and lengths of shaft extensions, etc.

   Recently some Technical Provisions have begun to invade the engineering and design responsibilities of the speed reducer designer by specifying materials, hardness values and other considerations that rightfully are the responsibility of the reducer manufacturer.

3. Plans

   Contract Plans illustrate the speed reducers and define its envelope dimensions, means of mounting and assembling with other machinery components, as well as describing the performance requirements - HP rating, speed, ratio and service factor.

4. Supplemental Specifications

   ANSI/AGMA Standards detail the means of rating the gear sets, designing and evaluating the shafts, keys, fasteners and all other components to certify the unit will fulfill the required performance criteria as designated on the name plate.

5. Standard Specifications

   Owner's Standard Construction Specifications cover a very broad range of construction requirements and normally do not include speed reducer considerations. However, under the broad interpretation of the priority of documents, it could be argued that some components such as bolts and fabrications could be subjected to them.

In view of the multitude of documents that may enter into the design, manufacture, assembly and testing of speed reducers, it's easy to understand that inconsistencies may exist between some of the documents, interpretations of the specifications can vary and the owner and supplier may suffer delays and resultant undue costs.

For example, threaded fasteners.

- Standard Specifications frequently call out high strength bolts per ASTM A325, Grade DH or 2H, with hardened steel washers.

- Current Technical Special Provisions for high strength bolts tend to include both ASTM A325 and A449.

- AASHTO/AREMA designate specific materials.

- ANSI/AGMA 6013-A06 requires threaded fasteners to be selected according to clause 8 of ANSI/AGMA 6001-D97, *Design and Selection of Components for Enclosed Gear Drives*.

In order of priority it is seen that ANSI/AGMA Specifications follow the Technical Special Provisions as well as AASHTO and AREMA requirements. Accordingly, many owners feel that the threaded fasteners used in speed reducers should conform to callouts in the Special Provisions. No one would argue that A325 and A449 bolts are anything but high-quality fasteners; however, they are not always the best selection for all applications in speed reducers, which have varying demands for bolts, depending upon where they are used. For instance, the housing cap bolts, which have the job of firmly clamping the casing base and top joint together, must have sufficient tensile strength to withstand the maximum internal and external design loads and prevent movement of the joint members. Additionally, often the diameter of the fastener is restricted so that bolts with allowable stresses greater than permitted by A325 and A449 grades are required. For example, an A449 bolt, 1-1/2 to 3 in. diameter, has an allowable stress of 33,000 psi. Yet, today, with the very high load test requirements, it is not unusual to have housing bolts stressed to 60,000 psi or even higher. Of course, the solution is to use an SAE Grade 5 or 8 bolt.

Other applications in the same reducers, such as those used for bearing cover plates to close off the shaft end or serve as a seal carrier, often have no applied tensile load to support. The bolts only hold the cover plates onto the housing. In such locations it makes little sense to use expensive bolts when SAE Grade 1 fasteners are entirely suitable.

In all speed reducer applications the prudent engineering decision is to select the fastener based upon its use and loading and not upon a general, one-type-fits-all approach.

Another example of conflicts in the various specifications is that of keys and keyways.

- Most Special Provisions call out forged steel keys, frequently ASTM A 668 CL D or CL K, situated in closed end keyways with the ends of the keys rounded to suit the keyway.

- AASHTO Specifications are similar, but the only specified material is ASTM A668 CL D; and keys not located in closed end keyways must be secured by safety set screws or other means. The requirements of AASHTO also state, "the keys shall have sufficient resistance to develop full torsional strength of the shaft."

- AGMA Specifications provide for the use of several materials for steel keys, having allowable compressive stress values from 37,800 psi to 77,000 psi. The allowable compressive stress is based upon 70% of the material yield strength, and the allowable shear stress is 50% of the allowable compressive stress. Closed end keyways and rounded keys are not required.

Keys in speed reducers are sized to resist the maximum design torque, which includes the applicable Service Factors as well as the specified test run loads. In addition to this, gears not cut integrally with the shaft are shrunk on the shaft with an FN-2 fit. The shaft diameter at the gear hub is selected so that the resultant torque resistance of FN-2 fit is greater than the maximum applied torque. The need for this is obvious because the torque direction to raise the span is opposite to that when lowering and it is absolutely necessary to prevent any, no matter how slight, rotational slip between the shaft and gear hub. In fact the key serves only as a redundant member--probably never carrying any of the torque loading.

Feathered keys in closed end keyways generally are not considered good design practice in speed reducers for several reasons. Firm axial positioning of the gears is essential and is normally accomplished using annular spacers between the hub ends and bearings or other shoulders. Key ends protruding beyond the gear hub interfere with this design need. Also, customary practice is to have full width bearing of the key in the hub keyway. Containing a feathered key within the hub width results in reducing the bearing area and having potentially greater stress in the key. Accordingly, full-width, square-end keys are used, which enable maximum torque capacity together with the ability to provide for accurate axial location of the gear and uniform transfer of any axial gear loads to the bearings.

In spite of the priority of documents, Special Provisions or AASHTO Specifications would dictate an inferior design if imposed upon keys and keyways for internal components in speed reducers.

When writing a specification for speed reducers for movable bridges, the owner, engineer and manufacturer must have a distinct understanding and comprehension of just what that specification embodies. In the case of ANSI/AGMA 6013-A06, the current American National Standard for Enclosed Gear Drives, the requirements extend well beyond the gear ratings and minimum bearing life expectancies. Clause 5 of that Standard clearly states:

> "Throughout this standard the term 'unit rating' is defined as the maximum power that can be transmitted without exceeding the lowest individual rating of the following: gearing, housing, shafting, keys, bearings, threaded fasteners, motor connection for

gearmotors, and other components of the basic gear drive and auxiliary systems."

The point here is that when the Special Provisions require a speed reducer to be designed and manufactured to ANSI/AGMA 6013-A06, that specification covers not only the gears and bearings but also all the normal components. It is necessary for the manufacturer to design the entire unit to the performance and test specifications in order to certify compliance with the Special Provisions. To impose "boiler plate" specifications upon each and every one of the myriad of parts that collectively make up the speed reducer is not prudent on the part of the owner. Doing so can lead to inferior and more costly products as well as conflicts in responsibility for the performance of the speed reducer, unwarranted delays and inconveniences to those who use the bridge.

We know that specifications can be contradictory. We also know that in some cases, applying inappropriate specifications can lead to inferior design. We also know that as Dr. Waddell said, no specification is going to be perfect. But we still need to strive for a good specification.

What is a good specification? One that accurately describes that which is required to accomplish a goal. What is the goal? In this case, the goal is a reducer that makes the bridge operate for a very long time without interruptions and with minimal maintenance. Some may argue that the goal is to get a reducer that meets the specification, but, as we have already discussed, specifications are not perfect and require judgments. Therefore, successful service should be our ultimate goal.

How do we write a good specification? Obviously it must be clear and concise. There should be only one section of the documents, usually in the Technical Special Provisions, that specifically addresses speed reducers and contains all of the specifications for performance, features, and testing. All applicable supplementary specifications such as AGMA or AASHTO specifications should be referenced within that section. This eliminates the possibility of specifications being missed in the bidding process. Often the reducer manufacturer is a third tier supplier to the overall bridge project. Due to the relatively low volume of reducers constructed for bridge projects, the manufacturer may be unfamiliar with the particular requirements of bridge service. They are also unlikely to receive or review a complete set of specifications and plans. Therefore, having all the requirements in one section simplifies the process of getting all the right specifications to the right people.

A good specification should also clearly define its scope. Critical components under highly loaded conditions warrant specific attention and stricter specifications. Therefore, the specification should address which provisions apply to which components. Statements such as "All gear reducers shall . . ." must be carefully considered. As an example, many rotary cam limit switches are driven at extremely slow speeds with no significant torque by small gear reducers. These small units are typically off-the-shelf catalog reducers. Requiring 40,000 hour B-10 bearing life calculations or load testing does little toward accomplishing the goal and contributes significantly to cost and wasted efforts during approval review and requests for information (RFI).

The type of specifications used is important. A reducer is an engineered product similar to couplings, brakes, motors, etc. As such, the engineer of record (EOR) is not responsible for the design or component details of the reducer. Therefore, the specifications should describe the desired performance that the EOR requires. For most reducers, the performance specification is simply the horsepower, speed, ratio, and service factor that the EOR requires to complement his or her machinery design. In addition to the performance specification, certain desirable features may be specified. These features may be as simple as requiring a dipstick or something critical to the design, such as differential gearing or through hardened gearing. Other types of specifications include physical constraints, manufacturer experience qualifications, quality specifications, testing specifications, warranty, and quality assurance specifications. The applications of each type of specification must be coordinated with the performance specification to ensure that all of the requirements complement each other.

The performance specification is the most important since it is the basis for sizing all components of the reducer. In addition, it is also this basic information that is used in all the AGMA specifications which govern the design aspects of the reducer. Typically, this information is not difficult to specify and is rarely an issue.

Testing specifications, on the other hand, often create serious issues and delays. First of all, load testing of reducers is not standard in the industrial reducer market. Several reducer manufacturers do not have in-house load testing equipment. Therefore, it is very important that all testing requirements be included within the reducer specification section so the manufacturer will be aware of these specifications and include them in the proposal. In the past, load testing requirements have been listed under "shop tests" or other similar erection specifications and not in the reducer specification. Such practices can contribute to failure of the manufacturer to include the required tests in the proposal. Of course the tests must be performed to satisfy the contract. Delays will result because testing requires time to assemble and set up the required equipment as well as to conduct the tests, and all parties will suffer.

The specified testing parameters can cause problems as well. Any tests, whether for motors, reducers, concrete, weld quality, etc., should be relevant for the application. As stated above, the specification must also complement the performance specification. The load testing requirements must never exceed the performance specifications of the reducer. For example, if the reducer is specified to have a 1.5 service factor, then the test load should not exceed 1.5 times the rated horsepower of the reducers. When it does, several situations occur, and sometimes, the results are detrimental to the overall project. It's been proven that any load testing reduces the service life of the reducer by some amount. Loading a reducer beyond its design limits reduces the service life significantly and may cause failure. When the test requirement exceeds the required performance rating, the manufacturer must make a choice in his design and component selection. The manufacturer may decide to supply a unit that meets the performance specification and then evaluate that unit at the overload test condition. The manufacturer is basically making a calculated gamble that, due to the relative short duration of the test, the unit should survive. The manufacturer's other option is to design a unit that is actually rated for the test condition and not the performance specification. This, of course, will lead to a larger, more expensive reducer. The question that should be asked is whether the testing specification is necessary or relevant to the application. If it is, then the performance specification most certainly should equal the test specification. If it's not, then the owner is adding requirements that are increasing costs unnecessarily or allowing the manufacturer to make a gamble that if lost, impacts the entire project. If the cost of larger units and higher than necessary test loads is not a concern, why not raise the service factor on the performance specification to complement the design testing? If the performance specification and the testing specification are consistent, there will be no question or gamble by the manufacturer in the design or size of the unit. This approach can have benefits to the EOR as well. If physical constraints exist, the EOR must know the maximum size reducer that will likely be supplied. Typically, he will base his design on a catalog unit that meets the performance specification and service factor. If the testing loads exceed the service factor, the supplied unit may be significantly larger than anticipated in the machinery design. When test loads exceed performance specifications, the possibility for failed tests, physical interferences, and job delays is greatly increased.

The best approach is for the testing specification to resemble actual service. Most bridges operate for relatively short periods. Why does AASHTO require a four-hour continuous no-load test when the longest service run is two minutes? What benefit to actual service is it that the reducer's oil temperature not rise more than 30 degrees over a two-hour load test? More importantly, like the bolt specification example above, an apparently more stringent specification may actually be resulting in a less desirable product. In this case, a reducer with a very high oil level will heat up due to churning of the oil during extended operation. Therefore, the oil level must be lowered to prevent exceeding the temperature rise restriction in the test specification. In service, where the reducer sits for long periods, the higher oil level would have been much more beneficial to long-term service since the bearings would be completely covered, preventing corrosion in the static state. We are not suggesting that the test specification be a 30 percent load for two minutes (typical actual service), but that the test specification be more consistent with the performance and more relevant to actual service.

Within many testing specifications, there are references to "abnormal" or "unusual" noises, wear patterns, temperatures, etc. These vague requirements have cost millions of dollars. The basis for these types of requirements is, of course, to prevent problem reducers from being put into service. However, the application and enforcement of these requirements is problematic at best. These situations are where the owner, EOR, and the manufacturer must remember Dr. Waddell's comments that common sense and professional intelligence must be applied. As with all specifications, quantify or eliminate vague requirements if at all possible.

Specifications that require quality control submissions should be considered carefully. Obviously everyone wants a quality product. Including the manufacturer. However, the process of achieving that quality and the interpretation of quality level and quality standards can cause significant issues and delays. Each reducer designer and manufacturer have quality procedures in place that are part of their normal process. However, these procedures vary with each manufacturer and each design. Since the reducer designer is responsible for the design and not the EOR, only the designer knows what quality levels are required to achieve the desired performance. For example, certain types of NDT may be applicable for gears that are made from weldments. However, that NDT process would not necessarily be used if the gear were cast or cut from a solid blank. It should be the designer and manufacturer's option to use the materials, processes and quality control testing required to meet the performance specification. Requiring submissions of certain design or quality documents is fundamental to quality assurance. However, specifying very specific levels of quality for internal components and dictating certain quality control processes with rejection criteria will most likely result in problems.

In all movable bridge applications, the reducers are either completely custom units or special adaptations of standard catalog units. Catalog units are often specified in plans and specifications. The performance ratings and dimensional information is readily available to the designer. This makes it easy and simple for the designer to lay out connecting machinery and complete the mechanical component design. The model number of the catalog unit will be listed in the plans for reference. However, when the specifications are written for the reducer, they often contain design and construction restrictions that the catalog unit used in the design does not meet. The EOR and owner must be very careful to make sure that any catalog units specified can conform to the bid specifications. The specifications that most often become an issue with catalog units are the 40,000 B-10 bearing life, design restrictions, proprietary information submittals, and testing requirements. None of those requirements are standard for the reducer industry. In most cases, the specified catalog unit would function quite well in the application—especially since there is significant field experience for the particular model selected. However, due to inappropriate application of specifications, substantial expense and time for all parties is expended in the review of specifications, RFI's meetings, teleconferences, etc. in order to get the exact unit specified in the plans approved. Nobody wins in these situations.

The current trend in reducer specifications has been to eliminate the use of standard catalog units for movable bridge use. It is best to recognize this situation early in the design process. That way, the EOR can use the benefit of custom-made units to his or her advantage during the overall machinery design. Special ratios, internal clutches, unusual shaft arrangements, integral motor or brake mounts, etc. can all be incorporated if a custom-made unit is used. However, the plans and specifications should clearly state that custom-made, not catalog, units are required. The design and construction of the custom-made units should be tailored to meet all rational requirements. (Maybe even a few irrational ones.) The drawbacks to custom-made units are always going to be cost, delivery, and lack of operational experience for the particular unit.

All engineers know that it is better to specify what you want rather than try to exclude everything you don't want. Therefore, the following section attempts to list the components of a good, rational, speed reducer specification.

1. Specify approved vendors that have a proven reputation producing custom-made reducers for movable bridge applications.

2. Clearly specify the performance required. Include power, speed, ratio, and service factor. Ensure that all values are consistent, particularly if a torque rating is listed. Include performance specifications for all inputs, including auxiliary or manual drives.

3. Reference all applicable specifications (AASHTO, AGMA, etc.). If inconsistency exists, identify which will govern. For example, state that the AASHTO, 40,000 B-

10 bearing life requirement applies but all internal components of the reducer (keys, etc.) will be per AGMA.

4. Specify any design constraints. Examples: Steel housings, through hardened gearing. This is where problems can occur from over-specifying.

5. Clearly define any mechanical features required. For example, parallel shafts differential, right angle, dry well on vertical down shafts, double seals, hygroscopic breathers, splash lube, etc.

6. Detail any physical constraints, for example, shaft center distance envelope, operating angles for rolling lifts, height restrictions, etc.

7. List all required submittals. Keep in mind that proprietary information and intellectual property are going to be issues. Based on recent experience, submittals should be limited to outline drawings, gear rating calculations, and material certifications for gearing.

8. Testing requirements. These should be consistent with the performance specification and actual service. Avoid vague or subjective requirements. Clearly state acceptance and rejection criteria. List all data to be recorded during the test. Note requirements for witnessing the test by owners, representatives, or inspectors.

The current multiple volumes of specifications have many layers of sometimes conflicting requirements. We have illustrated only a few simple examples of where improper interpretation or application of the many specifications may result in inferior designed speed reducers for bridge applications. We have also suggested guidelines which hopefully will result in a more rational approach to speed reducer specification.

As Dr. Waddell stated, no specification is perfect. When issues arise, all factors must be considered. Careful evaluation must be done to determine if the issue is a result of a specification problem or reducer problem. The engineer, owner, and manufacturer must keep in mind that the ultimate goal is to make the bridge go up and down safely and efficiently for a very long time.