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Abstract

The domestic gear industry annually manufactures several billion dollars of gear products, yet utilizes quality control practices in manufacturing which need to be greatly improved. The specific area of quality control addressed here involves the dimensional metrology assessments of precision gears. The domestic gear industry requires the development of a national metrology infrastructure to improve the traceability of dimensional measurements to the international standard of length. Such a metrology infrastructure must be built with cooperation from all sectors of the gear industry, spearheaded by NIST.

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Introduction

Gears are ubiquitous items in our society. In 1988, the domestic gear industry shipped approximately $13.4 billion in gears for military and commercial applications [1]. Gears are basic components in most industrial machinery and equipment, construction equipment, agricultural equipment, motor vehicles, ships, and aircraft. Gears are vital elements of the industrial base of this nation; moreover, the present and continued strength of the domestic gear industry is critical to both U.S. national security and economic competitiveness.

There is a conspicuous void existing in the quality control aspect of gear manufacture in this country. Quality control measurements in this industry are not traceable to the international standard of length through the U.S. national standards laboratory, NIST. The assessments of the dimensional characteristics of gears, and most other consumable items produced in this country, in all military applications and many commercial applications are required to be traceable to the international standard of length. Traceability requirements in gear manufacture are formalized and imposed mainly as contractual agreements, or as requirements in satisfying the conditions of written standards. The U.S. military requirements for traceability are clearly articulated in specific military standards, such as the MIL-STD-45662A [2]; commercial requirements for traceability arise from several potential sources, including conformance to international quality standards, such as ISO 9000 [3]. NIST is not directly integrated into the domestic gear industry's quality control of manufactured gears. The American gear industry has needed and pursued improved traceability through NIST to the international standard of length for several years.

In order to have a significant impact on the quality assurance of manufactured gears, the traceability of quality measurements to NIST standards must be improved to optimize the link to the international standard of length. Gears tend to be extremely complex in their geometric characteristics, giving rise to quality control issues in their manufacture which are exacting and often unique. The improvement of the traceability of measurements associated with the quality control of gear manufacturing is a broad issue that requires the development of a national infrastructure for gear metrology.

Traceability to NIST

The development of a metrology infrastructure for the domestic gear industry relies upon improving the traceability for quality control measurements to standards maintained by NIST. Traceability is a reference to the international standard of length throughout the entire supply cycle as the means of maintaining dimensional integrity of the end product of a manufacturing process. Further, traceability involves the interdependencies of suppliers and consumers as the interdependencies propagate throughout the supply cycle from the beginning of the cycle, the international standard of length, through the manufacture of systems and subsystems to the end of the cycle, the gear.

What is "traceability to NIST"? How can "traceability to NIST" be achieved? In order to fully answer these questions, the four recognized possible definitions of traceability should be examined [4].

1. Traceability is the ability to demonstrate conclusively that a particular instrument or artifact standard either has been calibrated by [NIST] at accepted intervals or has been calibrated against another standard in a chain or echelon of calibrations ultimately leading to a calibration performed by [NIST].
2. Traceability to designated standards (national, international, or well-characterized references based upon fundamental constants of nature) is an attribute of certain measurements. Measurements have traceability to the designated standards if and only if scientifically rigorous evidence is produced on a continuing basis to show that the measurement process is producing measurement results (data) for which the total measurement uncertainty relative to national or other designated standards is quantified.
3. Traceability means the ability to relate individual measurement results to national standards or nationally accepted measurement systems through an unbroken chain of comparisons.
4. Traceability implies a capability to quantitatively express the results of a measurement in terms of units that are realized on the basis of accepted reference standards, usually national standards.

In attempting to assess and apply the above definitions, several issues should be considered. First, a traceable measurement does not necessarily imply a correct measurement; for example, measurement uncertainty, a vital element of a measurement system, is independent of measurement traceability. Hence, traceability is one of several aspects of a measurement system to consider in the assessment of that system's correctness. According to NIST policies, a claim of traceability in measurement implies the ability to relate individual measurement results through an unbroken chain of calibrations to a common source, usually U.S. national standards as maintained by NIST, or intrinsic standards based on fundamental constants of nature with values assigned or accepted by NIST [5].

Of primary importance in assessing the relevance of a particular system of traceability to a particular application (here, the manufacture of gears) is what the "real intent" of traceability is assumed to be. In the case of the domestic gear industry, the intent of measurement traceability is to ensure that measurements made throughout the manufacturing processes and supply cycle are of adequate accuracy in order to ensure the production and delivery of a part with geometric dimensions that conform to design specifications. Dimensions that are manufactured "in tolerance" conform to design dimensions within a specified and acceptable range. This provides the basis for quality parts that fit into assemblies and are interchangeable.

Recent Metrology and Traceability-Related Workshops

NIST has hosted or co-sponsored two industrial workshops in the past year which have addressed metrology issues in U.S. manufacturing. In August, 1992, NIST hosted "Metrological Issues in Precision Tolerance Manufacturing," in Gaithersburg, Maryland. This workshop revealed a concern among a wide cross-section of American industry that the quality control practices in the production of gears are not sufficiently traceable to NIST standards [6]. In response to this finding, NIST teamed with the Department of Energy Y-12 Plant in Oak Ridge, Tennessee, to conduct an "Advanced Gear Metrology Workshop," at the Y-12 Plant in April, 1993. Significant planning assistance for the workshop was also provided by the Defense Logistics Agency (DLA), which is responsible for the procurement of gears for U.S. military weapon systems. A purpose of this workshop was to announce to the domestic gear industry the intent of NIST, along with Y-12 and the DLA, to assist the industry in improving metrology issues associated with quality control, and also to solicit input from the industry as to the means by which their needs could best be satisfied.

Several findings and results of these workshops are striking. A few of these findings are listed here.

The most common practice in the domestic gear industry, whether the application is automotive, aerospace, industrial, or other, is to establish traceability of quality control measurements to a nominal gear form (an involute or a lead master, for example) which may or may not be traceable, in turn, to a national (or international) standard. This practice raises several issues as to whether a claim of traceability is a good indication of effective quality control. The practice implies the utilization of the first and/or third definitions of traceability stated previously through artifact calibrations leading to NIST, or through an unbroken chain of comparisons to national standards or nationally accepted measurement systems. The claim that definition one (calibration of artifacts) is relevant can be disregarded immediately, as there is a requirement for calibrations to be performed at accepted intervals. The last calibration of <u>any</u> gear-related artifact performed by NIST was a measurement of a lead master conducted in June,1987, for the Fellows Corporation in Vermont [7]. The claim that definition three is relevant can also immediately be rejected as there are no national standards, nor are there nationally accepted measurement systems with standard procedures, through which to establish an unbroken chain of comparisons for gears or gear forms to NIST.

The domestic gear industry, regardless of the application of the gears, does not have standard artifacts, nor does it have a formal standard set of nationally accepted measurement systems to use in measurement comparisons. There are definitely practices and artifact types existing in the industry that are used more than others. There are, however, no standards for artifacts or measurement procedures providing the establishment of traceability to the international standard of length. The "Advanced Gear Metrology" workshop documented not only the lack of standard artifacts and procedures, but also the industry's need for standard artifacts and procedures [8].

It should be noted here that the American Gear Manufacturers Association (AGMA) and the American Society of Mechanical Engineers (ASME), as well as the American Standards Association (ASA) in earlier years, have developed standardized systems to assist gear manufacturing for several decades. The standardized systems, which are adhered to extensively by the industry, are basically documented functional requirements for the fundamental parameters of gears. The systems are tolerance requirements for specific quality classes of gears; the systems do not consist of standard procedures for measurements, nor do they include standard measurement artifacts. The standards have been developed to assist design engineers and gear producers in the manufacture of gears. While the standards do make recommendations of how to measure certain gear parameters, the standards do not specifically address metrology issues associated with gear production. The standards also do not establish a traceability link to the international standard of length.

Gear Geometries and Measurement Practices

The gear industry does not have standard sets of artifacts or standard measurement procedures; there are, however, certain practices which are quite common throughout the industry. In order to best explain these practices, it is necessary to first understand the complexities of typical gear geometry, as well as the numerous different types of gears that are common in the industry.

Among the more abundant gear types produced by the industry are the following: spur gears; helical, double helical, and crossed-helical gears; internal gears (several configurations); straight, zerol, and spiral bevel gears; single-enveloping and double-enveloping worm mesh gears; face gears; hypoid gears; and spiroid gears.

Figure 1 depicts the fundamental geometry parameters for an arbitrary gear. These are the basic parameters that must be considered when assessing the dimensional quality of a gear: root diameter, base circle diameter, tooth thickness, tooth profile, lead angle (not shown), face width (not shown), and tooth spacing or index. Note that a gear and a pinion are shown in Figure 1. This figure illustrates that gears are elements that are used for transmission. Using gears to effectively and efficiently transmit power, motion, or some other entity, from a driving prime mover to a driven machine requires that the gear elements of a system mesh as intended in the design of the system. In order to mesh properly, it is obvious that the basic dimensions of the gear elements must be manufactured properly, within design tolerances.

When a gear is designed the dimensions illustrated in Figure 1 are specified for a particular application. The specified dimensions are always toleranced, indicating the amount of variance that can exist in the manufactured actual dimensions, as compared to the designed intended dimensions. In order to assess whether the dimensions of a gear has been manufactured in tolerance, the dimensions must be measured. Moreover, the measurement of the dimensions of the gears must be reliable; the measurements must give an accurate indication of the gears' dimensions.

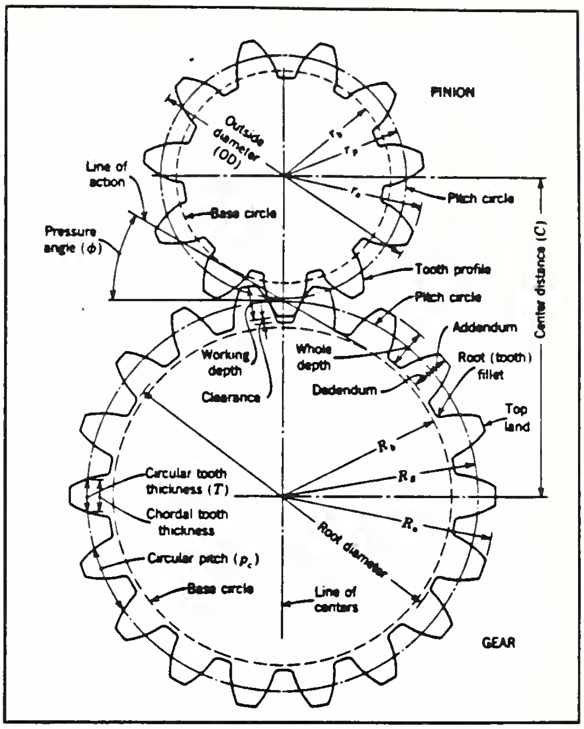

Figure 1 Basic Gear Geometry Parameters [9]

There are several means by which manufactured gears can be assessed dimensionally. These means can generally be grouped into two categories: analytical assessment and functional assessment. Analytical assessment of a gear can be accomplished through direct measurement techniques, such as gaging a gear. Functional assessment of a gear involves monitoring a gear during functional rotation in mesh with a mate, from which analytical dimensional data about the gear can be extracted. An example of a functional technique is roll-checking, where a gear is rolled with a master in a variable center distance tester.

For purposes of this text, analytical and functional methods of gear measurement will be summarized. The subtleties, advantages, and disadvantages of the different methods of dimensional assessment of gears will not be discussed in detail. This text is intended to be a discussion of the gear industry as it now exists in order to clearly indicate the need for improvement in the quality control methods associated with gear manufacture. The quality control problems in the industry that specifically deal with the dimensional assessment of a gear are problems that require solutions that need to apply to all sectors of the gear industry. The most realistic means of having an impact on the industry involves changes which will build the infrastructure for quality control in the industry. This will be accomplished through addressing the industry's metrology practices and needs.

The first major means of assessing the geometric dimensions of a gear is by analytical inspection. Analytical methods of gear measurement in practice today range from low-technology applications, such as manually using a micrometer to determine a tooth thickness, to higher-technology applications, such as using a computer-controlled measuring machine to determine the geometric deviations of a manufactured gear from nominal design values.

Focusing on the more modern, higher-technology applications of analytical analysis, there is debate in the industry as to the most optimum means of measurement. This debate centers around the use of computer controlled coordinate measuring machines (CMMs). In gear measurement applications, there are two basic types of CMMs that can be used by the industry. The most common type of machine used today is the generative-type base circle machine. A CMM of this type is basically a computer-controlled comparitor, which traces the profile of a gear or gear form using a probe that contacts the surface of the part to collect data. The output data of such a measurement are the deviations of the dimensions of the part as measured from the dimensions of the nominal part form input by the operator. These types of machines can be used to measure most of the fundamental gear parameters, with the measurement technique relying heavily upon comparison to nominal design dimensions. The other type of machine used today is the universal style of CMM. This type of machine collects data from the surface of a part based upon a programmed inspection path in a two- or three-dimensional volume utilizing any of a number of contact or non-contact probing devices to collect data. The output of a measurement from a universal style CMM is a set of data points which are the three-dimensional coordinates of points located in a user-defined workspace. These data points can be reported by the machine as raw data, or they can be reported as information about calculated geometric features. An example of calculated feature information is the three-dimensional location of the center of a circle as calculated by a least squares fit machine software algorithm applied to three data points.

Regardless of which of the above two types of analytical method may be a better technique for a particular application, the fact is that there are different techniques used throughout the industry. The industry has debated for years about these two techniques, because the two techniques often produce different answers for the measurement of the same parts or artifacts. This is a problem. Another problem with analytical methods involves the reliance on comparison in part measurement. There are presently no acceptable comparisons to make due to the lack of a standard set of gear artifacts. Also, there is the lack of acceptable traceability to NIST for the artifacts and measurement procedures that are in use, especially when making comparison measurements.

The second major means of assessing the geometric dimensions of a gear is by a functional inspection or test. The most common application of functional measurement involves roll-checking a gear, as mentioned previously. Roll-checking a gear basically involves placing the manufactured gear on a testing apparatus, or inspection machine, and performing a "composite" inspection. The "composite" inspection entails contacting the manufactured gear with a master gear (sometimes racks or worms are used) at a specified input load, then rolling the two gears throughout several cycles of contact under the specified load. Several parameters can be revealed by a functional inspection, and a few issues should be mentioned. Functional inspections rely heavily upon the "nominal" dimensions of a master gear against which to compare the test gear. This means that the dimensions of the master gear must be accurate and well known to make a meaningful functional comparison. The ramifications of measuring based on comparisons are the same for functional inspections as they are for analytical inspections, described in the previous paragraph. A feature of functional inspection worth noting is inspection of a gear under conditions very similar to those in the application. Another feature of functional inspection worth noting is that particular attention must be given to whether all possible errors are revealed during inspections due to the sensitive effects of cumulative position errors.

The Call for Action

The quality control issues facing the domestic gear industry are not new. The lack of traceability to the international standard of length through NIST is not new. The problems of the domestic gear industry are not isolated to specific sectors of the industry, nor are they isolated to specific companies or organizations. The problems of the domestic gear industry are readily acknowledged by those in the industry experiencing the problems. The means by which the problems of the industry can be solved is through a vehicle of change. The vehicle of change must be spearheaded by the U.S. national standards laboratory, NIST, and this vehicle must be supported by the industry as a whole. The vehicle of change is the development of a metrology infrastructure for the domestic gear industry as a means of improving manufacturing quality control.

The development of a gear metrology infrastructure involves the following activities, which should optimally occur in parallel.

- A mechanism must be established by which the dimensional measurements performed by the gear industry associated with manufacturing quality control can be clearly traceable to the international standard of length, through NIST. The traceability mechanism can be achieved in a relatively short term by developing a calibration service for standard gear artifacts with direct traceability to NIST. NIST must, in turn, clearly demonstrate traceability of its measurements to the international standard of length.

- A set of standard artifacts must be developed by the industry to meet the application needs of the industry. The development of this set of artifacts should include NIST input, and the artifacts should be used initially by the established calibration service.

- A location, or locations, must be designated as facilities where the domestic gear industry can assemble to receive gear metrology training on the latest equipment utilizing the latest measurement techniques, and also receive information on standards.

- Metrology must be directly linked to manufacturing processes throughout the gear industry as the means of closing the quality control loop. This integration of metrology into manufacturing involves a cultural change for the industry. This entails education, which can and should be conducted jointly with metrology training at the designated sites, and which can also be extended to university classrooms.

- Gear metrology techniques, equipment, standards, and traceability must be advanced to the next generation of technology as the industry nears the twenty-first century. This requires that research (some basic, mostly applied) be conducted in these areas. This research should be conducted jointly by the infrastructure elements to produce the maximum industrial impact.

- Each change and advancement (both technical and industrial culture) associated with the establishment and development of a national metrology infrastructure for the domestic gear industry must have relevance to both commercial and defense applications for gears. This means that there must be extensive input from these industrial sectors. In order to effect this, a "steering" group from industry should provide the guidance to direct the efforts of the infrastructure development.

Summary

The domestic gear industry is large, shipping several billion dollars in products annually. Gears are omnipresent in our society and economy. Recently, the domestic gear industry has requested assistance from NIST to improve the quality control practices associated with the manufacture of precision gears. These requests have been formalized and documented at two industrial workshops, referenced in this text. As a result of these workshops and analysis of the industry, it can be concluded that several changes need to occur in the industry.

The nature and breadth of the changes required to have significant impact on the domestic gear industry call for the development of a national metrology infrastructure for the industry. This infrastructure must be built around a demonstrable traceability of manufacturing quality control measurement to the international standard of length. The successful development of such a metrology infrastructure requires input from all sectors of the gear industry, including gear producers and users from the aerospace, automotive, and construction industries; gear production and measuring equipment manufacturers; national laboratories; university researchers; and defense re-work and maintenance facilities. A primary goal of receiving input from all these sectors of the industry must be to build an infrastructure that is based upon the real needs and applications of the industry, giving the industry ownership over the metrology infrastructure. Another primary goal of using widespread industrial input in developing the metrology infrastructure is the effective dissemination of information regarding the various quality assurance benefits that can potentially be derived by the gear industry.

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