History of

GEAR MEASURING MACHINES AND TRACEABILITY 1900–2006

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No one is quite sure when gears were invented. Archaeologists believe the wheel was invented around 5,000 B.C. Gears came some time after that, when lazy human beings in different parts of the world had the idea of not lifting water from the ground themselves, but letting animals do it. They needed to transfer the rotation of the axis of rotating buckets from the horizontal to vertical direction. Animals can drive a horizontal toothed wheel and, if this is connected to a toothed vertical wheel, buckets will lift water by a geared mechanism (Fig. 1). This is one of numerous examples of lazy people being very helpful.

The first descriptions of gears were found around 300 B.C. In the beginning, gears for basic industrial purposes were made out of wood. By around 100 B.C., intricate gears made of soft metals such as bronze were well developed, as evidenced by the Antikythera device, which dates to around 80 B.C. Many different uses for gears had been developed in ancient times. Although iron had been used for weapons and tools for a long time, it wasn't until the industrial revolution that methods for forming or cutting gear teeth became prevalent. Cast iron gears provided a huge improvement over wooden gears, but these early cast iron gears were of low accuracy and not worth measuring.

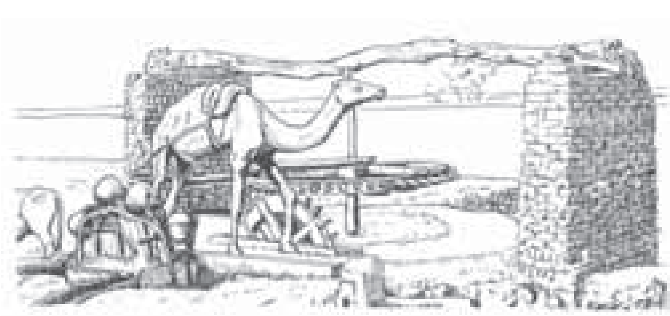

Figure 1—Water lifting gearing mechanism in Egypt.

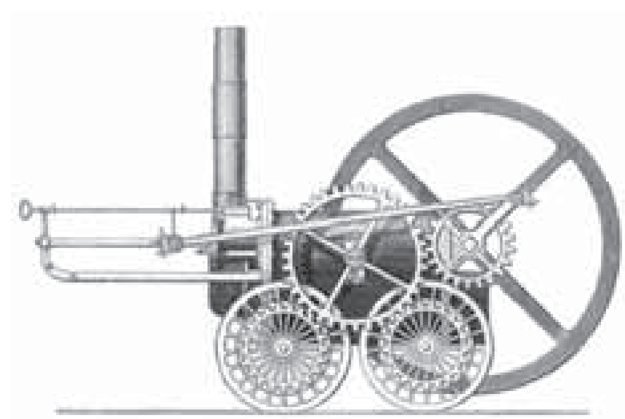

Figure 2—Steam activated locomotive with gear drive, circa 1803.

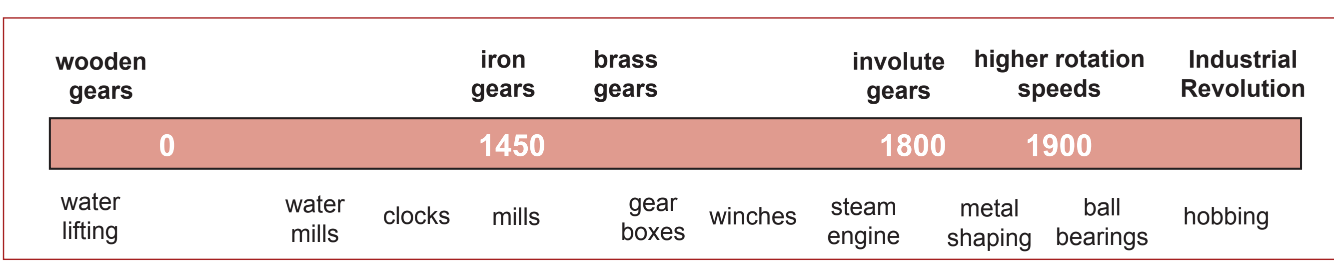

Figure 3—History of gear manufacturing, 0–1900 A.D.

In the 1800s, steam engines became practical, and a tremendous amount of development followed (Fig. 2).

Machines for pumps, vehicles, ships and railroads became popular. Electricity became important, but was only economical working with high speeds of rotation. The invention of ball bearings pushed speeds higher.

But low-quality gears were insufficient for these speeds. Fortunately, this situation came at the same time as the development of metal cutting machine tools. Hobbing became possible around the start of the Industrial Revolution. The gear shaping machine was developed around 1900 and made it possible to cut better gear flanks. Figure 3 shows a timeline of gear development through around 1900.

Special companies were founded for gear production, such as ZF in 1915. But still no satisfying machining and inspection equipment existed. These specialized companies took over the responsibility for future development. Responsibilities always push creativity. It was in Switzerland in 1922, when the tricky method of measuring the involute flank by generating from the base circle was invented (Figs. 4–5).

In 1923, the involute testing instrument with fixed base circles was introduced to the industry with enormous success. More companies went into this business and built similar machines with various designs. The simple mechanics made this type of inspection machine very reliable. Some features had to be made very accurately: the diameter of the base disc, the straightness of the straightedge, the position of the probe over the straightedge and the scaling of the graph by mechanic transformation. The discussion about accurate measurements for gears started in the 1920s and is still a hot topic today. The accuracy of these involute testers was proven by artifacts; thus the first involute master was born.

The new-found ability to inspect caused us to think about the errors found. This ultimately led to better manufacturing abilities. Sometime after 1930, helical gears could be manufactured efficiently and found their use in automobiles. Gears with a helix angle are much more complicated than spurs. The helical flanks cause new problems in accuracy and measurement. A solution for measuring the lead on helical gears was invented around 1945. A sinebar disc mechanism included in base circle involute testers made it possible to inspect the lead of helical gear flanks (Fig. 6).

The straightedge was moved by this mechanism while the probe was moved up and down along the tooth flank. A complete correct flank produced a straight line on the graph similar to the graph for the correct involute flank.

However, the sinebar disc mechanism was difficult to set accurately. The setting was only possible by the use of a lead master with a known helix angle. This was the birth of lead artifacts. They had a long face width with different helix angles. These machines were mechanically set to show the result of the known helix angle of the lead artifact (Fig. 7).

The mechanical design using a sinebar disc for the helix angle taught the engineers to use a similar solution for involute flank inspection. To check the involute profile correctly, exact base circle discs have been necessary for each base circle diameter of a gear. Learning from the sinebar disc, this mechanical solution was designed into the machine for a variable base circle mechanism as well. A second sinebar disc and lever

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DEUTSCHES REICH

AUSGEGEBEN AM 4. NOVEMBER 1922

REICHSPATENTAMT

PATENTSCHRIFT

— № 363176 —

KLASSE 42b GRUPPE 26

Albert Aeppli in Zürich.

Profil-Kontrollapparat für Evolventen-Zahnräder.

Figure 4—First patent for involute testing instrument in Switzerland.

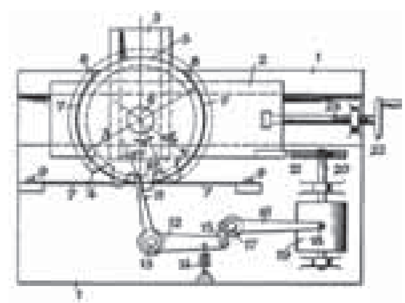

Figure 5—Drawing from the first patent.

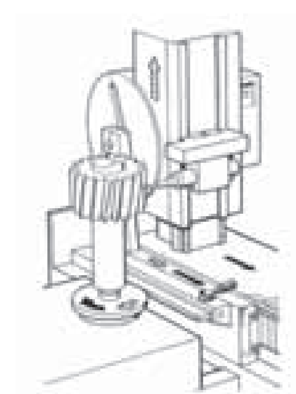

Figure 6—Mechanical solution for lead inspection by sinebar mechanics.

Figure 7—National lead artifact (PTB and NCL).

Figure 8— Maag PH 60 involute and lead tester, around 1962.

Figure 9—Maag SP 60 variable involute and lead gear tester, 1968.

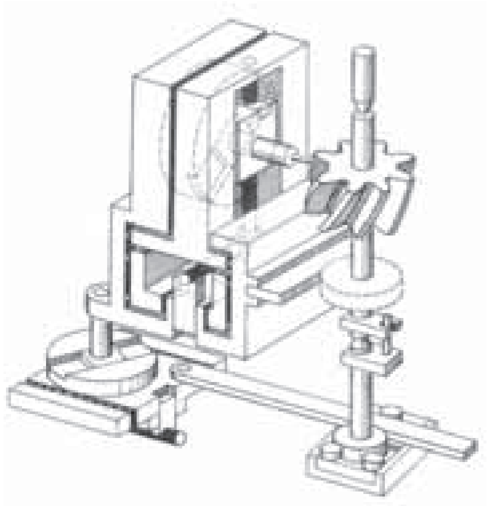

Figure 10—Mechanical solution for sine bar mechanics of lead and variable involute diameter.

Figure 11—Involute reference artifact.

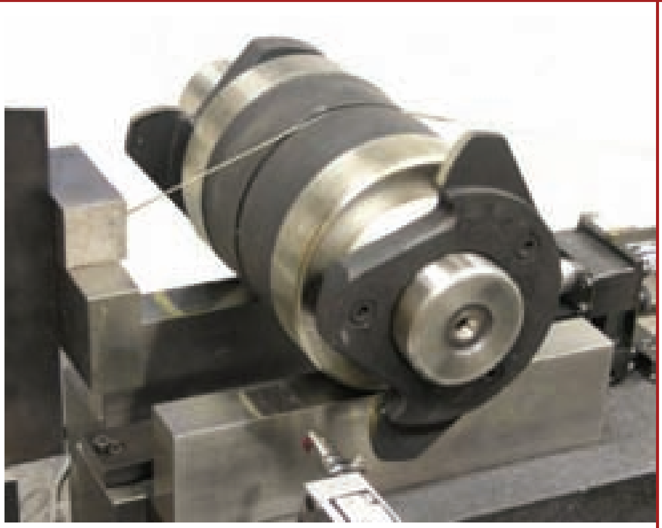

Figure 12—National involute artifact measuring system (PTB Germany).

Figure 13—Lead reference artifact.

Figure 14—National pitch artifact (PTB Germany).

Figure 15— Höfler EFR S gear testing machine for involute, lead, pitch and runout, 1976.

Figure 16— Klingelnberg P35 NC Gear measuring machine, 2000.

Figure 17— Zeiss Gagemax universal 3-D coordinate measuring machine with rotary table for gear measuring.

system compared the difference in size of the used base circle to the correct size. In industry, complete measuring machines for variable base circles and helical lead measurements were commonly used after 1960 (Figs. 8–10).

Like the setting problems of the mechanism for the helical lead measurement, the same problem occurred for the variable base circle mechanisms. A real involute artifact with known contour was necessary (Fig. 11). These involute artifacts had a large module to enable an accurate setting of the mechanism over the total travel of variation. Together with the lead artifact, these artifacts became the unique base for accuracy of gears. A number of different designs for the artifacts was created and used for calibration from those days until today.

The national governments and their national metrology institutes started to take care of gear artifacts from 1920–1930. Greater importance was placed on these artifacts when the calibration of gear measuring machines depended on them after 1960. National artifacts were developed to allow the most accurate measurement and comparison between the different national institutes (Figs. 12–14).

Solutions for pitch and runout inspection by special machines started around 1935, and special machines for these features have since been built. Pitch artifacts have been developed which are useful for direct comparison measurements and calibration of measuring machines.

Electronics were evolving rapidly. Developments of measuring index and runout variations were integrated into involute and lead measuring machines. These complete gear measuring machines started to conquer the market in 1975 (Fig. 15). The direct graphing methods were changed to plotted solutions using electronic connection from the stylus to the graphing instruments. These machines were difficult to operate and represent the last step of development before CNC gear testing machines entered the platform of general use.

The development of computers changed the world of machine tools. In industry, the normal use of numerical-controlled (NC) machine tools began around 1975. Beginning in 1980, CNC was integrated in gear measuring machines as well. The well-known artifacts for profile and lead were used to prove the accuracy of an inspection machine's mechanism, electronics and evaluation software. The combination of these three items working together made the artifacts more important than ever. Since 1980, CNC measuring machines for gears and 3-D coordinate measurement machines (CMM) have superseded all the old mechanical solutions (Figs. 16–17). CMMs with rotary tables work like gear measuring machines.

The old fashioned use of measurements with "high" or "low" accuracy is not good enough any longer. Measuring results now have to show the actual measurement uncertainty. But how do

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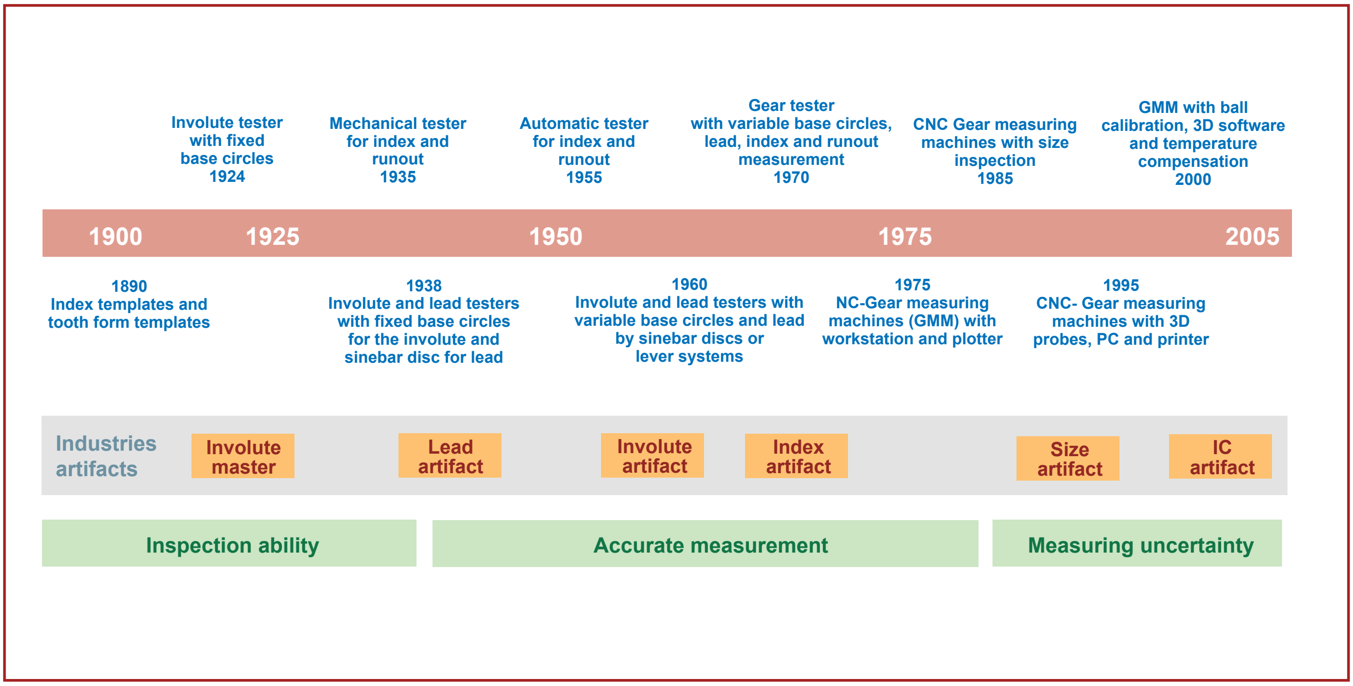

Figure 18—History of gear inspection, 1900 to 2005.

we quantify measurement uncertainties? Several methods were created and found their way into standards and guidelines (ISO, VDI, VDA). See Figure 18 for a timeline of the development of gear measurement capabilities.

The most attractive method that simplifies the uncertainty evaluation is the experimental technique using comparison measurement with calibrated and, thus, well-known artifacts. It can be applied to gear measurements if artifacts similar to workpieces exist.

This sounds rather easy, but completely new gear artifacts had to be designed to assess and quantify the uncertainty of measurements. Artifacts represent, in near ideal form, the geometric characteristics of gearing. These characteristics are calibrated and traceable to national artifacts. Artifacts are the highest authority. They are used to set up and carry out final acceptance tests, and to trace gear and spline measuring machines. There are different artifacts depending on the measuring task and the spectrum of the gearing to be measured. The closer the artifact is to the measuring task, the more certain is the traceability of the measurement.

The measuring uncertainty found by comparison measurements is based on four fundamental conditions:
A. The variation and the measuring uncertainty of the artifact itself have to be known for sure.
B. The size and geometry of specimen and artifact have to be similar.
C. Comparison of the results must be made under different environmental conditions.
D. All kinds of measured features have to exist on the artifact.

The equipment of gear measurement machines changed step-by-step during the last 80 years. Now, the time has come to tailor the artifacts to modern demands. A new concept of gear artifacts developed by Frenco is named IC artifacts (Figs. 19–22).

The IC gear artifacts contain all important gear characteristics and have a similar profile to that of the workpieces to be tested. Thereby they meet the identity condition (IC) as defined in ISO 15530 for the determination of measurement uncertainty of coordinate measuring machines (CMMs) and form an important part of an extensive package to determine the measurement uncertainty.

With these artifacts it is possible, for the first time, to determine uncertainty in gear and spline measurements in an easy and quick way. Figure 23 shows how IC artifacts relate to industrial metrology and the world traceability of gear measurement uncertainty.

IC artifacts are possible in any imaginable design. They can be manufactured for gears and splines and for internal teeth and external teeth of different modules and different pitch circle diameters. The geometric size can be adapted to small plastic gears or large industrial gearboxes.

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Figure 19—IC artifacts (m=0.8) for small gears.

Figure 20—IC artifacts (m=2) for medium-sized gears.

Figure 21—IC artifacts (m=2) for internal gears.

Figure 22—IC artifacts (m=1) for involute splines.

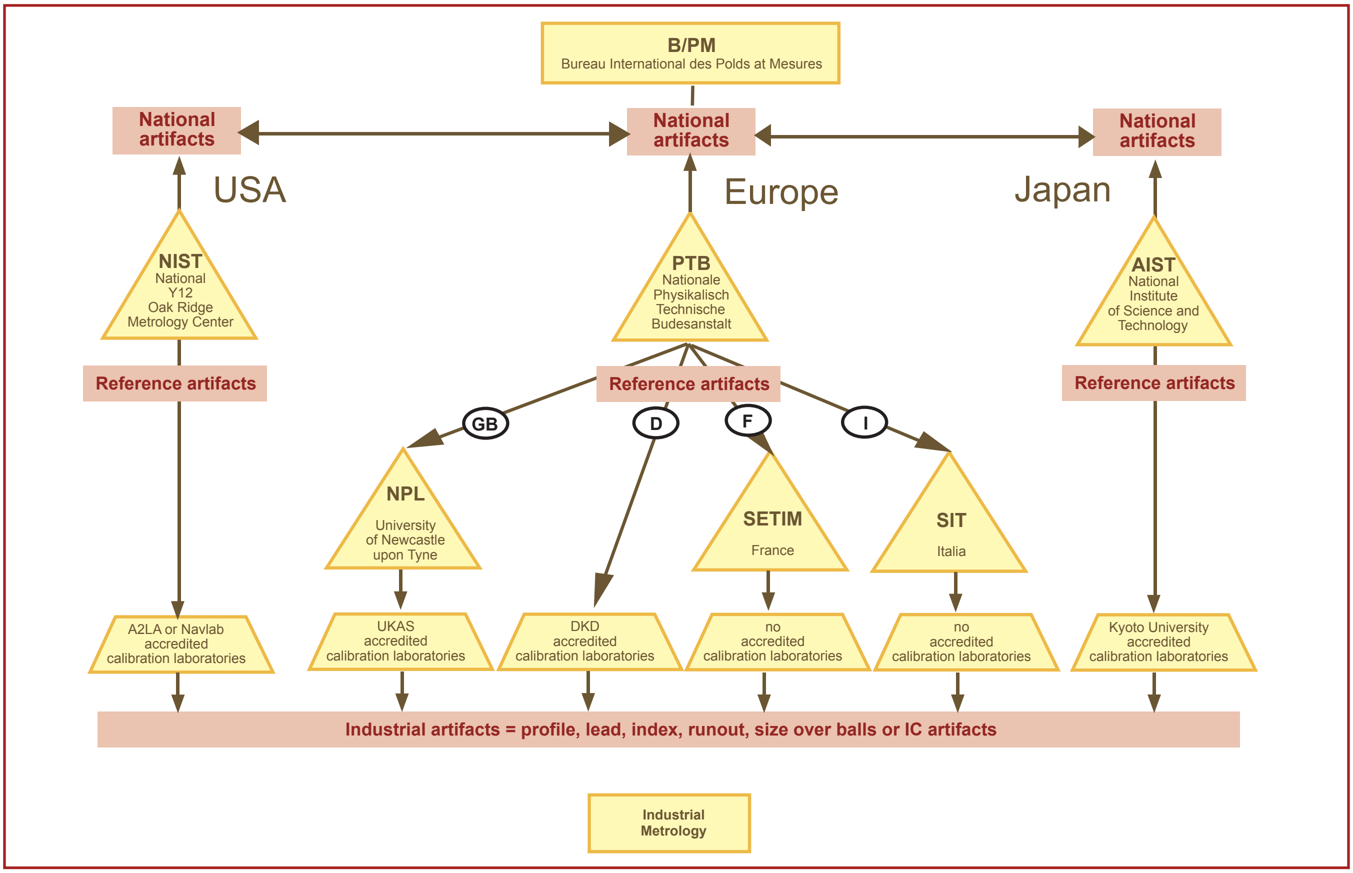

Figure 23—World organization of the traceability of gear artifacts.