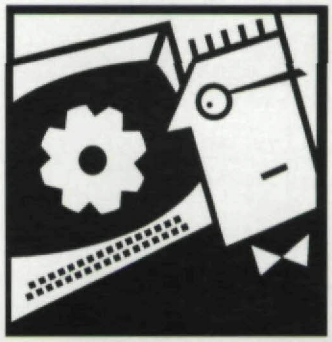
A Clockwork Gear

William L. Janninck



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Address your gearing question to our panel of experts. Write to them care of Shop Floor, Gear Technology, P.O. Box 1426, Elk Grove Village, IL 60009, or call our editorial staff at (708) 437-6604.

Question: Could you explain what is meant by "horological gearing"? I never heard of this before, although I understand it has something to do with watches. Could you also explain the meaning of a "going gear train"?

Horology is the science of measuring time or the art of constructing instruments that indicate time. In earlier days this was as simple as tracking the sun using a sundial; today we use the vibration of a quartz crystal. For ultra-precise timing, the atomic clock uses a resonant frequency of Cesium 133 and is accurate to one second in 250,000 years. Not quite what you need around the house for telling time!

Although sundials can get quite sophisticated, they utilize no gears; neither do most modern digital timers and watches. But for the several centuries in between, clocks, watches, timers, fuses, and other such devices were prolific users of gears. An entire field of design and manufacture of these mechanical gear elements developed, and all the gears used in clocks, watches, and other timing devices, whether for driving the pointers, setting the hands, winding up springs, or driving the escapement mechanism and pendulum, were called "horological gearing".

Many books were written that covered the special concerns involved in this application of gearing, and the serious student could even enroll in correspondence courses in "horological science."

The problems of design faced by watch builders, especially considering the very small size of some mechanical watches, were totally different from those experienced by power train designers in transportation, construction, machine tools, and general machinery applications.

Some of the problems facing the horological gear designer come from the necessity of using multiple-stage, high-ratio, step-up gear sets. They are the opposite of the more usual application problems of step-down or speed reducing drives faced by most designers. In addition is the absolute need for low friction and high efficiency.

In a mechanical watch or clock, the driving energy is stored in a spring-wound drum and is slowly released as minute pulses through the step-up drive train and into an escapement mechanism, with the gear train starting and stopping completely with each cycle of the escapement wheel. The friction through the gear train must be minimal for the successful management and release of the available energy.

One of the first areas of concern in step-up drives is gear tooth friction. To reduce surface contact friction, surface finishes must be extremely good, and frequently the pinion teeth are polished. The reduced friction experienced in the arc of recession, or exit path out of mesh, rather than the arc of approach, or entry path into mesh, is used. To accomplish this, a cycloidal tooth form is used, and to further reduce the approach action, the cycloidal tooth form on the pinion addendum is modified, concentrating the action near the pitch line of the gear set.

For compactness, pinions of as few as 6, 7, or 8 teeth and step-up ratios of as much as 12:1 in a single mesh are used. The teeth can be as fine as 250 diametral pitch with depths as little as .012". To avoid friction losses from side thrust, the teeth are always spur.

Many tooth forms and proportions have been established suitable for horological purposes. Some of these used in step-up drives are the Ogival Form, British Standard 978, Black Forest Clock Standard, the Swiss Cycloidal, the Prescot, and the Circular Arc. Another one frequently encountered

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is the Wickenburg form.

Fig. 1 shows a typical cycloidal form pinion and gear in mesh. The flanks on both members are radial lines below the pitch line. A special type of pinion having six teeth or more and used in step-up drives is called a lantern pinion and is shown in Fig. 2. A tooth layout is shown in Fig. 3. The teeth are formed of polished pins or wires set in a pair of end plates. These pinions are not recommended for reduction drives in horological applications.

The number of the tip modifications used on clock gears may cause one to question the functionality of these gears, since the tooth form departs from true conjugacy. Cycloidal gear ing is that one exception to the rule requiring a contact ratio of at least 1.0 for a pair of gears to be used successfully. Contact ratios of less than 1.0 on involute gearing are a signal of problems and, with an involute profile, indicate a possible damaging edge contact and lack of proper uniform transmis-

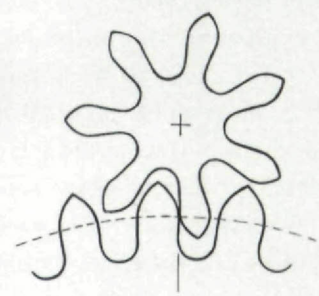

Fig. 1 - Cycloidal gear set.

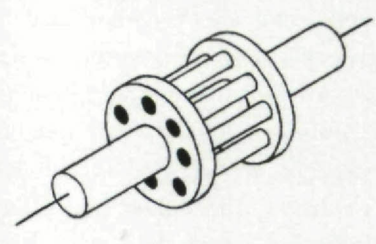

Fig. 2 - Lantern pinion.

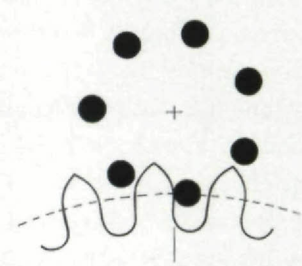

Fig. 3 - Lantern pinion gear set.

sion of rotation. This is not the case with cycloidal profiles, and edge contact is rare.

A step-up drive in a clock is one application where efficiency of energy transmission, rather than uniform transmission of rotation, is the primary objective. If these gears were inspected by the single flank method, the results would show a tooth-to-tooth rotational error, but this is not a concern for clock and watch gearing.

Not all the gears used in horological gearing have the cycloidal tooth form. Many applications can and do use involute gearing, such as those for winding drives, time setting, minute-

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hour hand synchronizing, or other motion transfer. In electric clocks using a synchronous electric motor power source, the gearing is all in reduction stages, and most use involute gearing. Electric meters used in measuring energy may use some special high-reduction worm drives and then end up with involute gearing for the dial recording drives. Liquid and gas meters also tend to use involute gearing.

It might be helpful to diagram the gear trains used in a typical, hand-wound chiming mantel clock, where several clock gearing applications can be shown and explained. Fig. 4 shows the main clock drive used for precise time keeping and display. Starting with the spring drum gear there are five step-up cycloidal tooth form stages located on six axes. The last stage

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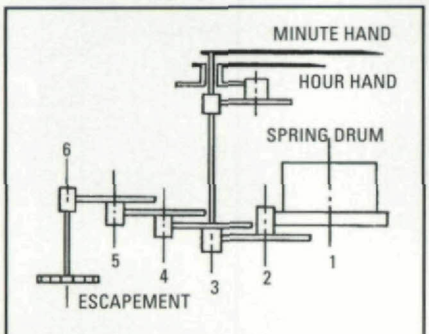
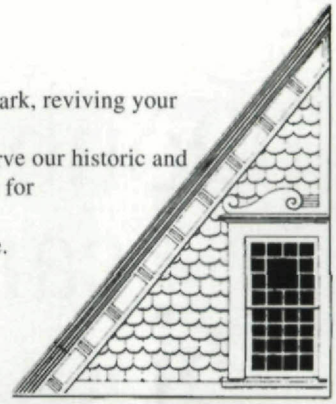
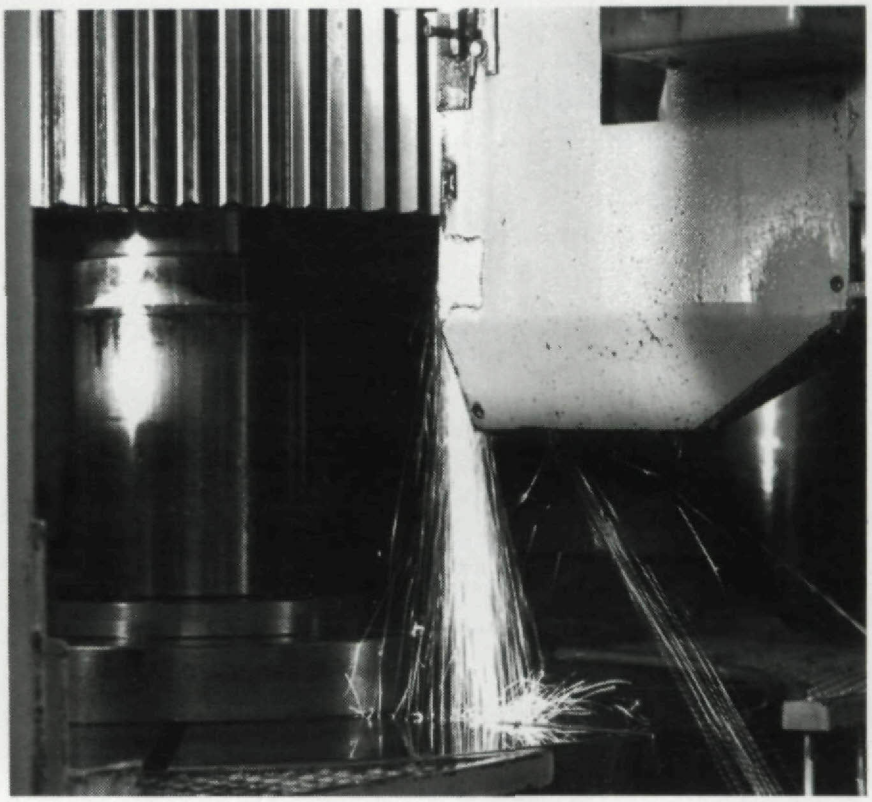


Fig. 4 - Main clock train.





pinion ending on the sixth axis drives the time controlling mechanism, consisting of the escapement wheel and a rotary pendulum, while axis three is the take-off to directly turn the minute hand. This also drives another two stages in reduction to synchronize and drive the hour hand.

Fig. 5 diagrams the second segment of the clock, the quarter-hour chiming section. It also has five stages of step-up cycloidal gears running from the spring drum to an air paddle type speed governor. From axis number three, motion is taken off and passed through a chain of four idler gears to drive a set of chime cams. These idler gears are conventional and utilize typical involute gears.

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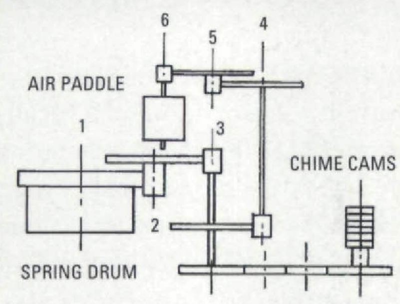

Fig. 5 - Quarter-hour chime train.

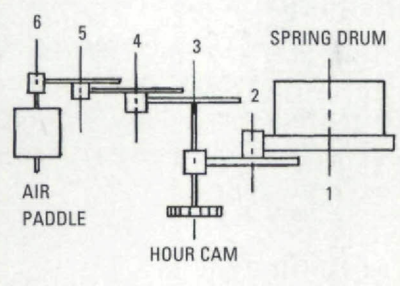

Fig. 6 - Hour-striking train.

In Fig. 6 the third section of the clock, used for striking the hours, is shown. It too uses a five-stage, step-up cycloidal train, starting with the drum and ending with another air paddle speed governor. There is a take-off from axis number three, and it turns the hour striking cam.

All in all, excluding cams, ratchets, and escapement parts, there are 38 gears in this clock.

Another name for the step-up drive described above is a going gear train. As shown in our dissection of the mantel clock, the going trains are five stages of step-up gearing using driven pinions of very small numbers of teeth.

In the above case, the energy was stored in hand-wound springs, but this can be accomplished by other means. A small, geared electric motor can wind a smaller, lighter spring, or an electrical solenoid and a ratchet can do the same thing. Another interesting design uses a sealed air chamber, which expands and collapses with atmospheric pressure fluctuations to do the winding. One of the oldest methods uses gravity by means of a weight, a rope, and a pulley to store the energy.

Another interesting application is seen in the traditional mechanical aneroid altimeter that is required on all aircraft, at least as a back-up instrument. It uses cycloidal gearing in a step-up train. The gears are of higher quality or precision and usually use highly polished pinions. The small movements of the aneroid chamber are magnified through the gearing, driving the indicating pointers.

Pressure measuring gages driven by a Bourdon tube sense the flexure of the tube to indicate the pressure. The driving force is quite high, and a pair of step-up stages will suffice. Those gages I have seen utilize involute gearing.

Mechanical dial indicators usually use geared step-up drives, and these too are of involute form.

Except for the very small teeth and small size of the gears, the usual manufacturing methods are used. Small hobbing machines using small cycloidal hobs and automated form milling machines using miniature rotary form milling cutters are employed. Most of these machines are of Swiss, German, or English origin.

Inspection, particularly for the elements of profile, tooth thickness, and adjacent tooth spacing, of these very fine-pitched, cycloidal, profiled gears and pinions, can best be done by optical means, using magnified projected images and by comparing the shadow against enlarged tooth layouts. Any visible bumps or hollows are cause for concern, especially in the immediate area of the pitch line. If the inspection layout includes several teeth, then any adjacent spacing errors can be judged. Surface finish can also be assessed by using microscopes and comparison samples.

In the clock gear field, backlash also requires special consideration. The dust and fiber particles that can get into gear teeth are larger in comparison to the small teeth in watch applications. Provisions must be made for space for this debris to settle without binding. Oils and greases catch and hold the debris and are not normally used on the very fine pitches.

The suggestion has been made that all of this special technology and procedure are not really necessary and any difference between clock gearing, and the more common involute gearing might be small. I personally became aware of the significant difference between them many years ago. We had a damaged drive gear set in a timing device which we replaced on an emergency basis, cutting the gears ourselves, using an available fine-pitch, involute hob. After all, we thought, a gear is a gear as long as the tooth ratio is correct. We could not make this apparatus work no matter how much buffing, polishing, oiling, and prodding we did. Finally, in utter frustration, as a last, desperate resort, the original tooth forms were copied, at some expense, and upon assembly, the mechanism took off running. We were pretty well convinced. ■

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