The Next Step in Bevel Gear Metrology

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In recent years, gear inspection requirements have changed considerably, but inspection methods have barely kept pace. The gap is especially noticeable in bevel gears, whose geometry has always made testing them a complicated, expensive and time-consuming process. Present roll test methods for determining flank form and quality of gear sets are hardly applicable to bevel gears at all, and the time, expense and sophistication required for coordinate measurement has limited its use to gear development, with only sampling occurring during production.

The Gleason Works has developed an innovative bevel and cylindrical gear tester which addresses these issues. The Phoenix® 500 HCT allows a performance-related forecast of the quality of a gear set and delivers data for tooth geometry corrections. The first of these new machines were delivered in December.

New Test Concept for Gears

The Phoenix® 500 HCT (Hypoid Cylindrical Tester) was developed to determine the behavior of a gear set under load and at realistic speed before mounting it in the vehicle. The machine features a state-of-the-art combination of digital tooth contact imaging, high-speed single flank testing and 3-D, structure-borne noise analysis. Its mechanical construction is based on the 6-axis Phoenix® free-form concept (Fig. 1).

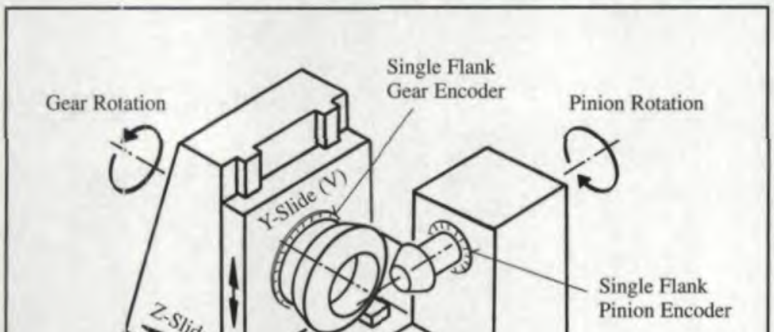

Fig. 1 — Location of the main component of the universal HCT concept.

Extensive analysis has shown that in roll testing, the quality of the results greatly depends on the precision of the setup (Refs. 1, 3). Solid-wall, ribbed cast iron machine frame and spindle housings, preloaded roller bearings on slide ways and optimally located linear scales and angular encoders were used to ensure the highest precision and stiffness. Hypoid offset (Y or "V"), pinion cone (X or "H") and gear cone (Z or "G"), as well as the shaft angle (B or "α") can be changed. A shaft angle adjustment between zero and 90° enables the HCT-testing of cylindrical as well as bevel gears. All axes can be adjusted during testing. Together with a gear torque of 72 ft/lbs. or 100 Nm (144 ft/lbs. or 200 Nm optional) and pinion speeds up to 3,000 rpm, this enables simulation of critically noisy situations in the vehicle.

During actual operation of a transmission, the gear axes are translated and the shaft angle is deflected. Optimization of the pinion cone in such a deflected position can be accomplished while under torque loading. The result is a pinion mounting distance for the load-free, undeflected state. During the pinion cone search under load with adjusted (deflected) X, Y and α settings, the backlash is kept constant. Because pinion speeds of up to 3,000 rpm require adequate lubrication during cycles, a flow of oil is periodically directed on the gear mesh. Four-quadrant operation ensures realistic test cycles simulating drive conditions. Drive and coast sides can be tested in the same direction of rotation, with positive or negative brake torque. Conventional testing using forward and reverse rotation is also possible.

In the 500 HCT tester, the chucking cylinders are not attached to the rear of the spindles by rotary joints, which would cause vibration, but are integrated in the spindles between the bearings. A newly developed lightweight construction concept delivers a low-vibration spindle with minimum inertia. All setup work, such as installing and fastening the draw rod, can be done conveniently from the machine's work area. The linear Z-axis, which moves the gear axially, has a spring-loaded, ball-screw nut, which prevents damage to the spindle in case of top-on-top interference during the Z-slide advance for meshing. When the spindle nut is displaced by such an interference, a proximity switch is tripped, initiating withdrawal of the Z-axis slide, rotation of the pinion and a repeated mesh attempt. This mechanism is also used to set backlash by advancing the Z-axis to a metal-to-metal position, followed by a defined withdrawal of the gear slide. All slides are fitted with direct linear measuring systems, so that the effective position of the Z-axis slide is always known, even when the ball-screw nut is displaced. The fact that the gear slide is loaded against a spring also enables composite testing. A single revolution of the gear with double-flank contact is sufficient to determine the face runout of the gear, shaft runout of the pinion and an optimized gear mounting position (with guaranteed minimum backlash). If face runout and shaft runout exceed predetermined tolerances, the gear set will be rejected right at the beginning of the test, and the cause attributed to pinion or gear will be displayed on the screen.

For designation of the machine axes Y, X, Z and B, the traditional gear testing axis nomenclature, V, H, G and α, has been chosen as the best compromise between Gleason's traditional designations (E, P, G and α) and the common worldwide designations (V, H and ?).

All tests and measurements on the 500 HCT tester can be performed on cylindrical gears as well as on bevel gears. This means that parallel-axis gears for applications where deflection and noise are critical can be tested for tooth contact pattern, structure-borne noise and transmission error, just as bevel gears can.

Laboratory and Production Floor Use

The 500 HCT measuring and testing machine is not only a high-precision measurement tool for the laboratory, but also a 100% inspection tool for the production environment or for quality control. It is incorrect to assume that a production test can be less precise and should be without advanced measurement and analysis features. Today's quality standards demand a full-featured production testing machine that brings lab testing abilities to the shop floor. The laboratory investigation can establish the combination of criteria to be fulfilled by an individual gear set in order to pass acceptance in the vehicle. This can include requirements related to tooth contact, structure-borne noise emission or single flank variations. It is not necessarily evident beforehand if criteria for all three test types can be established or if it is mandatory to do so.

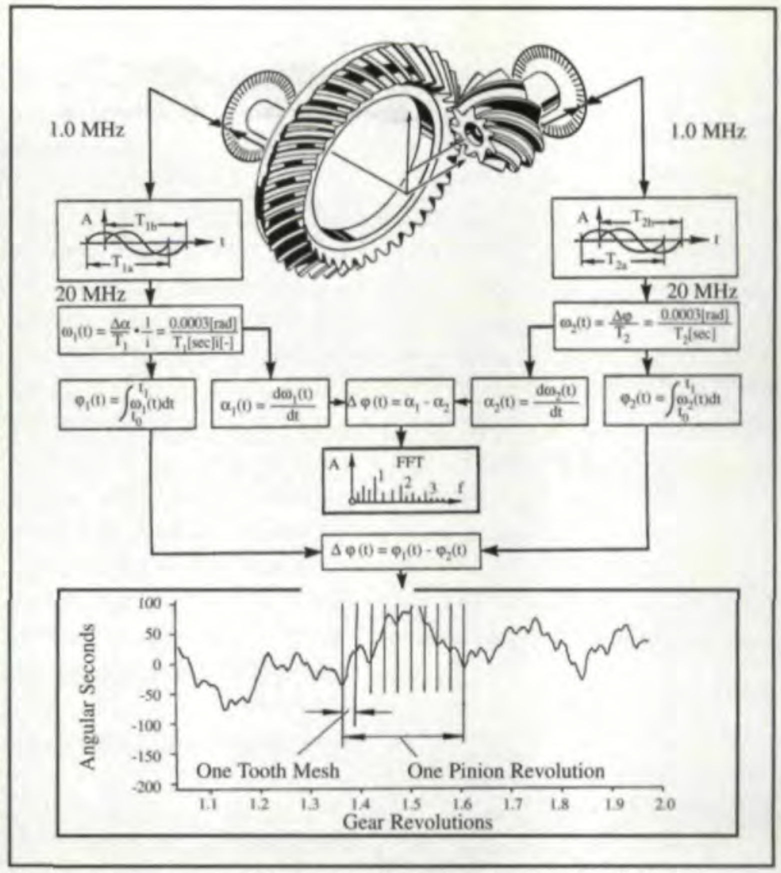

Fig. 2 — Measurement and structure of data processing for single flank tests.

It is quite possible, for instance, that the analysis of vibrations a gear set transmits to the spindle housing of the testing machine does not reveal a correlation with the noise in the vehicle. The noise levels of a "quiet" gear set may well be higher on the testing machine than those of a "loud" gear. In this case, the single flank test or a combination of single flank test and structure-borne noise analysis will provide a criterion for testing.

Automatic test cycles are not required in the laboratory, and digital image detection of the tooth contact pattern is only necessary in certain cases. For optimum use in the laboratory, the 500 HCT has an operator panel that pivots 90° and houses two color monitors, all hardware controls and an electronic handwheel. While tests and experiments are carried out, the gear set and panel both can be conveniently viewed from one position. The handwheel can be switched to move an axis or to rotate the pinion. Thus, the simple and practical handling of the old mechanical testers is being realized for the first time in a CNC tester. This ease of use means an enormous increase in effectiveness. In production testing, the electronic handwheel can be used for setup. In automatic operation, the panel may be pivoted back to be flush with the machine front.

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All options and features described below are equally important in both laboratory and production use. Specific software and electronic hardware components for single flank testing and structure-borne noise analysis will be discussed later (Ref. 2).

High-Speed Single Flank Analysis

Circular Heidenhain ERA angular encoders with 18,000 lines are integrated into the spindle units of the Phoenix 500 HCT behind the front end plates. Their location between the gear/pinion and the front spindle bearing is optimal, based on Abbe's principle. The integration of the encoders into the spindle housing and the use of a positive pressurized atmosphere protects them against damage and contamination. All wires are located inside the spindle housings to prevent interference in the work area and accidental damage. Behind the circular front cover, the encoder reading head is positioned at an angle to eliminate all linear relative vibrations between the head and the encoder disk, thus preventing corruption of measurement results. Both spindles (pinion and gear) are constructed identically.

The new generation angular encoders do not transmit a current signal as conventional encoders do. Instead they send a voltage signal to the digitizing unit (called "IVB" instead of "EXE," as in older systems). This allows twice the conventional data transmission rate between the reading head and IVB of 1 MHz (Fig. 2, top), with full-time resolution corresponding to a spindle speed of 3,333 rpm. The transmission speed between IVB and the counter board is 20 MHz, allowing measurement with a time resolution of 50 ns.

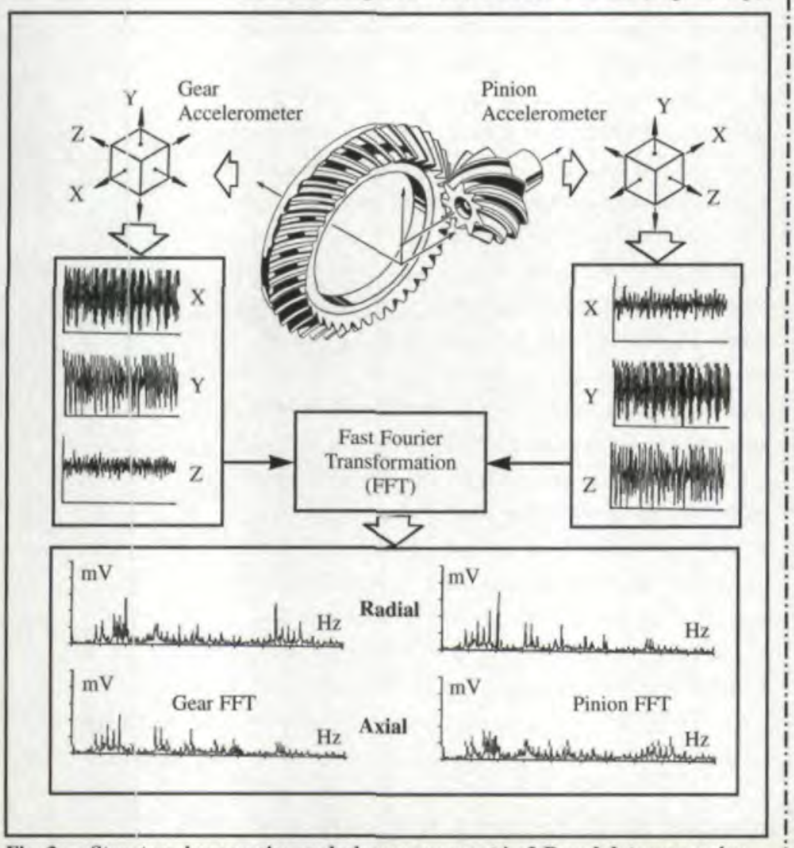

Fig. 3 — Structure-borne noise analysis measurement in 3-D and data processing.

3-D Structure-Borne Noise Analysis

Behind the front spindle covers, accelerometers capable of measuring vibration components in three dimensions are mounted next to the reader heads of the angular encoders. Therefore, three independent signals are available from both pinion and gear housing for structure-borne noise analysis. Conventional testing machines analyze structure-born noise by measuring only the radial vibration near the front gear bearings. However, the front bearings of a tester, similar to the bearings of a gear in a gearbox, transmit both radial and axial vibrations from the rotating gear set to the housing. The Phoenix 500 HCT was designed to capture all components of structure-borne noise in order to parallel reality as closely as possible. Since the pinion as well as the gear can induce and transmit vibrations, both spindles are equipped with 3-D accelerometers.

As shown in Fig. 3 (top right), the axial pinion vibrations are measured in the direction of the X axis. The vibration signals in the Y and Z direction can be added as vectors to obtain the radial component ($S_{radial} = [S_y^2 + S_z^2]^{1/2}$). Regardless of the direction in which the largest radial signal S_{radial} occurs, it is automatically found with a simple calculation. This is important, since the orientation of the maximum radial vibration differs slightly between designs and even between individual gear sets. The slightest variation can cause a fixed sensor operating in only one dimension to become insensitive to even significant vibrations in other directions. The sensor on the gear side measures the axial vibrations in the direction of the Z axis. The radial vibrations are calculated from the equation given above.

Digital Image Recognition of Tooth Contact Pattern

Even with CNC testers, unattended testing has been possible only under very limited conditions. Only when both the position and form of the tooth contact pattern were assumed to be always acceptable, and documentation of the pattern in production testing was not required, has a fully automatic test been possible. Again setting a new standard, the Phoenix 500 HCT employs two video cameras for the automatic recognition of the contact pattern on both the drive and the coast sides.

The cameras are mounted inside the chamber and can be pivoted in two directions. During setup, manual pivoting of the cameras ensures that the gear segment investigated coincides with the center screen portion; thus, the distance and position of the measured object to the camera are exactly reproducible without the use of special measuring equipment. The video cameras send their data to an image processor board (Fig. 4), which delivers a data file with binary information, allowing 256 different shades of gray per pixel. The problem of oil mist obscuring the view of the cameras has been solved by a unit that removes the oil, leaving no dirty compound mist behind, and applies marking compound with a rotational brush to the teeth. To save time, this is done while the gears are rolling together.

Image data computation redefines the 2-D video image of the picture of a gear segment into 3-D information. To quickly and precisely locate the position of a tooth and its outlines, a virtual tooth was previously generated. This virtual tooth is transformed in the machine coordinate system and rotated until it matches with the video image. Subsequently the picture pixels within the tooth contact pattern are mapped to tooth surface coordinates. The contact information of all teeth investigated is superimposed on one tooth, resulting in only one contact pattern image each for the drive and coast sides in which the influence of light reflections and camera viewing angle is largely eliminated.

Tooth contact patterns obtained by video in this way can be displayed in color on the screen of the HCT tester and archived. In the automatic test run, the contact pattern information obtained is compared to information for a master gear. The patterns are stored together with the acoustic and geometrical test results and can be used for documentation of statistical quality control.

Modular Design of the Test Cycles and Special Options

In designing the HCT operating software, great effort was made to develop a completely universal, modular program structure, which allows for maximum flexibility for the individual user in determining appropriate test cycles. The script function in Fig. 5 lists a subset of the basic features required in a test cycle. These and many more basic features have been made into stand-alone routines or script functions. They can be called up in random order and as often as desired. The script functions or "modules" take the necessary data directly from the test summary to which each is interfaced. The summary is a set of test data containing all information on the gear design to be tested as well as on the specific cycle. The order of operations comprising a cycle is determined by the script commands; all data is taken from the summary.

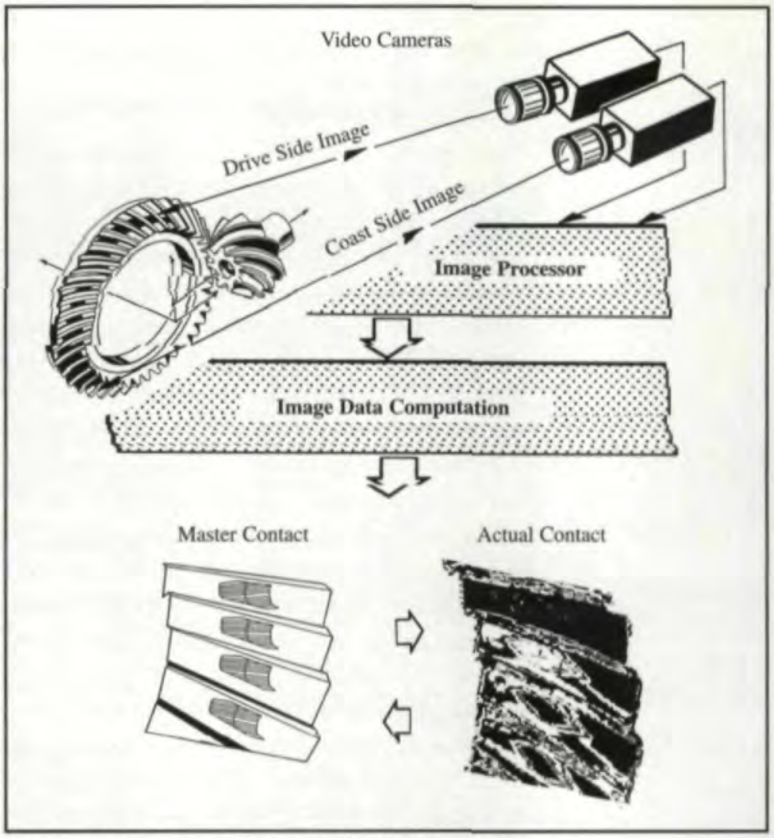

Fig. 4 — Contact recognition system by video image processing.

Part Program / Subscript Functions (Summary)

Steps				Subscript Functions
1				Premesh Position (Gear Cone Retracted)
2				Advance to Mesh (Location 1)
3				Backlash Withdraw
				Average Backlash
4		14	20	Run Test (Four Quadrant Conditions)
6	10	15	21	Set Contact Load
7	11	16		Set Test Load
8				Single Flank Test
	12	17		Vibration Analysis
9	13			Move to Location n (Constant Backlash)
5				Apply Lubricant
		18		Remove Lubricant
		19		Apply Marking Compound
			22	Take Video Image of Contact
			23	Stop Test
			24	Part Load Position

Fig. 5 — Modular structure of HCT tester operation software.

To minimize testing time, either all measurement tests at a given axis position or the same tests at all axis positions can be grouped together to organize the cycle. It is possible, for instance, to perform a single flank test, a noise analysis and a contact pattern recognition for the drive and coast sides in axis position #1 and to make the same test in position #2. This allows termination of the cycle in the first acceptable axis position.

Closed Loop Between Vehicle and Tester

The running vibration of the gear set provides an excitation to the vehicle as a total acoustic system. The various components of suspension and body amplify or attenuate the amplitude of the excitation. As the vehicle speed changes, these vibrations excite certain vehicle resonances, which in turn transmit these structure-borne vibrations to airborne vibrations, i.e., sound. The rise and fall of these excited resonances are the perceived sound in the vehicle as it passes through a resonant "noise period." The amplitude and duration of these noise periods are functions of the entire vehicle system, although changes to the excitation source (gear set) can cause improvement overall. The acoustic noise amplitudes transmitted by the vehicle can sometimes be dramatically different from the characteristics of the gear set alone, but the relationship remains just a function between the gear set and the ear of the driver (Ref. 4).

In order to establish correction guidelines or to quantify the transmission function of structure-borne noise and deduce a quality criterion from it, a mobile "sound analysis system" is being developed as an additional tool for use with the Phoenix 500 HCT. A laptop computer equipped for measuring structure-borne or airborne noise is carried in the vehicle during the road test. One or two accelerometers, each emitting up to three orthogonal signals, are mounted near the gear and pinion bearings. A microphone is installed at the ear height of the driver, and its signal is fed to the computer, together with the accelerometer signals (Fig. 6, top). Operation information from the vehicle, such as speed, torque, load and ratio, if available, can also be input to the portable computer. During the road test, the driver hits a push button at the very moment he objects to a noise. This may occur several times in differing driving situations. Pressing the button adds a time-related mark to the recorded information.

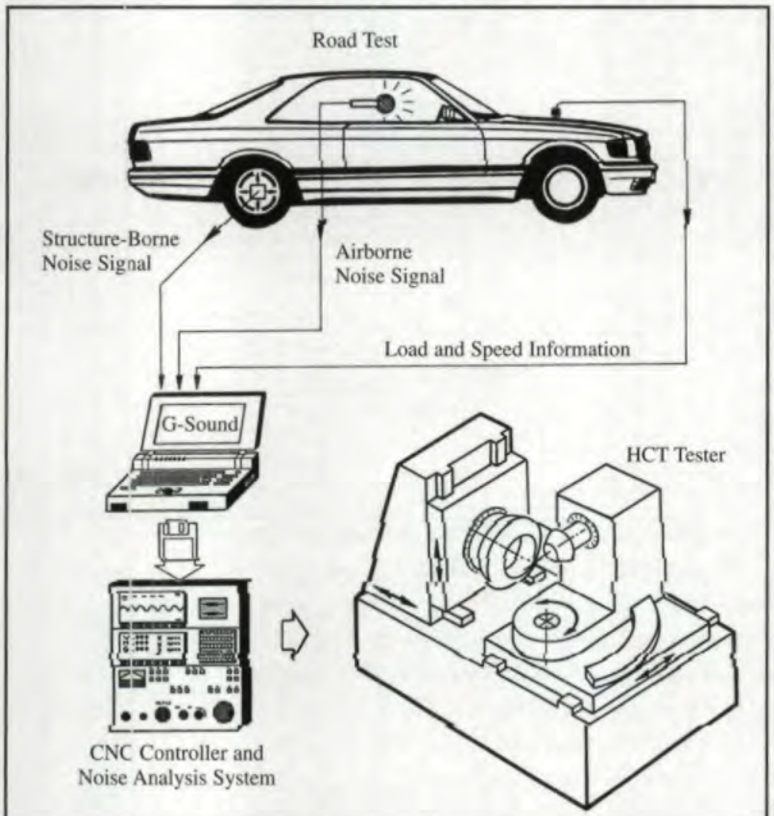

Fig. 6 — Closed loop between vehicle and HCT tester.

All results are transmitted by diskette to the analyzing computer of the HCT tester (Fig. 6, bottom). Subsequently, the same gear set is analyzed in the tester, using the same speed and torque as existed when the test driver indicated objectionable noise. Axis deformations will be simulated in V, H, G and α directions by using a strategy of search that leads to the most significant vibration results. The levels of the previously known critical frequency bands will then be transmitted as numerical values into a file for statistical evaluation and will be labeled with the grade the test driver had given. From at least four different gear sets and test drives, a valuation scheme can be established by the statistical program for use in 100% production testing. Use of more than 20 gear sets will provide a degree of certainty, depending on user-manipulated tolerances, which has never been reached by past methods.

In laboratory operation, results of just one test drive will be sufficient to calculate corrective values for production. From the objectionable frequencies, the levels of the first three harmonics of the tooth mesh frequency and their sidebands for calculation of fourth-order flank modifications, as well as the simulated axis deformations for initial correction of the tooth contact pattern location, will be used as a trigger for correction.

Conclusion and Outlook

The Phoenix 500 HCT tester represents the next step in the testing and measurement of gears. In the seventies, many gear manufacturers started to use single flank testing and structure-borne noise analysis. It was assumed that gear sets showing small amplitudes above the tooth mesh frequency and its multiples would run quietly. In too many cases, reality was different. The premature conclusion that dynamic measuring methods are unsuitable to indicate vehicle noise resulted in the continued practice of roll testing gear sets on manual testers and of relying on the auditory opinion of the operator. The operator was told what to pay attention to in critical cases. This information was often a feedback from the vehicle concerned.

What was realized there, under simple conditions, was an admittedly subjective, but quite

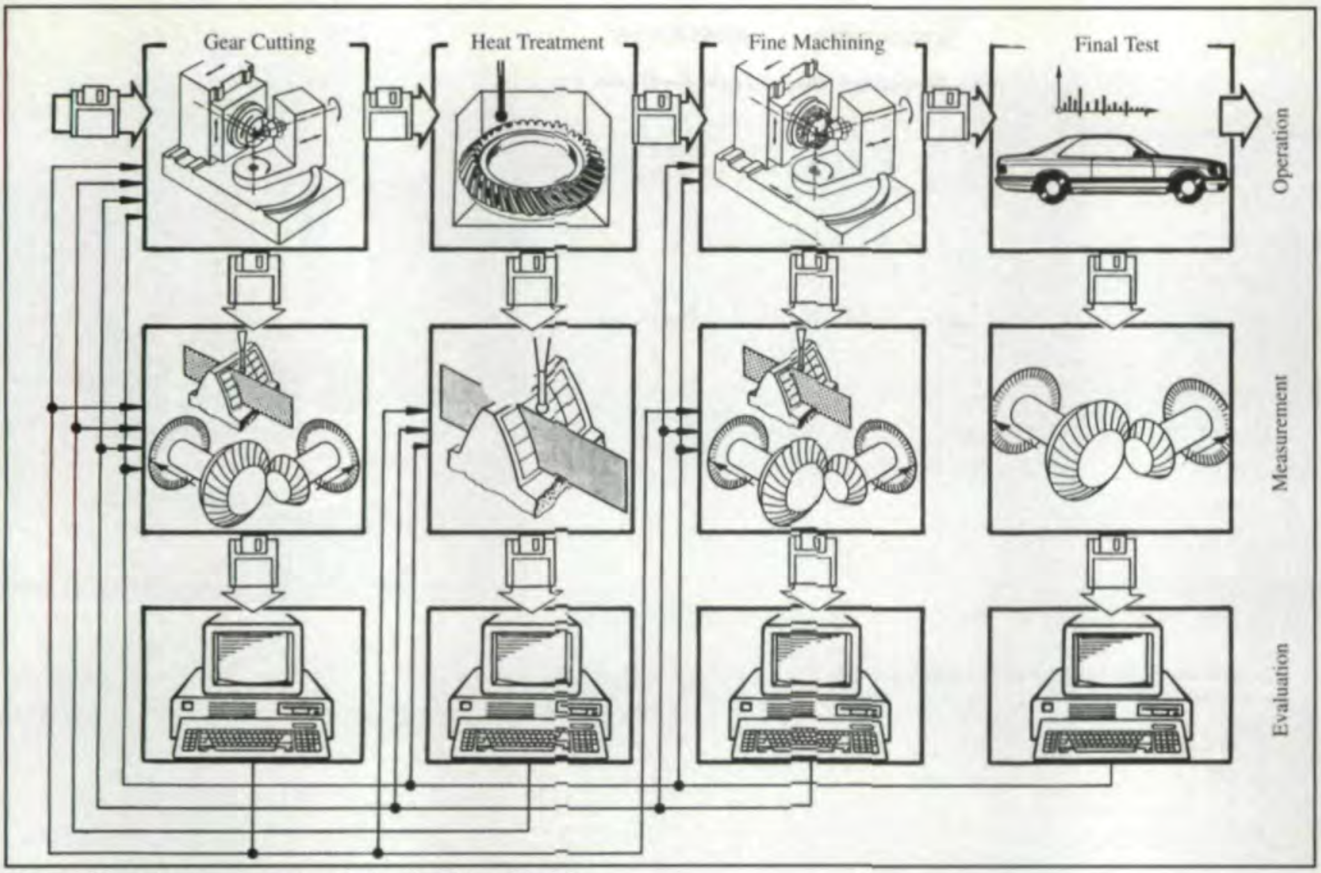

Fig. 7 — GLAB development system for bevel and hypoid gears.

sophisticated acoustic measurement. The operator at the manual testing machine took many factors into account, including different harmonic vibrations, their side bands, changes from drive to coast and whining noises during speed-up or slow-down. All these factors generally resulted from feedback from the vehicle test. After the test, the experienced operator checked the tooth contact pattern for acceptable appearance. The classical single flank test of the seventies could by no means be substituted for the abundance of information an experienced operator could absorb and evaluate during a test cycle of only a few seconds. Far more sensitive instrumentation and sophisticated evaluation techniques, as are offered in the Phoenix, are necessary to cover and quantify all the important relevant phenomena. The chief advantage of the new system, however, lies in achieving objective results to be compared against exact, consistent criteria.

Feedback from the gearbox, which in the best case is obtained when mounted in the final product, is indispensable, even when the objective measurement using the 500 HCT is made. Optimal gear development and production testing will be possible with the 500 HCT in the future (Ref.5). The chart in Fig. 7 shows the HCT's important function along with coordinate measurement. The duplication of basic geometry and the detection of heat treatment distortion is the task of coordinate measurement. All tasks related to the "fine tuning" of the tooth form (with respect to running performance and geometry) are the domain of the new tester. From the test results, changes of the tooth contact pattern position as well as higher order flank form corrections may be calculated as necessary to correct mesh interferences. ○

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