Single Flank Data Analysis and Interpretation

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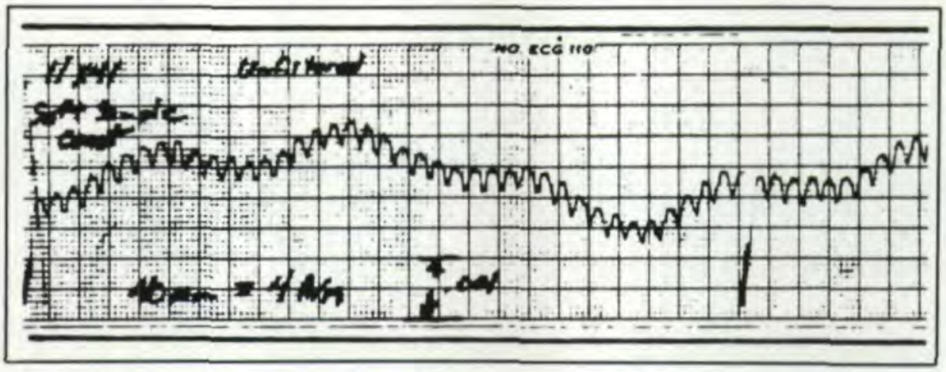

Fig. 1

Introduction

Much of the information in this article has been extracted from an AGMA Technical Paper, "What Single Flank Testing Can Do For You", presented in 1984 by the author.[1]

Single flank gear testing is a subject of increasing interest. Although it has been widely used and understood in Europe, its use has remained relatively rare in this country. However, as the measuring devices become smaller, less expensive and have better accuracy and resolution, they become more attractive as a production measuring device.

Single flank testing is concerned with the measurement of a parameter called Transmission error. Transmission error is defined as the deviation of the position of the driven gear, for a given angular position of the driving gear, from the position that the driven gear would occupy if the gears were geometrically perfect.[2]

Transmission error is generally seen in the form of a fairly regular once per tooth pattern, superimposed on large waves related to once per revolution type errors. Noise and vibration excitation is generally related to the once per tooth pattern, while accuracy problems are more generally related to the once per revolution type patterns.

It will be shown later that the study of noise excitation is more closely related to profile shape and the involute tooth form. Gear elements with perfect, rigid, uniformly spaced involute teeth transmit exactly uniform angular velocities.[3]

Measuring Device

A description of the measuring device, based on optical encoders, will be found in reference[1] and.[4] The encoders and associated electronics generate an analog signal that is directly related to portions of involute or profile variations, pitch variation, runout, and accumulated pitch variation. The graph in Fig. 1 illustrates a recording of a typical 11 × 41 pair of gears. The data shows two revolutions of the ring gear. The relationship of these parameters of gear geometry to the generated waveform is also described in the above two references.

Interpretation of Data

ANALOG DATA: The recording in Fig. 2 represents one revolution of a typical gear, run with a perfect master. Many bits of information can be read from this graph. These are: burr amplitude, adjacent pitch variation (f_p), accumulated pitch variation (F_p), tooth to tooth composite-single flank, (f_i'), total composite-single flank (F_i), and effective profile or conjugacy. If two non-miter test gears are run together, it is also possible to evaluate accumulated pitch variation for each gear separately, but the effective profile or conjugacy is the result of the combined tooth shapes of the two gears. If the gears are miters, it is possible to phase the accumulated pitch variation of each so that the resulting error is minimized.

Fig. 3 shows the resulting bar graph from a single probe/precision index test superimposed on a single flank test, of the same gear, run against a perfect master gear.

Examining the analog graph of a single flank test is always the best place to start with data analysis. The unfiltered, total information presents a good visual picture of the overall gear quality. Most instruments have provisions for use of high and low pass filters that aid in the separation and analysis of tooth to tooth type errors from runout type errors. Also, viewing analog curves of profile errors is useful in the determination of corrective actions (See Fig. 4).

REAL TIME ANALYSIS: Many times, the analog data becomes too complex to analyze in that form. This is due to various causes: running two test gears together, burrs, amplitude or frequency

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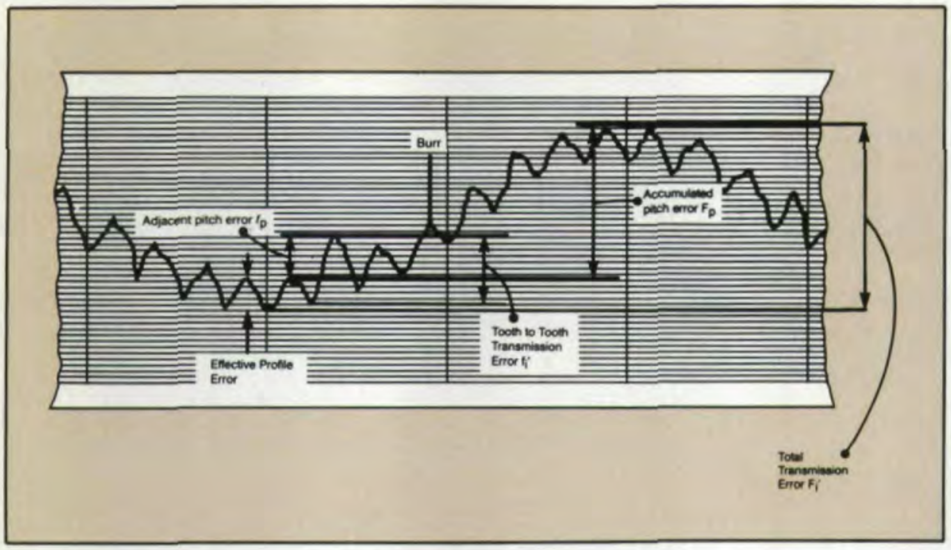


Fig. 2

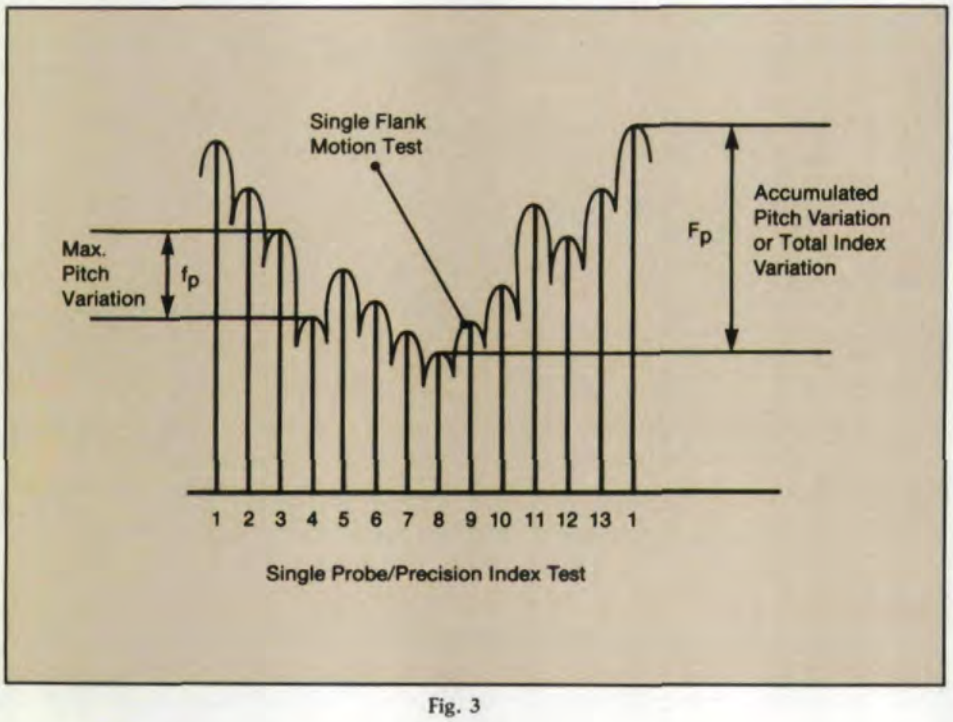


Fig. 3

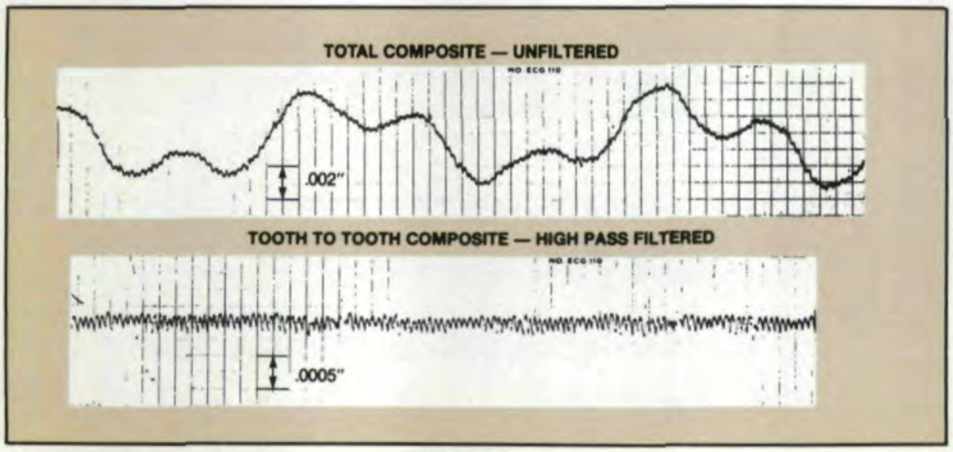
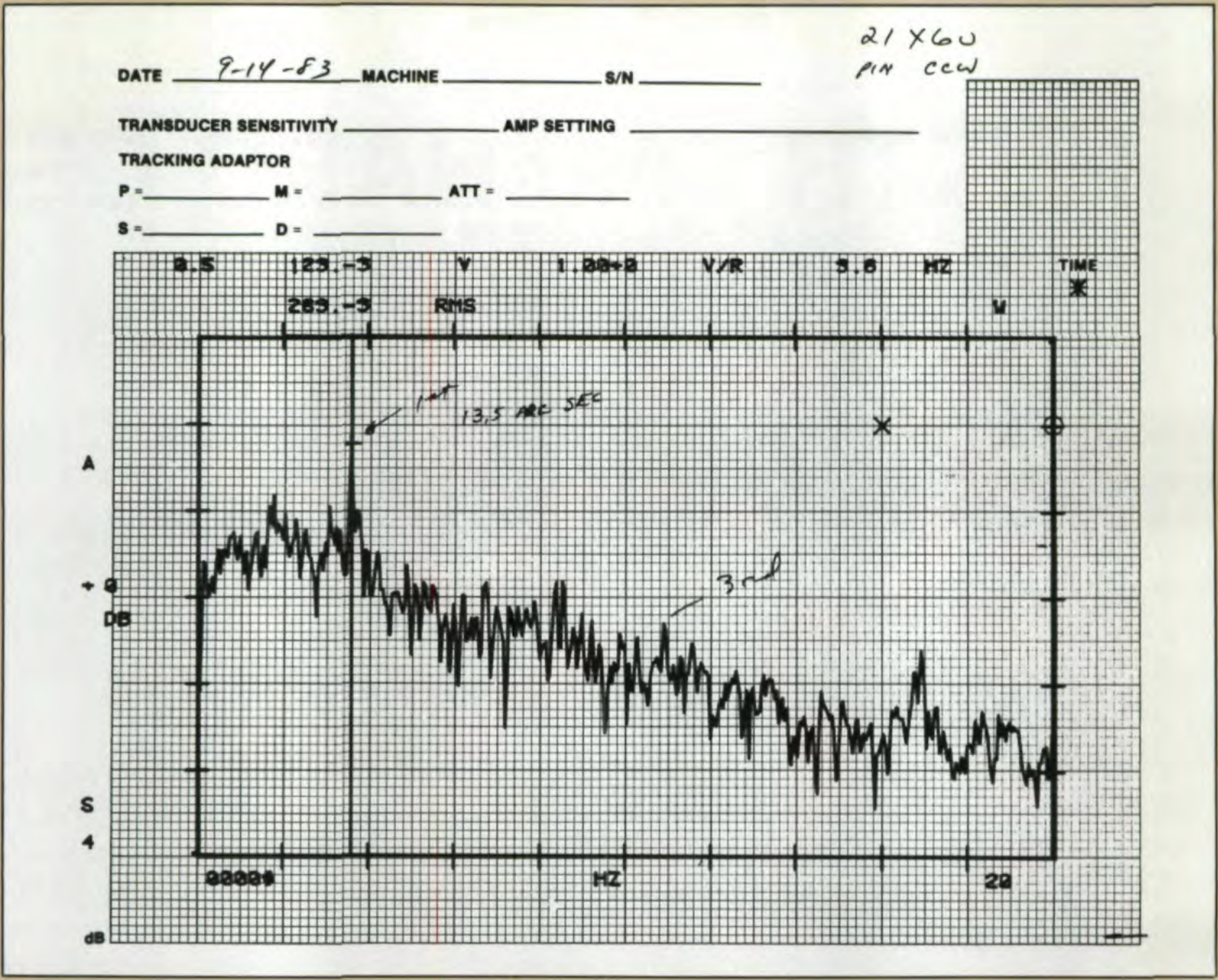


Fig. 4A

modulation, runout of gear and pinion phasing in and out, flats on tooth surface, etc. In these cases, it is useful to use a real time analyzer which performs a fast Fourier transform on the data. This converts the information from the time domain to the frequency domain.

Fig. 4b shows frequency domain data for the same gears. By taking several averages of the sampled data, it is possible to read repeatable amplitude values of the various frequencies contained in the analog chart. Mark[3] breaks this spectral data into two components. The "mean" geometric deviation component for a gear or pinion is defined, as the tooth surface formed, by taking the average of all tooth surfaces on the pinion or gear under consideration. The "random" component of the geometric deviation of a tooth surface is defined as the deviation of that tooth surface from the mean. The mean component comes from intentional or accidental profile modifications, while the random component comes from the runout effects. The mean component of the geometric deviations gives rise to the tooth meshing harmonics of vibratory excitation. Whereas, the random component of the geometric deviations gives rise to the rotational harmonics, and especially, to the sideband components of the spectrum which occur at the tooth meshing harmonic frequencies, plus or minus one or a few rotational harmonic frequencies.

TIME HISTORY AVERAGING: The use of time averaging, in the time domain, is a technique that has seen little use, so far, in single flank testing. However, in the future, it should become very common. It requires the use of an accurate once per revolution marker pulse on each shaft. Data from many revolutions of a given shaft are averaged together and, therefore, information that is synchronous with the marker will remain, while non-synchronous data will eventually average to zero. The advantage of this technique is that it allows one to separate out elemental errors, such as once per tooth conjugacy, pitch variation, and accumulated pitch variation attributable to each individual gear. In Fig. 5, Smith[5] shows the time history data of a twin mesh gearbox, as well as time averaged data of the individual gears in the same box. Time history averaging offers some very interesting possibilities.


DATE 9-14-83 MACHINE S/N
21 X 60
PIN CCW
TRANSDUCER SENSITIVITY AMP SETTING
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1st
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Fig. 4B

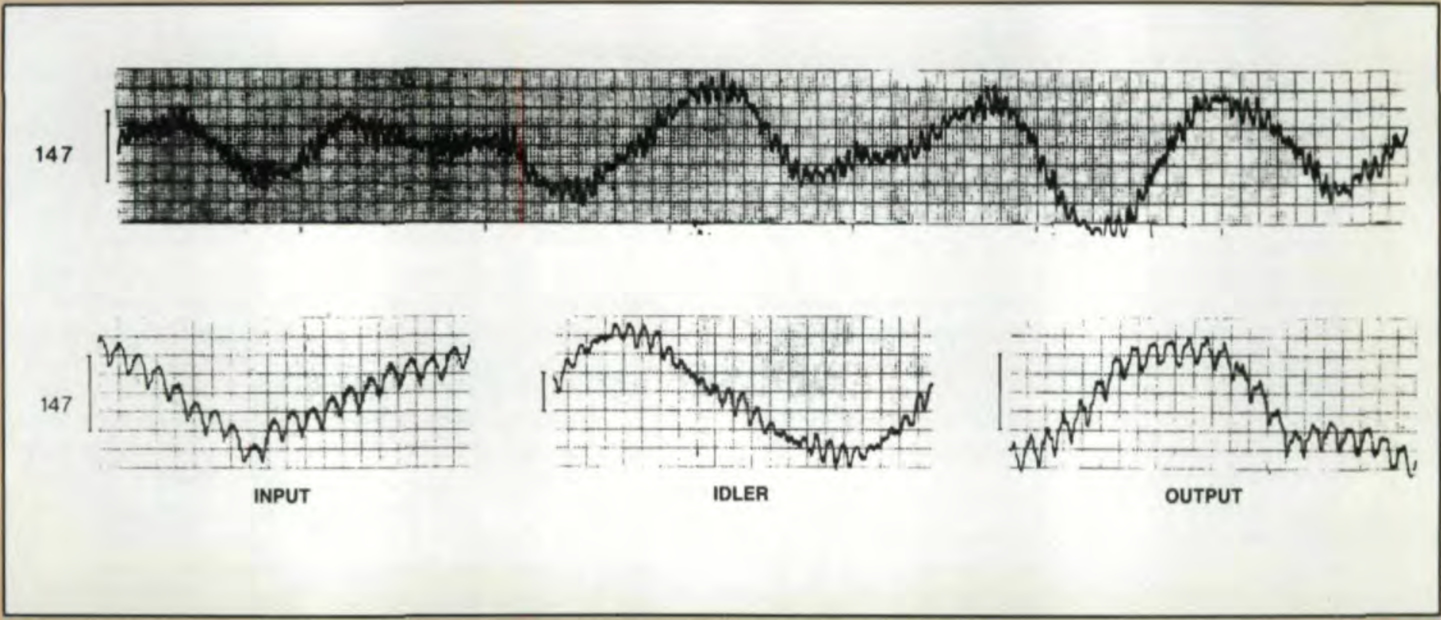
147
147
INPUT
IDLER
OUTPUT

Fig. 5

The State of the Art...

HURTH CNC HARD GEA

The HURTH hard finishing process is an entirely new approach to gear manufacture and finishing because it enables the manufacturer to alter the geometry of the teeth while smoothing the tooth flank surfaces of external and internal hardened gears. This process can correct errors in profile, spacing and lead, as well as such parameters as radial runout, pitch and cumulative pitch. The end product is a more accurate, smoother, quieter-running gear.

To accomplish this, the tool flank and the work gear flank being machined are positively guided in such a way that the workpiece and tool are rigidly linked during machining with the tool performing a plunge-feed motion for stock removal. All right-hand flanks are finished first. The machine then reverses and finishes left-hand flanks. This single-flank contact means no broken-out tool teeth due to workpiece defects and permits correction or "redesign" of the workpiece gear during finishing.

The tool, either Borazon® or ceramic, is conditioned and profiled for the work gear geometry and desired stock removal by using a coated dressing master. Dressing takes no longer than the time required to finish one workpiece and each dressing removes a minimal amount of material from the tool surfaces.

R FINISHING MACHINES

The hard finishing process gives the widest range of applications of all post-hardening gear finishing methods. Adjacent shoulders or collars rarely pose serious problems.

This illustration shows the tool finishing the work-piece gear and the external master gears engaged to control the operation.

Other advantages of the process:

- AGMA Class 14 achievable.
- Definitely no grinding burns.
- Tool marks run diagonally to gear diameter.
- Permits machining of gear teeth adjacent to shoulders.
- Equipment is ideal for automated work handling.

Please write or phone for details on this revolutionary new process.

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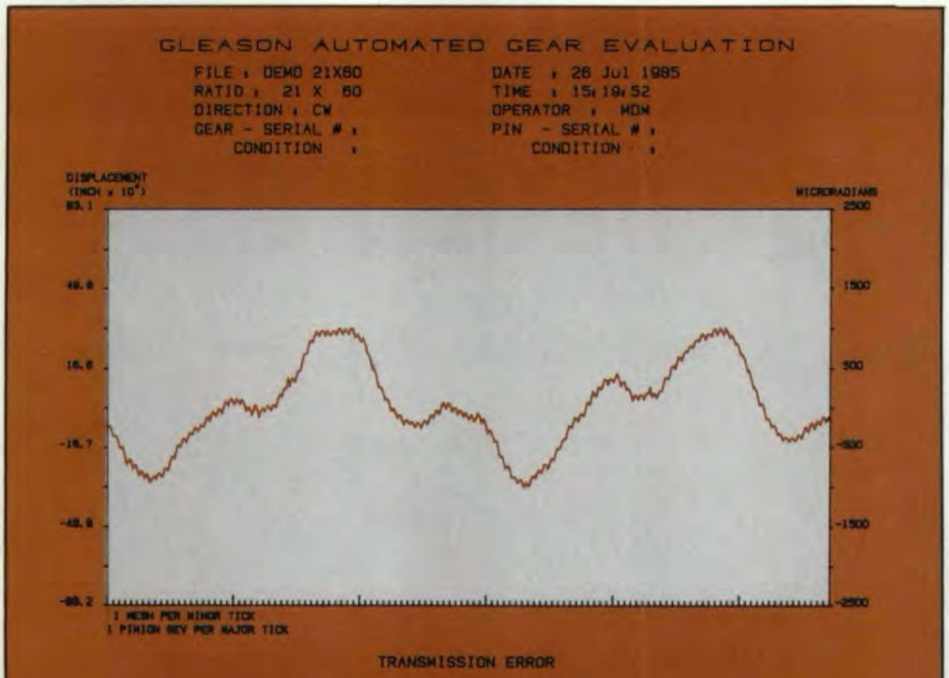


Fig. 6A

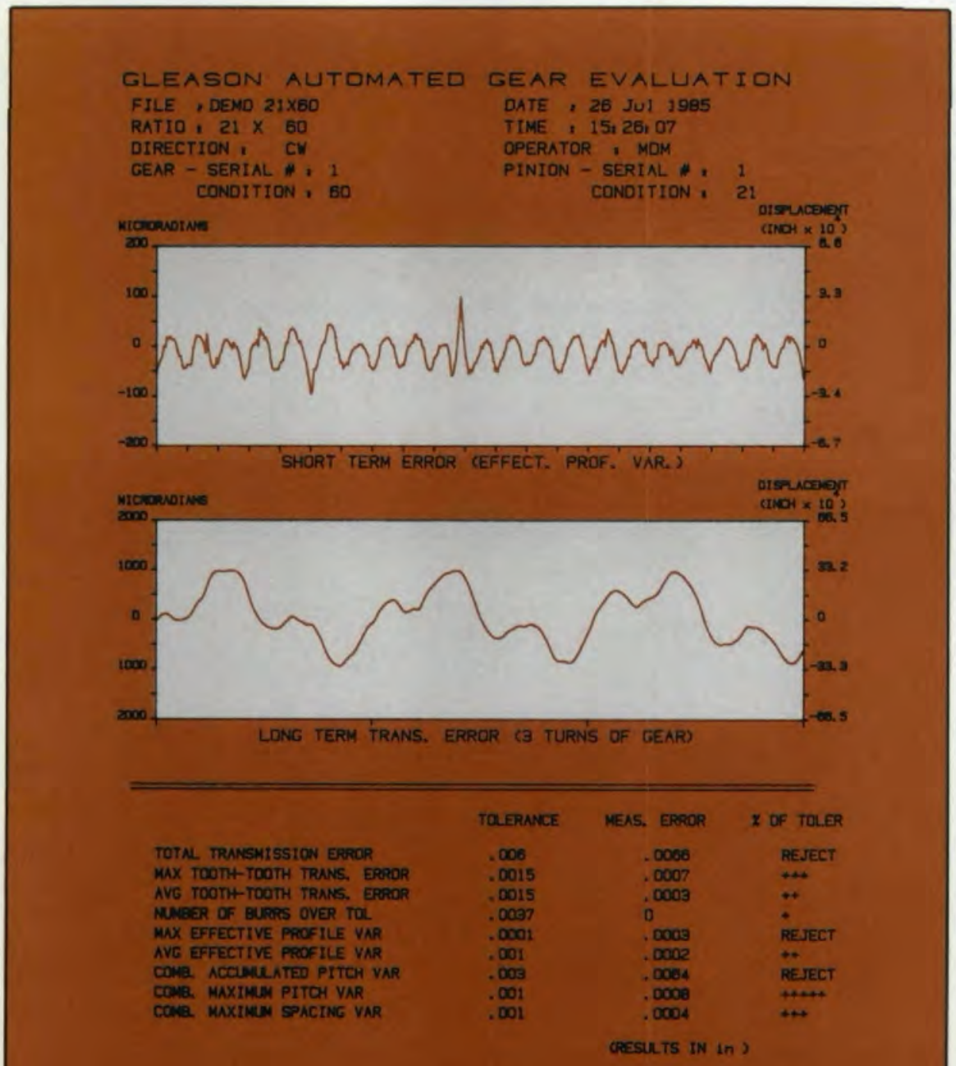


Fig. 6B

AUTOMATIC DATA ANALYSIS (COMPUTERIZED): In order to minimize the need for a skilled engineer or technician to analyze data, computers and appropriate software packages are now available for single flank testers. The computers are programmed to extract quantitative information, related to the various measureable parameters, from the complex analog data. These values can then be compared to previously established tolerance limits. The accept/reject judgements can be made by computer.

Visual data can also be displayed in forms unavailable in the other methods of data analysis described above. A typical series of displays would include the following:

1. Total transmission error
2. Long term component (related to once/rev. type errors)
3. Short term component (related to once/tooth type errors)
4. Average effective profile error (average component described in reference)[3]
5. Velocity and acceleration derivatives of 4 above (to look at the effect of peak acceleration caused by displacement waveshape)
6. FFT spectral analysis of data (also includes velocity and acceleration displays).

There are many other uses of computerized data analysis, such as master gear error correction, pitch variation, accumulated pitch variation, runout, comparison to AGMA, DIN, ISO, or company standards as well as statistical quality control and statistical process control. Fig. 6-6F shows some of this data.

Advantages of Single Flank Over Double Flank Testing

APPARENT PROFILE ERRORS: Munro[2] shows how profile errors affect the motion curves of a gear running with a master (Fig. 7). Curves of various tooth shapes are shown for single and double flank tests.

Double flank testing is a fast, inexpensive way to composite test gears, but it is usually impossible to interpret the tooth to tooth data in terms of elemental or transmission error. This is due to both sets of flanks being in mesh at one time.

Single flank composite testing does measure transmission error directly. Because the gears run with only one set of flanks in mesh (with backlash) it is possible to interpret the curve in terms of profile and pitch errors.

Munro concludes:

1. The single flank test always shows the profile error of the flank in mesh, but not over the whole of the flank.
2. The dual flank test gives a composite curve of the two flanks, and there is no method of ascribing an error to a particular flank.
3. The dual flank peak to peak value (tooth to tooth composite error) is often, but not always, approximately equal to the single flank peak to peak value multiplied by half the cotangent of the pressure angle.
4. With a barrelled profile error, the dual flank test gives a waveform with two peaks per tooth pitch.
5. The dual flank curve is sometimes identical for two quite different sets of profile errors.

RUNOUT VS. ACCUMULATED PITCH VARIATION: The ability to check accumulated pitch variation is an important attribute of single flank testing. First of all, there is a difference between "runout" and "accumulated pitch variation." A gear with runout does have accumulated pitch variation. A gear with accumulated pitch variation does not necessarily have runout.

Runout occurs in a gear with a bore or locating surface that is eccentric from the pitch circle of the teeth. Runout is shown as a variation in depth of a ball type probe as it engages each successive tooth slot. Or, it can be a large total composite variation, if it is observed on a single flank tester.

A gear can be produced, by various means, that will have little or no runout, as described above, and it will show excellent results when tested with a ball check or by a double flank test. This happens when a gear is cut with runout and then shaved or ground on a machine that does not have a rigid drive coupling the tool to the workpiece.

When the gear is cut with an eccentric pitch circle, the slots are at different radii and angular positions. When the gear is

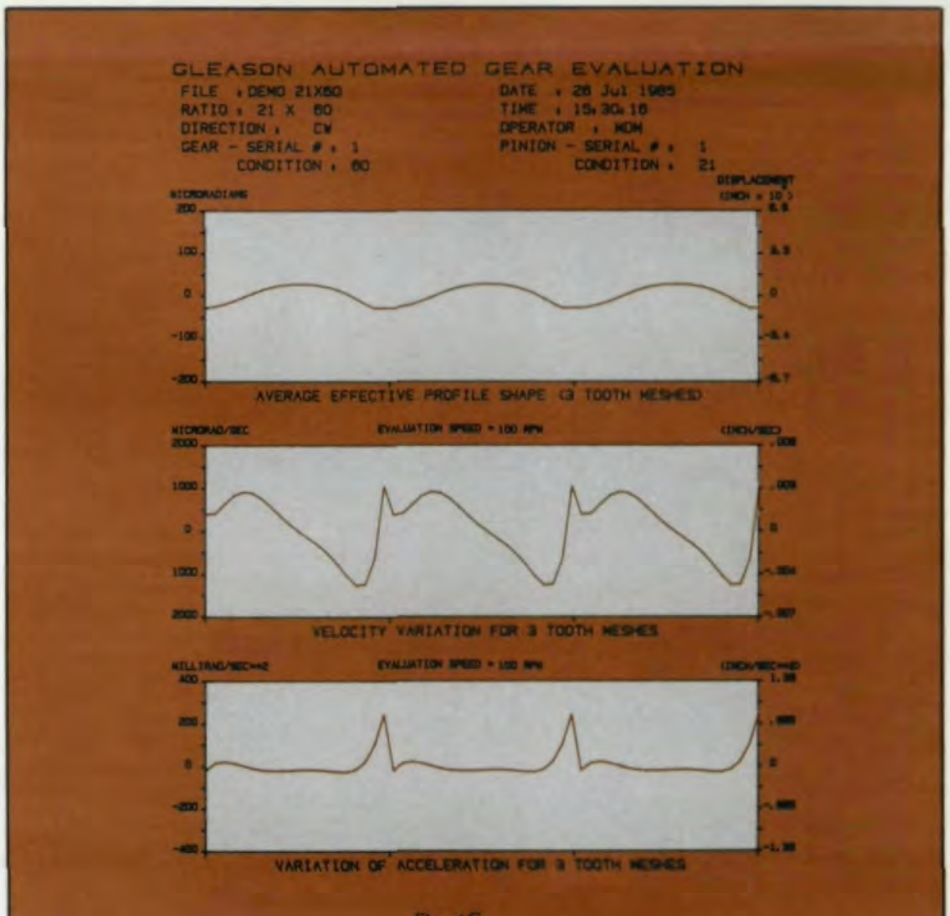


Fig. 6C

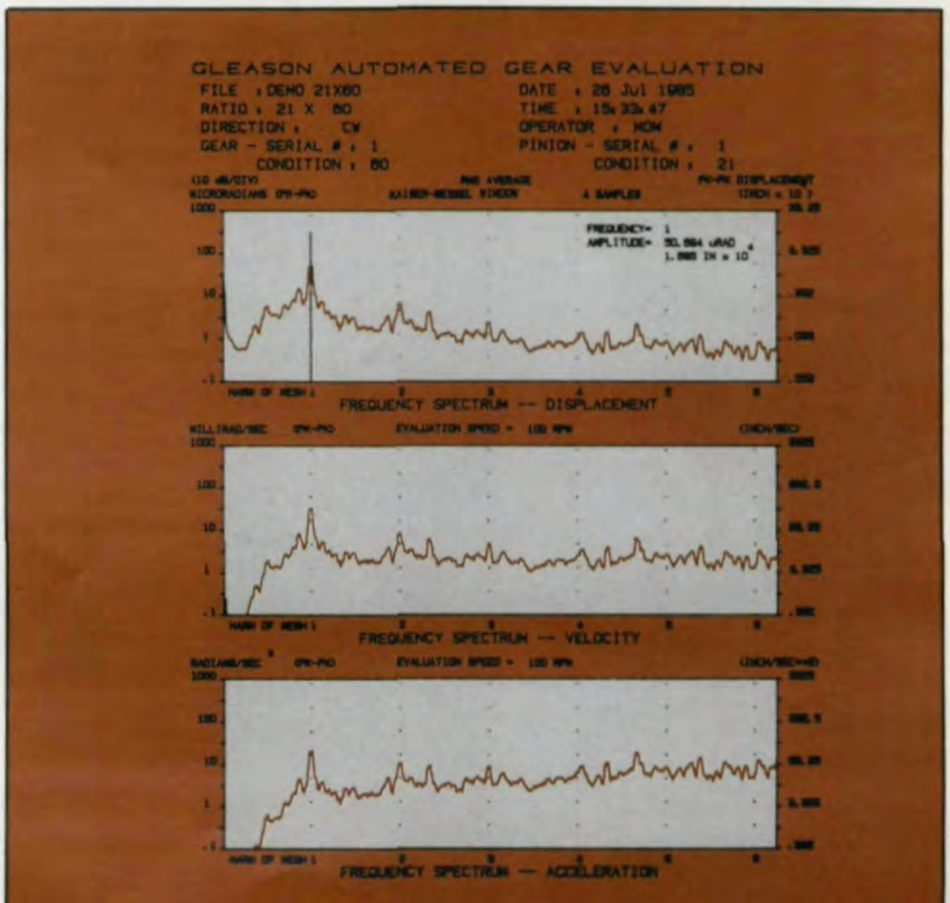
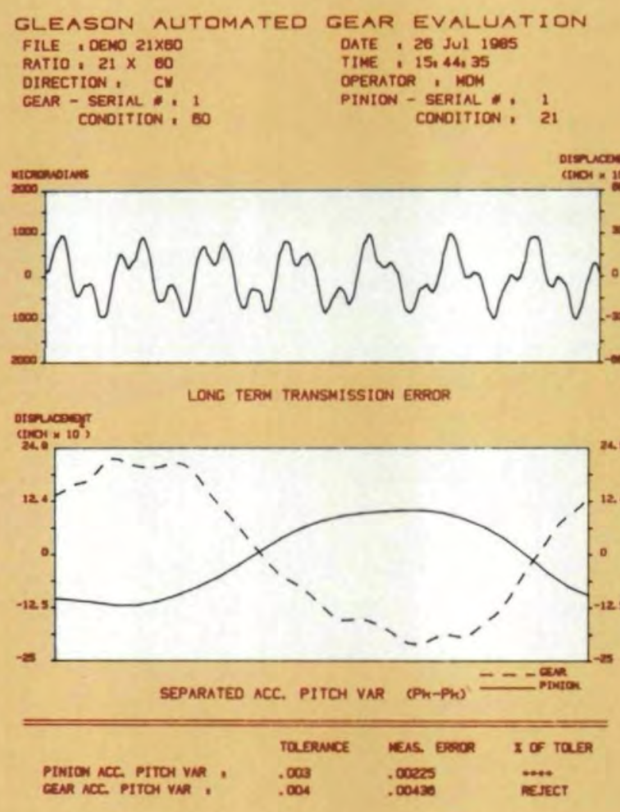
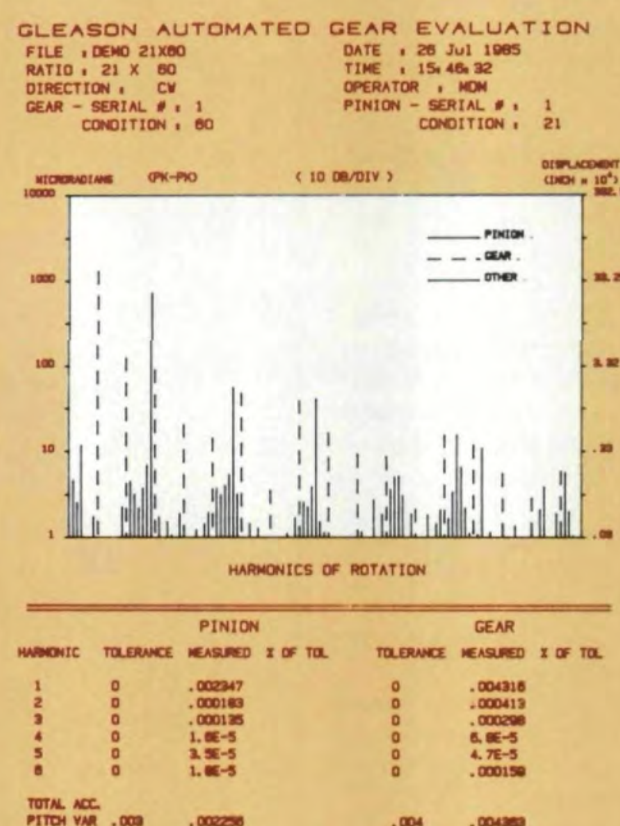


Fig. 6D



GLEASON AUTOMATED GEAR EVALUATION
FILE : DEMO 21X60
RATIO : 21 X 60
DIRECTION : CW
GEAR - SERIAL # : 1
CONDITION : 60
DATE : 26 Jul 1985
TIME : 15:44:35
OPERATOR : MDM
PINION - SERIAL # : 1
CONDITION : 21
MICRORADIANS
DISPLACEMENT
LONG TERM TRANSMISSION ERROR
DISPLACEMENT
SEPARATED ACC. PITCH VAR (Pk-Pk)
GEAR
PINION
TOLERANCE
MEAS. ERROR
% OF TOLER
PINION ACC. PITCH VAR : .003 .00225 ****
GEAR ACC. PITCH VAR : .004 .00436 REJECT

Fig. 6E



GLEASON AUTOMATED GEAR EVALUATION
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DIRECTION : CW
GEAR - SERIAL # : 1
CONDITION : 60
DATE : 26 Jul 1985
TIME : 15:46:32
OPERATOR : MDM
PINION - SERIAL # : 1
CONDITION : 21
MICRORADIANS
(PK-PK)
(10 DB/DIV)
DISPLACEMENT
PINION
GEAR
OTHER
HARMONICS OF ROTATION
PINION
GEAR
HARMONIC TOLERANCE MEASURED % OF TOL TOLERANCE MEASURED % OF TOL
1 0 .002347 0 .004316
2 0 .000183 0 .000413
3 0 .000135 0 .000298
4 0 1.8E-5 0 6.8E-5
5 0 3.5E-5 0 4.7E-5
6 0 1.8E-5 0 .000159
TOTAL ACC.
PITCH VAR .003 .002256 .004 .004363

Fig. 6F

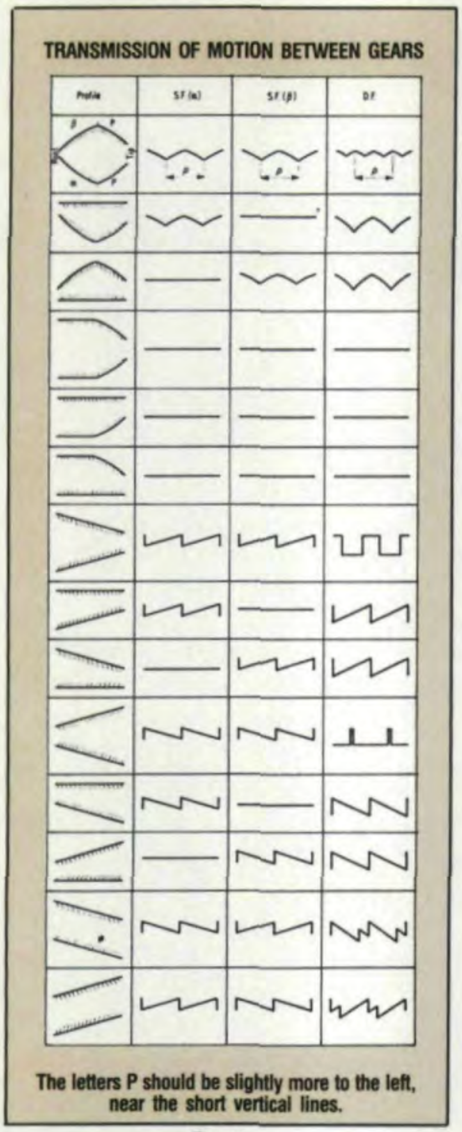

Fig. 7

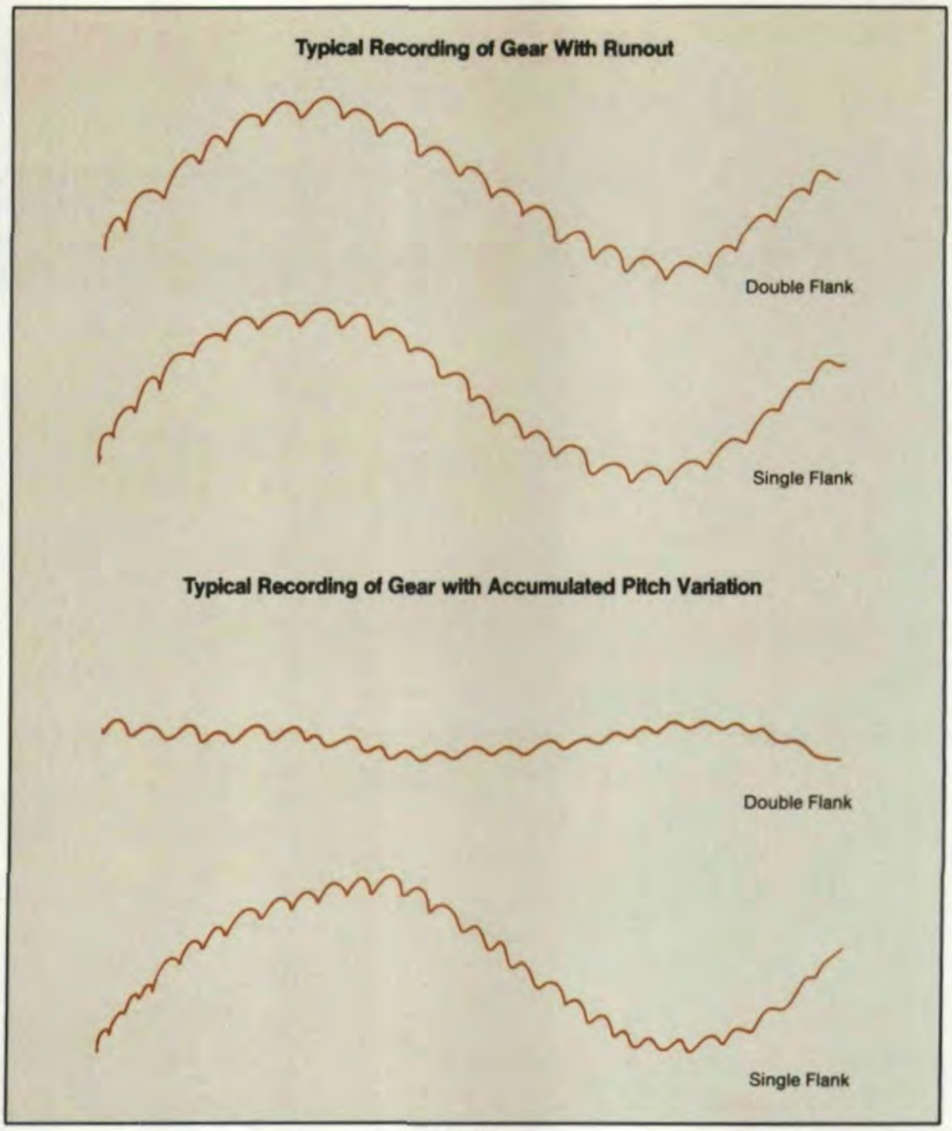

Fig. 8

shaved, it is run with a tool that maintains a constant rigid center distance, but is not connected to the workpiece by a drive train. The tool also cuts an equal amount of stock from each flank of every tooth. Therefore, all slots are now machined to the same radius, from the center of rotation, and are displaced from *true angular position* by varying small amounts. The resulting gear has very small amounts of individual pitch variations, but has a large accumulated pitch variations, to which the single flank tester responds.

These accumulated pitch variations have all the undesirable effects of a gear with traditional runout. It would check "good" by either a ball check or a double flank composite test. Fig. 8 illustrates the advantage of single flank for the two situations.

Application of Data

Before using the single flank data in an application, it is first necessary to define the problem. There are three basic areas of concern: noise, accuracy, and strength or durability. In a general way, single flank data in the form of tooth to tooth transmission error is related to noise and vibration; total transmission error is related to accuracy, and both types relate to strength in a secondary way. Lead is the element primarily associated with strength and this is best measured, by other means, such as contact patterns. Fig. 9 is a very generalized chart of cause and effect relationships. When evaluating noise problems, it is appropriate to run a sound analysis test with a real time analyzer to pinpoint the offending rotational order. In most cases, it will be at tooth mesh frequencies, however, when running at very high RPM, it will be at the once per rev. frequency.

When it comes to accuracy, all types of transmission errors will have an effect. Accumulated pitch variation will normally be the greatest contributor to total transmission error and inaccuracy.

Case Histories

The following case histories are included to demonstrate the capabilities of single flank testing.

(1) NOISE: Fig. 10 is used to illustrate the fact that accuracy isn't necesary for noise control. It shows a lapped hypoid pair of gears with a relatively large total transmission error from accumulated pitch and bolt hole distortions, but with a very low tooth to tooth transmission error (less than .0001"). This was a quiet pair in the axle.

Application of Single Flank Data

DEFINE PROBLEM!

Problem	Primary Application	Cause
Noise	Vehicle - High Frequency >100 Hz	Effective Profile
	Vehicle - Low Frequency <100 Hz	Accumulated Pitch Variation
	Machine Tools - High Frequency	Effective Profile
	Power Transmission - High Frequency > 100 Hz	Effective Profile
	Power Transmission - Low Frequency < 100 Hz	Accumulated Pitch Variation
	Aircraft Drives High RPM - (30,000)	Accumulated Pitch Variation
Problem	**Primary Application**	**Cause**
Positional Accuracy	Machine tools, indexing devices, Gun directors, robots, etc.	S.F. T.T. Composite S.F. Total Composite Pitch Variation Accumulated Pitch Variation
	Secondary Application	
Strength - Fatique	Marine & Power Drives	Use contact pattern or lead measurements for primary control S.F. profile, pitch variation, & accumulated pitch variation for secondary control

The above are generalities.

There will be exceptions such as:
Sideband (Sum and Difference Frequencies)
Contact Ratio — Helicals
— Spirals
— Lead Error

Fig. 9

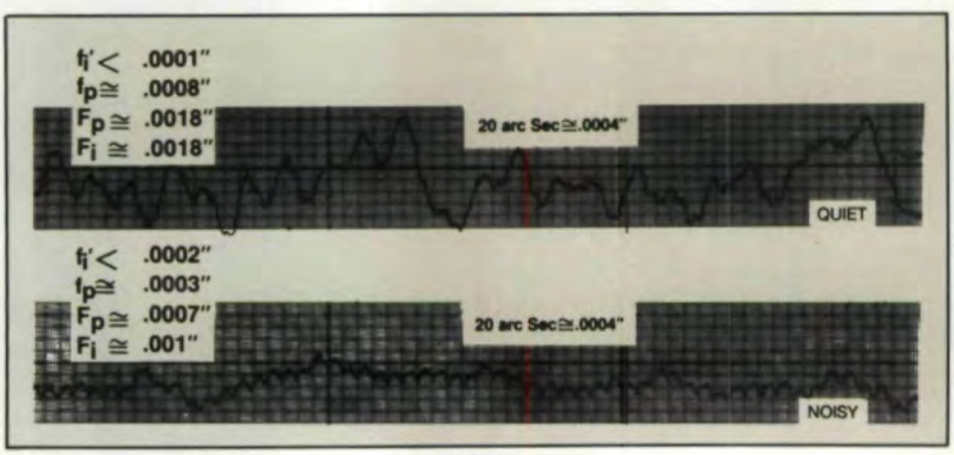

Fig. 10

The other pair was an experimental ground pair with very low total transmission error, but with a very regular high tooth to tooth error (.0002"). This pair was noisy in the vehicle at first and fourth harmonics of mesh frequency. In this case, the vehicle was a van type, which is typically sensitive to excitation due to structural dynamics.

(2) NOISE: Fig. 11 shows two lapped hypoid rear axle sets. Fig. 11a was acceptable in the vehicle and Fig. 11b was a reject because of noise due to the relatively high tooth to tooth transmission error.

(3) ACCURACY: Fig. 12 shows sets of ground high reduction gears used in the indexing spindle of a machine tool. Fig. 12a shows an unacceptable pair with excessive pinion runout (.0002"). Fig. 12b shows the next grind after improving the runout. In this example, it is no longer possible to detect a systematic error from gear geometry.

(4) ACCUMULATED PITCH VARIATION VS. RUNOUT: The last case is really two different sets of gears illustrating two aspects of Runout and Accumualted Pitch Variation (Fig.13). These are sets of final drive helicals used in the transaxle of a front wheel drive passenger car. The problem is related to a low frequency vibration in the vehicle, caused by once per revolution errors in the pinion.

Set number one (high accumulated pitch variation) caused excessive vibration in the vehicle. A double flank composite test accepted the part with .0025" pinion total composite error. However, the single flank test showed .0135" pinion total transmission error. In this case, the current pinion production test accepted a bad part.

Set number two (high runout) was acceptable in the vehicle as far as low frequency vibration. In this example, the double flank test rejected it because of a pinion total composite error of .009" while the single flank test still showed an acceptable amount of .003" pinion total transmission error. In this example, the current double flank production test rejected a part that should have been passed on to assembly.

In the two cases above, it is evident that double flank composite inspection does not correlate well to the application. On the other hand, single flank composite measurement of transmission error does.

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SINGLE FLANK DATA ANALYSIS . . .

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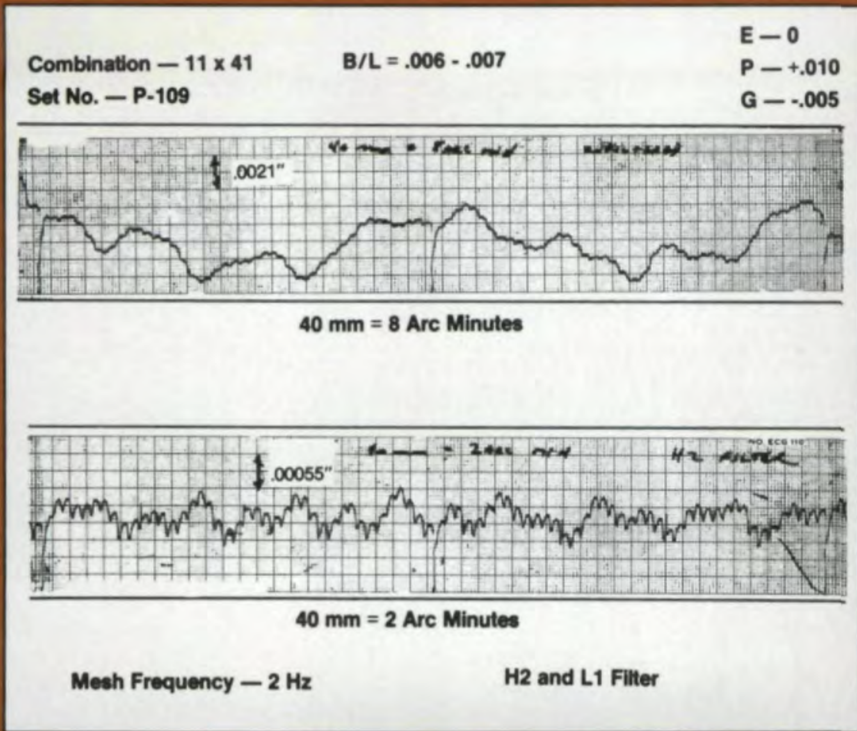


Fig. 11A – (Left) Acceptable lapped hypoid rear axle.

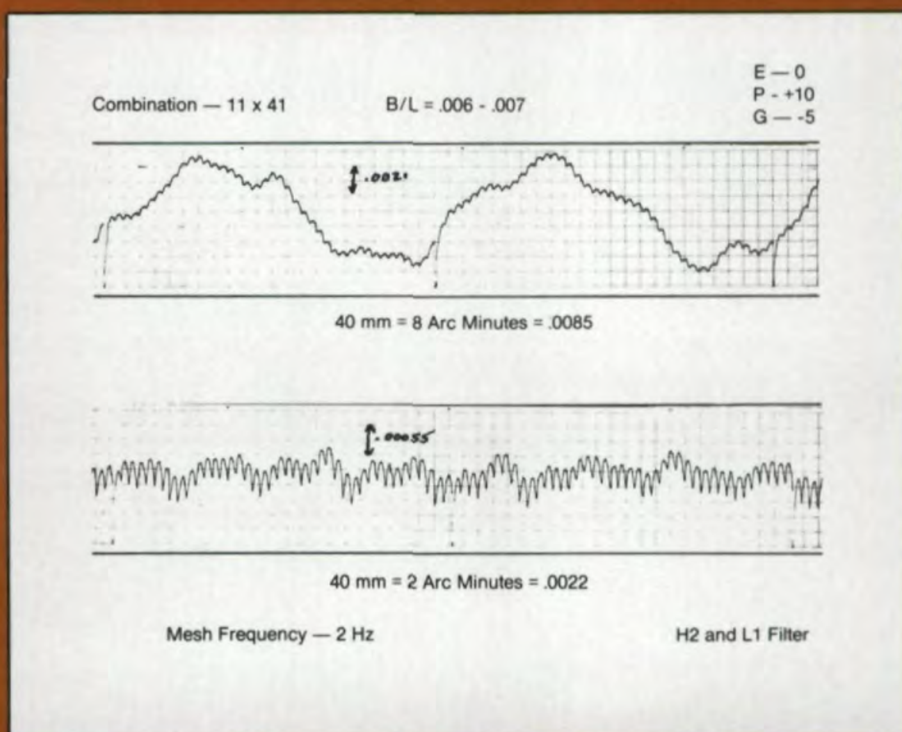
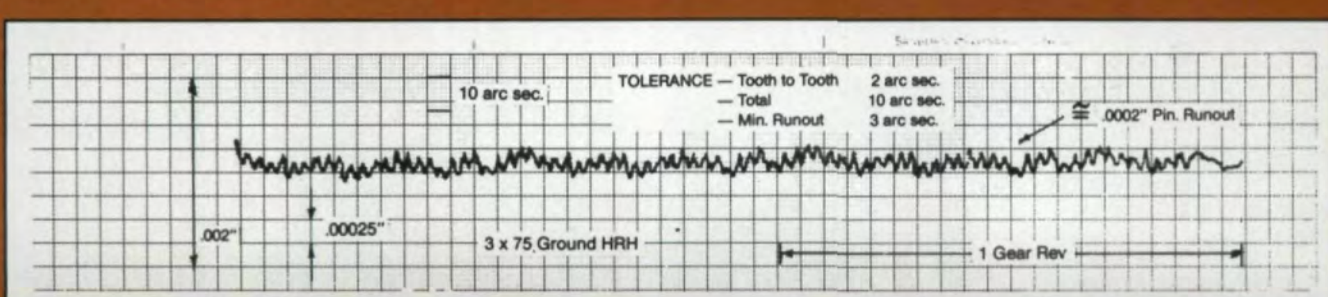


Fig. 11B – (Right) Rejected because of noise due to the relatively high tooth to tooth transmission error.

Fig. 12A – (Below) Pair with unacceptable runout.



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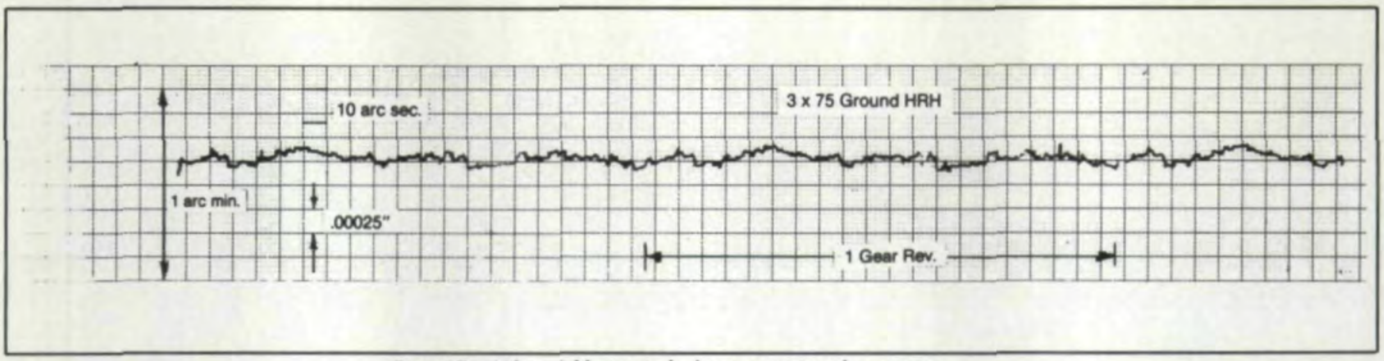


Fig. 12B – (Above) Next grind after improving the runout.

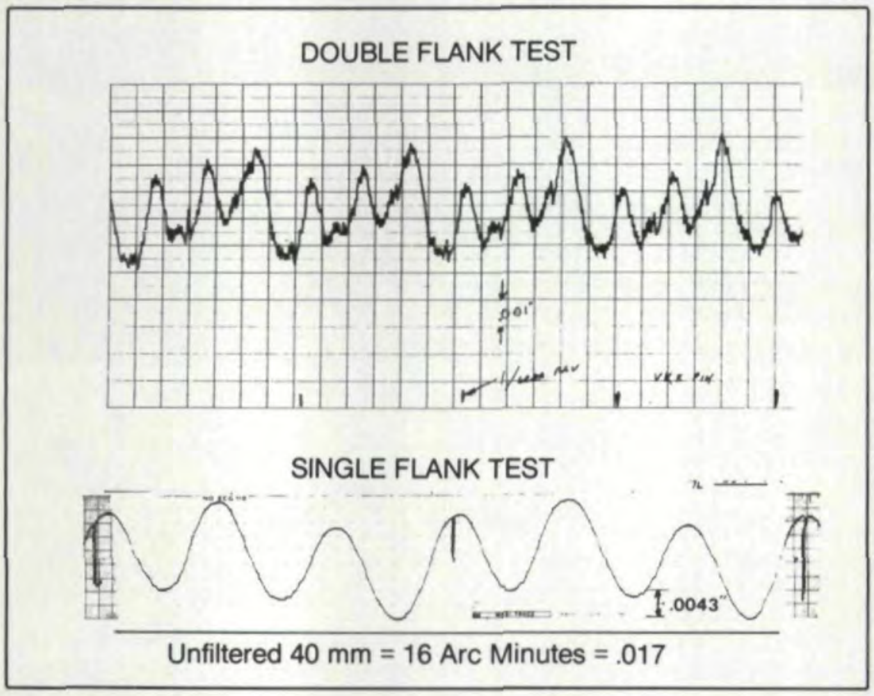
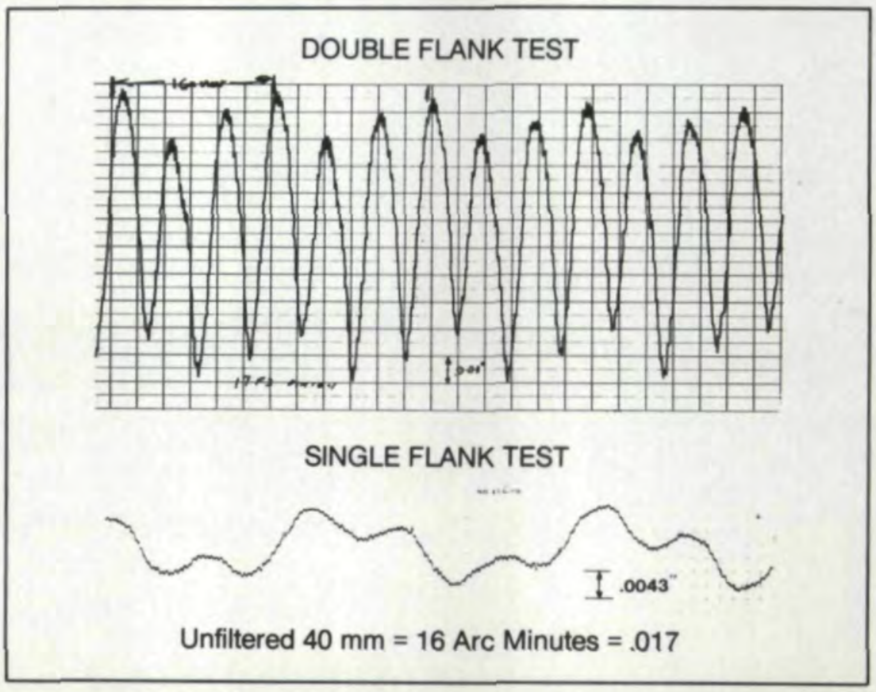


Fig. 13 – (Left) Set number one – high accumulated pitch variation

Fig. 13 – (Below) Set number two – high runout



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E-2 ON READER REPLY CARD