The Relationship Of Measured Transmission

Robert E. Smith, Consultant
R. E. Smith & Co., Inc.
Rochester, New York

The Gleason Works
Rochester, New York

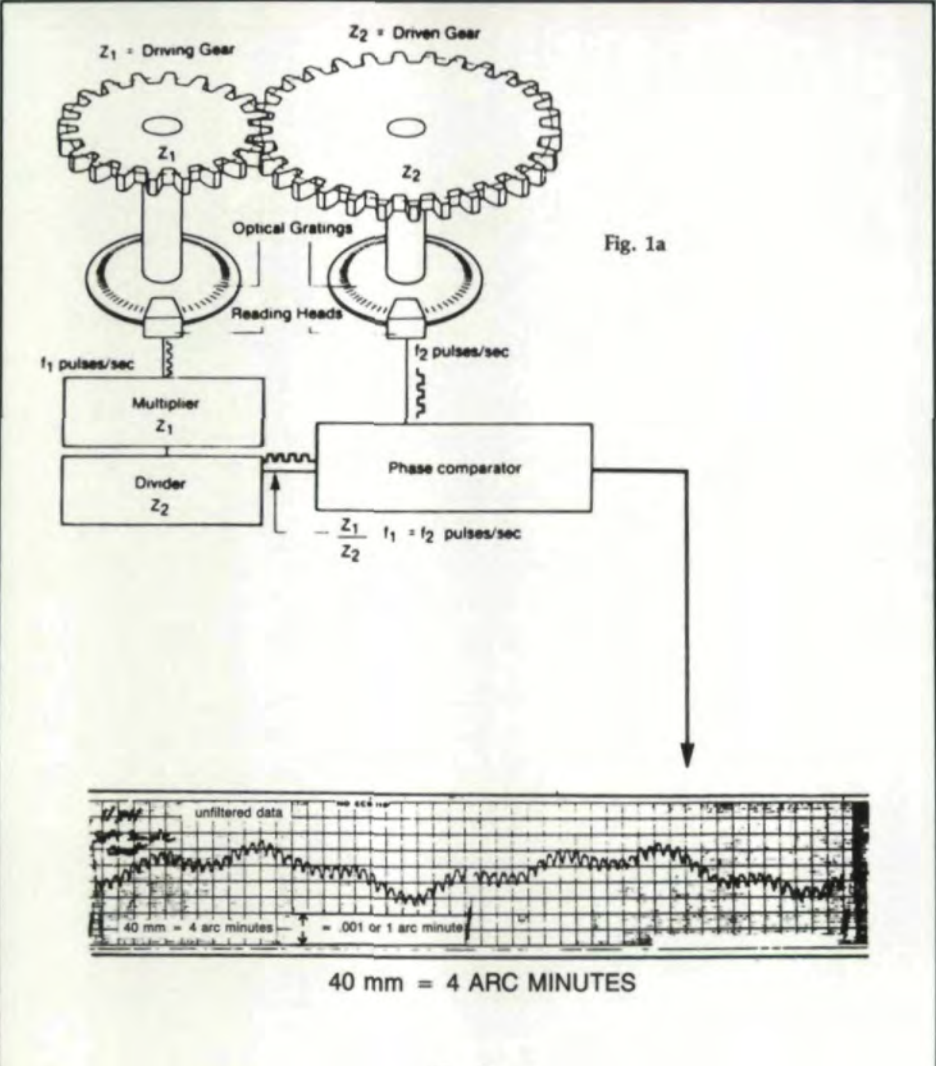


Fig. 1a

Fig. 1b

Abstract

Gear noise is not just a gear problem. It is a system problem and the gears are the exciters of the system. Transmission errors in the gears due to geometric variations are the source of the excitation. This article deals with the instrumented testing of noise in the system and how to successfully relate the results back to the measured transmission errors in the gears. The biggest difficulty in establishing the relationship is how to compare visually displayed sound analysis data to aural judgments of the human rater, and then relate the results back to measured transmission errors of the gears. This is referred to as the "missing link" in the article.

Introduction

Vehicle gear noise testing is a complex and often misunderstood subject. Gear noise is really a system problem.[1] Most gearing used for power transmission is enclosed in a housing and, therefore, little or no audible sound is actually heard from the gear pair.[2] The vibrations created by the gears are amplified by resonances of structural elements. This amplification occurs when the speed of the gear set is such that the meshing frequency or a multiple of it is equal to a natural frequency of the system in which the gears are mounted.

In order to make "quiet" gears, there must be feedback from vehicle testing to gear manufacturing. Unfortunately, this is where a "missing link" usually occurs. Much of the vehicle testing is done in a subjective manner, which is of little help to the gear maker as far as knowing what element of gear quality to improve to reduce noise. If instrumentation is used, such testing is often done by noise and

Gear Noise To Measured Gear Errors

vibration people who know little about gear geometry. Their data may show lots of peak vibrations that bear no relationship to what the human ear is hearing relative to gear quality. Many times the excitation may even be coming from another source, such as a rolling element in a bearing.

Frequency is the key to understanding gear noise. The problem is how to convert aural images to visual ones; in other words, how to find a way to display on a CRT or on paper what the human ear is hearing.

Gears As Exciters of Structures

Most of what we hear as "gear noise" does not come directly from the gear pair at all. The minute vibrations created by the gears as they move through mesh are amplified by resonances in the structural elements of the housing, such as panels, ribs, beams, etc. Gear noise in a vehicle generally occurs at tooth mesh frequency or harmonics of it and occasionally at sidebands of mesh frequency. The gears are the exciter. The structure resonates, amplifies the force and converts it to airborne noise. Transmission error or non-uniform motion of the gears is the mechanism of excitation. Transmission error[3] is the result of small variations from the correct or ideal tooth geometry, as well as runout, and can be measured in the production process by the use of single flank composite testing techniques. In the case of vehicle noise, these variations can be as small as 25 to 150 microinches, depending on the frequency.

Transmission Error Testing

Transmission error testing is done by rolling gears together with backlash and at their proper operating center distance. The input and output angular motion characteristics are measured by an encoder system and electronics as shown in Fig. 1a. The data can be presented in graphic analog form, as shown in Fig. 1b, or can be further processed by Fast Fourier Transform (FFT) techniques to aid in pinpointing the source of excitation. The Fourier technique takes an analog signal and breaks it down into a spectrum of frequencies that relate to the various elements of gear tooth geometry present in the transmission error. (See Fig. 2.) Fig. 3 shows how the geometry of a gear tooth (3a), including flats or waviness, rolls with a master and generates the transmission error curve (3b). This tooth to tooth transmission error curve would be further analyzed by FFT techniques to yield a spectrum as shown in Fig. 3c. The general tooth form or deviations from conjugate tooth shape give rise to the integer harmonics in the spectrum; waviness or flats relate to the "ghost" harmonics; and the long term errors (runout) cause the sidebands of tooth mesh frequency. See References 1

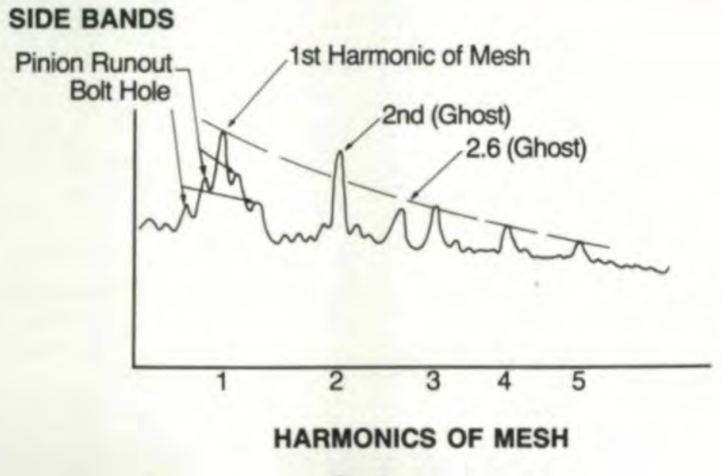


Fig. 2

AUTHOR:

MR. ROBERT E. SMITH *has over thirty years experience in the gear industry. He is currently president of R.E. Smith and Company, a consulting firm in Rochester, New York. He received his training from Rochester Institute of Technology. While employed by The Gleason Works, his engineering assignments included gear methods, manufacturing, research and gear quality. These assignments involved the use and application of instrumentation for the study of noise, vibration and structural dynamics. From these assignments, he expanded his ideas relating to gear metrology. Currently, Mr. Smith is chairman of the Measuring Methods and Practices and Master Gear Subcommittee, AGMA, and is also a member of the Rochester Industrial Engineering Society and the Society of Experimental Stress Analysis.*

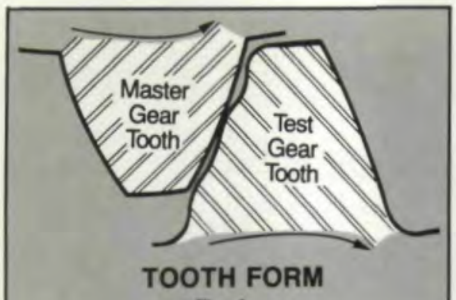


Fig. 3a

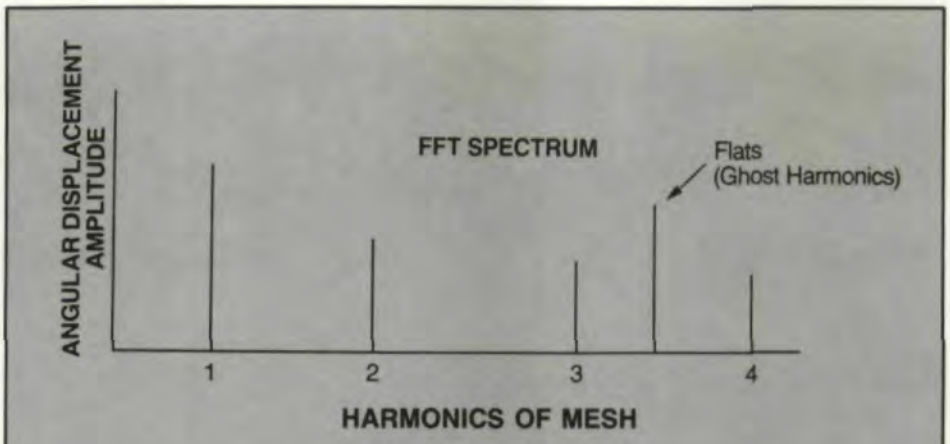


Fig. 3c

and 3 for further discussion of this subject.

The Missing Link

After the gears have been measured by single flank composite testing and all of the possible excitation sources have been identified, it is necessary to put the gears in the final application and measure the results. This is where the "missing link" usually is obvious. The missing link is "frequency discrimination". (See Fig. 4.) Many facilities at this point only use subjective rating techniques. A human rater judges the level of "gear" noise on a scale of one to ten. Ten is inaudible; five is borderline acceptable, and four is reject. Unfortunately, the rater may be rating on first harmonic of mesh in one test and second harmonic or a ghost harmonic in another test. He or she may even by listening to noise as excited by bearings rather than gears, even though the noise sounds like the gears.

The problem is that the vehicle is generating noise at many frequencies due to road and tire conditions, wind, engine, transmission components, final drive gears, etc. This masking noise or ambient noise level (Fig. 5) is several dB higher than the gear noise the human ear is sorting out and finding objectionable.[2]

Fig. 4

Even if instrumentation is used to evaluate the vehicle test, the displays or hard copy of data may show many peaks or frequencies unrelated to what the subjective rater is hearing. The challenge is to be able to sort out the important frequencies and relate visual data to aural observations.

Types of Vehicle Sound Testing

Two basic types of vehicle noise testing will be discussed here. Type I, frequency discrimination, involves identifying the problem – the "missing link" referred to above. Type II involves comparing the relative noise levels of various gear boxes as traditionally done with tracking filters.

Type I Noise Testing.

This is the most important "first step" to vehicle noise testing. As mentioned above, frequency is the key to understanding gear noise. The purpose of Type I noise testing is to properly use frequency discrimination to relate what the human ear is hearing to what the eye sees in graphic data related to gear transmis-

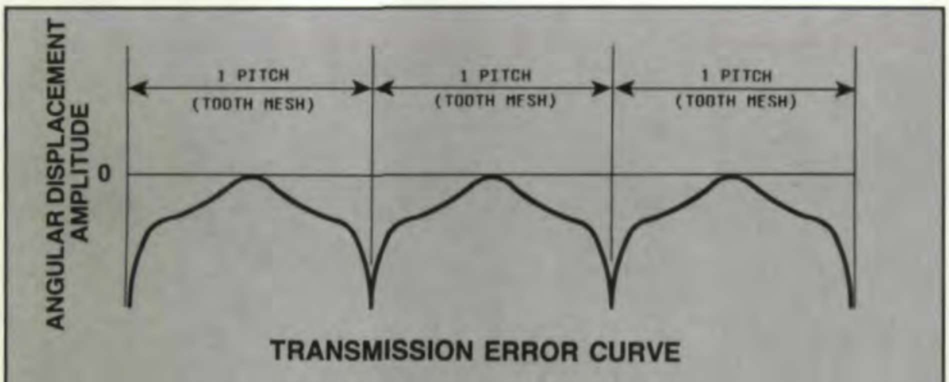


Fig. 3b

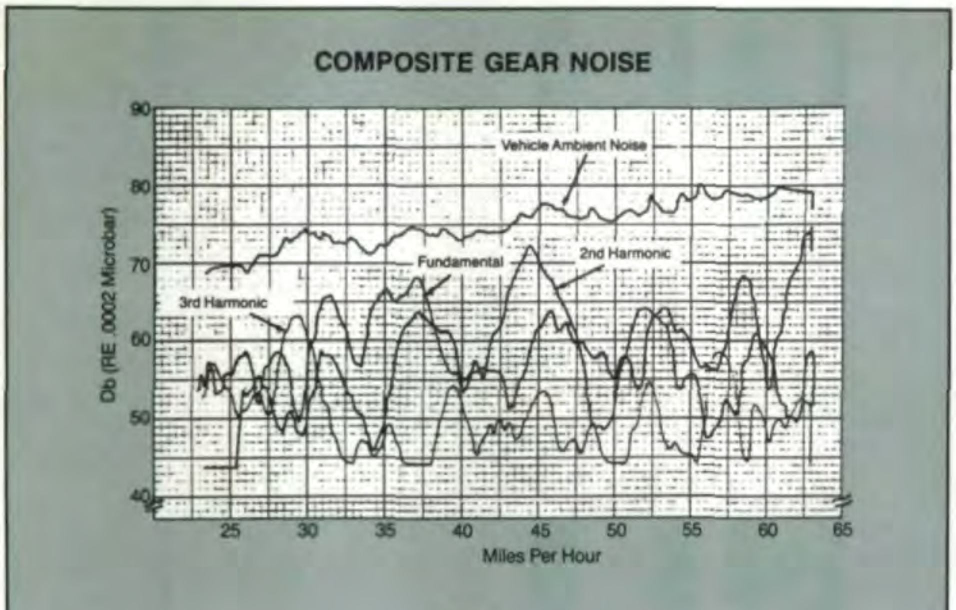


Fig. 5

sion errors. The necessary test equipment is pictured in Fig. 6.

Test Equipment:

1. Real time spectrum analyzer (RTA) with bubble memory.
2. Sound pressure level meter.
3. 12 VDC to 110 VAC Inverter compatible with microprocessor equipment.
4. Tachometer pulse generator and readout attached to drive shaft. (optional)
5. Tape recorder. (optional)
6. Digital plotter for hard copy of RTA data. (optional)

Test Procedure:

1. Calculate and plot ahead of time the drive shaft RPM vs. gear mesh frequencies at all vehicle speeds. This information can be used, along with the tachometer readout in the vehicle to identify mesh frequencies at any time during the test. (See Fig. 7a.)
2. Install the equipment listed above, except for the digital plotter, in the vehicle under test. Be sure to choose a gear box that is a definite reject or noisy example. It may be necessary to run several tests to find the optimum location for the microphone.
3. Make a test drive with the vehicle piloted by a qualified subjective rater and an instrument technician to operate the RTA and adjust it to optimize the display to relate to the subjective rater.
4. Set the analyzer to operate in Mode I to detect the peak noise frequencies at different vehicle speeds or Mode II to detect the resonant frequencies of the structure.
5. Mode I setup—Peak noise frequencies

Sound Pressure Level Meter	A Weighted
RTA Frequency Range	0 to 2000 Hz (1)
Voltage Scale Y Axis (log)	0 to 10 volts RMS
Input	A Weighted (2)
RMS exponential averaging	(3 or 4 averages)

Cursor identifying "peak" amplitude

NOTES:

(a) Frequency range will vary according to application.

(b) This results in an unconventional "double A" weighting. This is in order to enhance data in relation to what the ear is hearing and could be done by the use of other high and low pass filters.

6. Operate the vehicle at a speed and condition that allows the driver to hear gear noise. Then change vehicle speed and load conditions up and down through this noise period. The noise should change in amplitude or come and go. While the driver is doing this, the instrumentation operator can observe which peak in the frequency spectrum is varying in relation to what the driver is hearing. The cursor on the screen will indicate the frequency of interest. The frequency and RPM should be written in a test log. Tape recordings can be made, and the data on the RTA screen can be stored in bubble memory for plotting at a later time. The vehicle can then be driven at any other speed of interest and the test procedure repeated.
7. If desired, run the test in a slightly different manner. The vehicle can be accelerated or decelerated throughout a broad speed range. The RTA screen is observed throughout the test. The cursor will automatically shift to the highest noise level at any given speed. The frequency of the cursor location would be noted on the "fly" and may peak at one, two or several frequencies throughout the speed range.
8. Mode II setup – Structural resonances

   The setup for Mode II operation is the same as for Mode I, except for the cursor operation. The cursor should now be set for "peak hold" mode. The test would be run as described in Step 7. At the end of an acceleration or deceleration run, the display is held (pause) and stored in bubble memory or analyzed for peak frequencies. The

Fig. 6

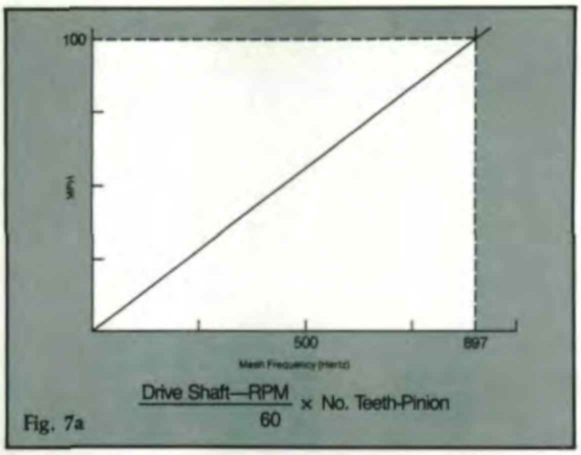


Fig. 7a

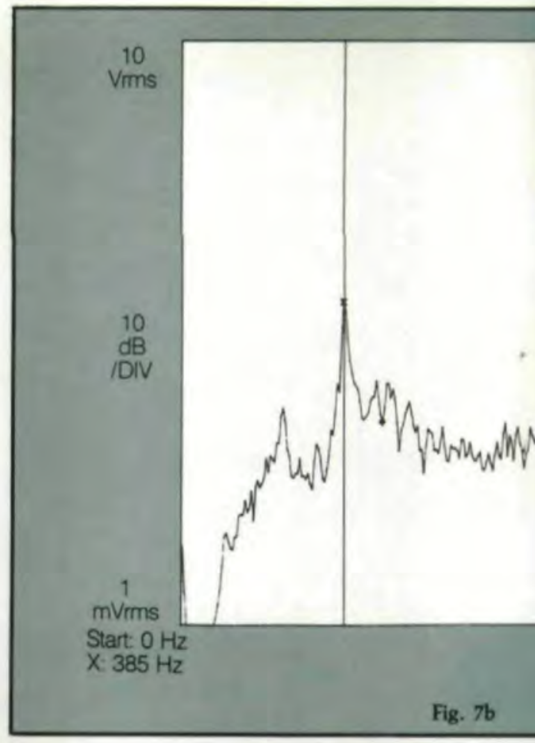


Fig. 7b

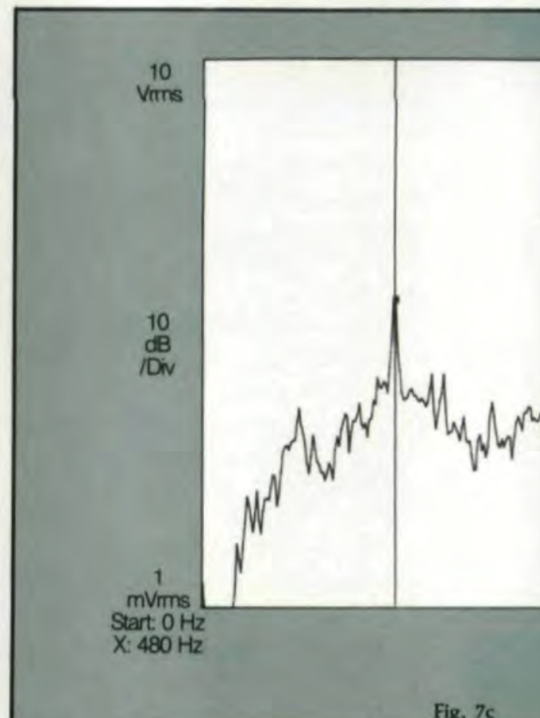
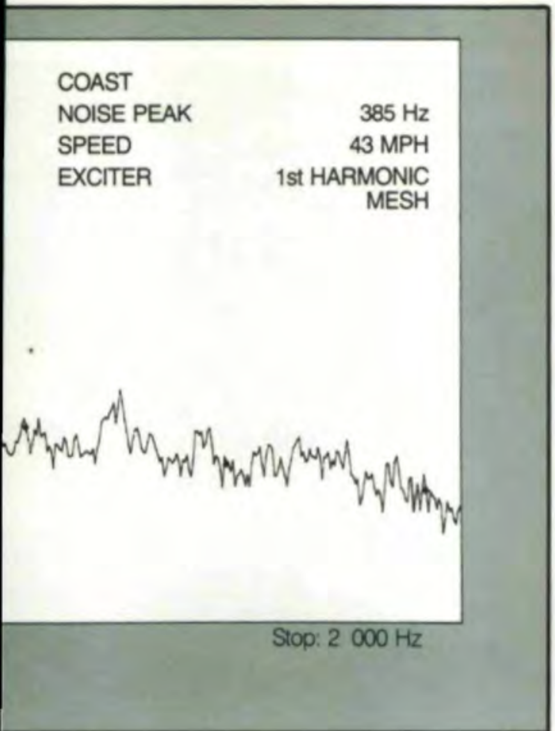


Fig. 7c

peaks in this display represent the structural resonant frequencies. These frequencies could be excited at any vehicle speed by the appropriate mesh frequency or harmonics that happen to coincide.

9. Compare the frequencies of gear mesh and the harmonics and sidebands determined from this test with the gear mesh and harmonic data generated in the single flank transmission error tests of the same gear sets. In



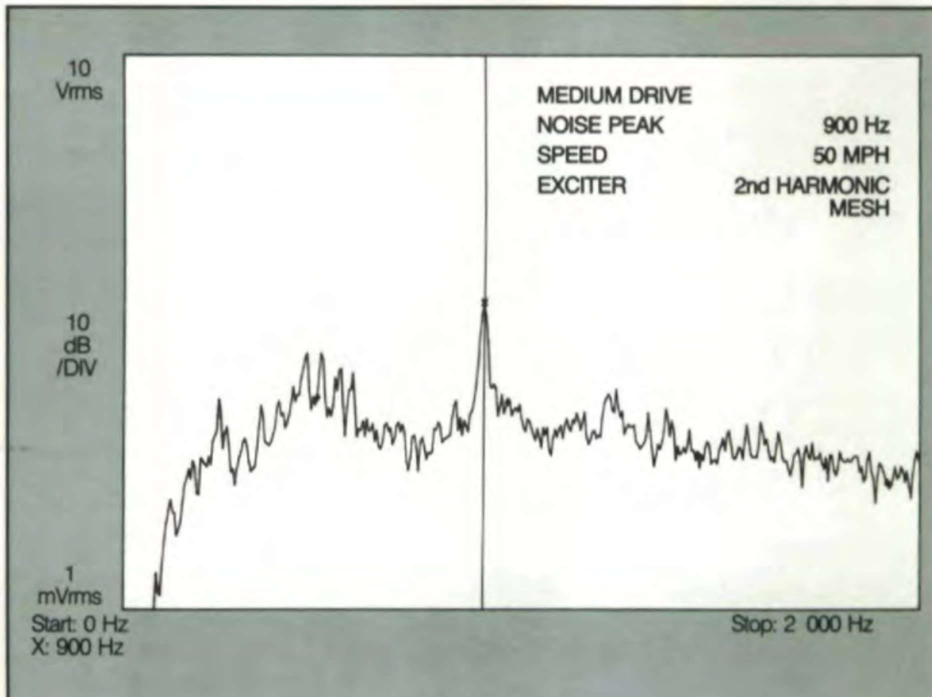
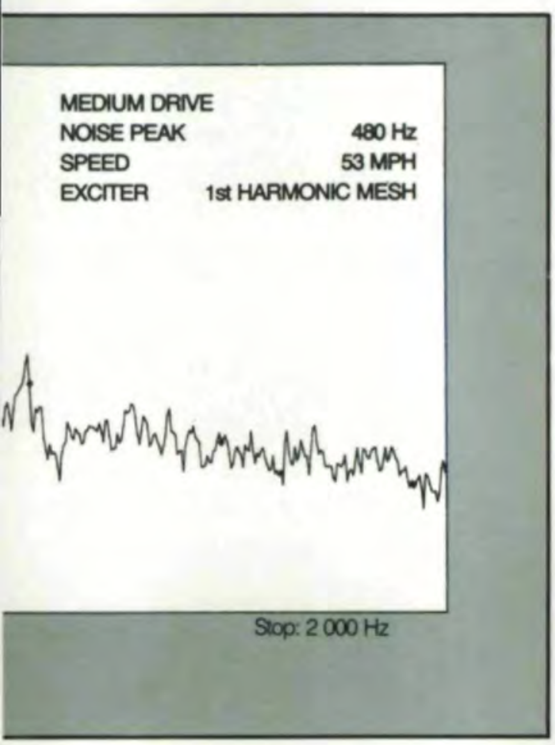


Fig. 7d



this way, characteristics of the gear tooth geometry can be related to the causes of gear noise in the vehicle. (See Figs. 7b, 7c, 7d.)

Type II Noise Testing.

Comparing the relative level of noise from one gear box to another has been done for many years by a method as described in Reference 2. This involves the use of tracking filters. These are narrow band pass filters of 5 or 10 Hz bandwidth that are tuned by pulses from a tach generator on the drive shaft, such that the center frequency is always at mesh frequency or some harmonic of it. As the vehicle varies speed, the filter is always tuned to a particular order of rotation of the drive shaft. A plot of the output of the filter will show any peak noises associated with the gear mesh at that particular order of rotation. The vehicle can be driven at various rates of acceleration and deceleration and a complete history recorded for analysis. The results are quite accurate and repeatable, so it is useful for the comparison of two or several gear boxes. Fig. 8 shows the

Vehicle Recording Unit

FLEXA-TROL™

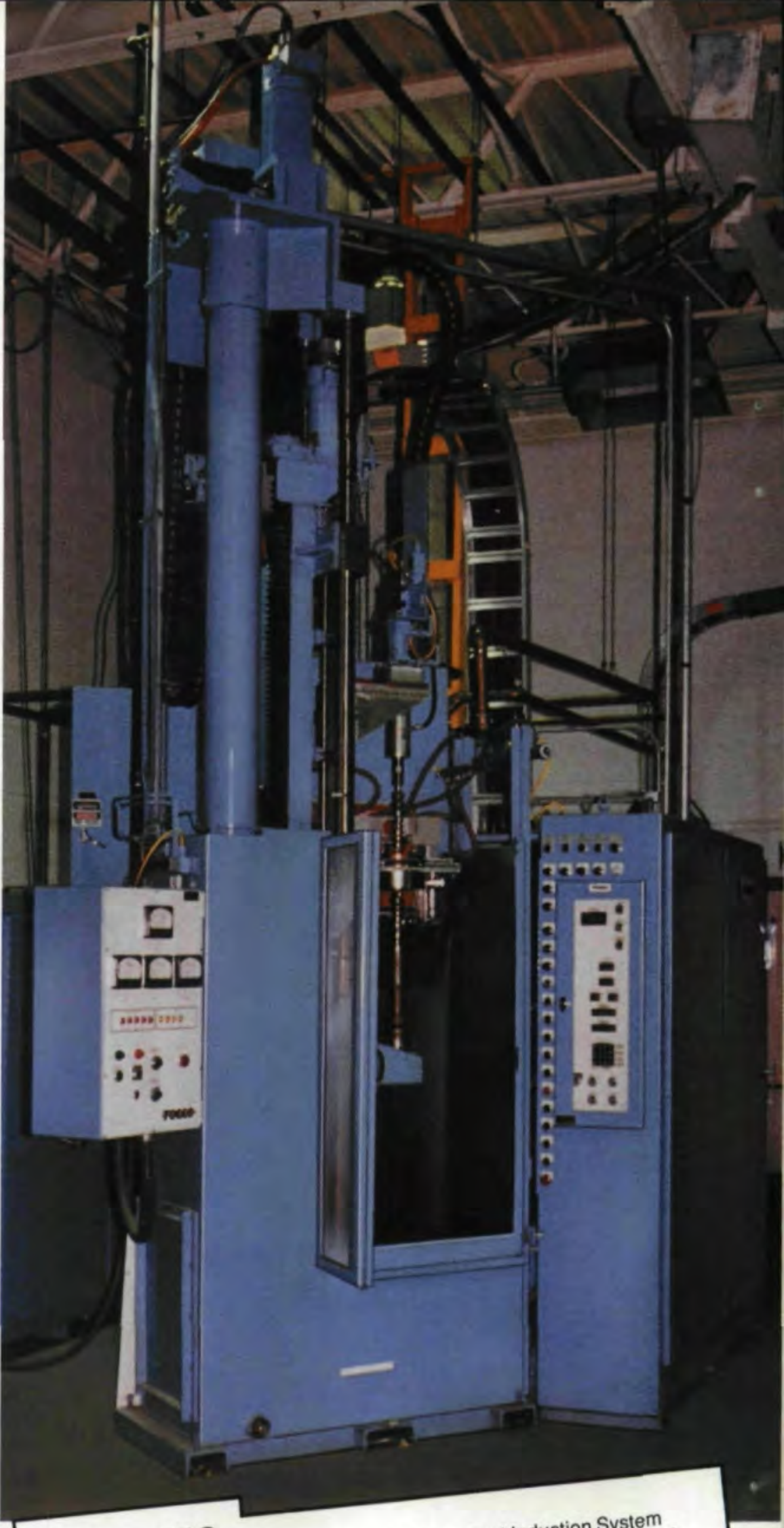
High Intensity, Multi-Frequency Scanners

REDUCE HEAT TREATING COSTS up to 40%

A recent TOCCO development, High Intensity Induction Hardening (HIIH)™, reduces heat treating costs substantially, in a variety of applications. HIIH has been used successfully with applications on automotive and off-highway engine and drive train components, as well as specialized gear applications. The HIIH scanning process, with present technology, can be adapted to parts up to 15″ diameter and lengths to 120″.

Parts that previously were flame hardened in a batch process, can now be induction hardened, in-line, with greater flexibility, more precision, individual quality monitoring, and at lower cost.

High Intensity Induction Hardening is indeed, a process of "The Future".



HIGH INTENSITY HARDENING PATTERNS

Cross section of camshaft lobe demonstrates uniformity of hardening. Multi-frequency, high intensity hardening of gears produces a high hardness characteristic for improved surface contact fatigue life. High residual compressive stress in the root area is also achieved for improved tooth strength.

NEW. . . TDS

TOCCO System Diagnostics are offered to document Induction System performance during dynamic, fault or standby conditions. This advanced TDS monitors digital and analog signals while recording, printing or modem transferring data to designated locations for system performance evaluation or trouble-shooting. Ask your TOCCO sales engineer for further details.

For the latest state-of-the-art heat treating technology, contact your TOCCO representative, or call: TOCCO, Inc., 30100 Stephenson Highway, Madison Hts., MI, 48071. Phone: 313-399-8601 or 1-800-468-4932 (outside Michigan).

TOCCO®

A unit of Park Ohio Industries, Inc.

CIRCLE A-12 ON READER REPLY CARD

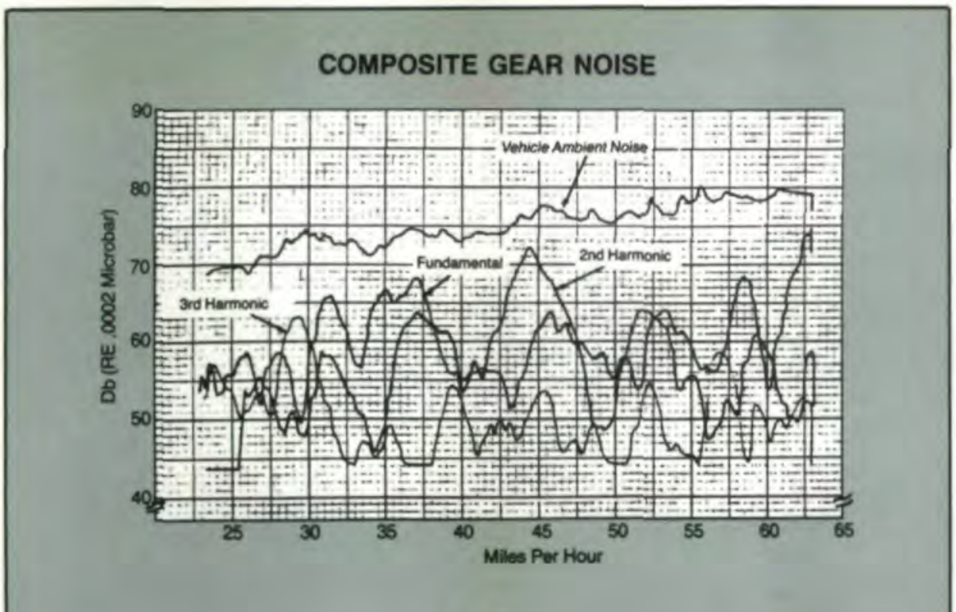


Fig. 8

test setup and results from such a system. There is a trend today to try to do this kind of analysis with digital Fast Fourier Transform (FFT) techniques, rather than with analog tracking filters. However, it is questionable whether the digital techniques are fast enough to detect the peak noise periods with sufficient accuracy when the vehicle is constantly changing speed. The FFT techniques are acceptable in Type I testing because only the frequency, not the relative amplitudes, is of interest. In Type II testing, one is trying to catch the absolute maximum amplitude for each set of gears being tested. There are times when the noise is heard only as the vehicle is changing speed or load conditions.

Case History

NOTE: Because permission was given by a European auto maker to use actual test results for this article, it was decided to present the data in metric units, kilometers per hour (KPH), rather than convert to MPH.[4]

During the process of installing a single flank transmission error tester at an automotive plant, a study was run to correlate transmission error with vehicle gear noise. Single flank data was analyzed by FFT techniques to quantify excitation related to first, second and other harmonics of mesh for several gear sets. The same gear sets were built in a test vehicle and rated subjectively for noise level during road tests. The vehicle was also instrumented and noise tested on a dynomometer test stand using FFT analytical techniques.

The data from the single flank test, subjective road test and instrumented dynomometer test was then compared for correlation. The results did not look good for several reasons.

In a subjective test, the driver rates noise heard at any speed on a scale from one to ten. He or she may rate one gear set for noise heard at 80 KPH caused by second harmonic of mesh and another set for noise heard at 160 KPH caused by first harmonic of mesh. The noise sounds the same, and the rater does not realize the excitation is coming from different sources. In fact, at some other speed a similar noise was being caused by excitation from bearings used to mount the pinion.

In the instrumented dynomometer test, FFT analyses were run at given fixed speeds. These resulted in spectral data showing peaks at many frequencies. The problem is to determine the one to which the driver is responding. When looking at first harmonic data from single flank and dynomometer tests vs. subjective ratings, the correlation was poor. The same was true when comparing only the second harmonic data. The assumption was that all gear noise was coming from the same source of excitation.

Gear Sound Analysis Console

A new test was then started by using the techniques described above for Type I Noise Testing. It was not feasible to run the RTA in the vehicle at that time, so a decision was made to tape record the road test data and analyze it later in the laboratory. This was done for several road tests with different gear sets. Subsequent analysis showed that the noise heard at 80 KPH was excited by second harmonic of mesh, at 160 KPH by first harmonic of mesh, and at 40 KPH at fourth harmonic of mesh. In all cases the frequency of noise was approximately 930 Hz. Now when the single flank data of first harmonic transmission error was compared to subjective ratings at 160 KPH, and the single flank second harmonic was compared to subjective ratings at 80 KPH independently a good correlation was shown.

(continued on page 47)

CLASSIFIED

Rates: Classified Display—per inch (minimum 3") **1X**-$120, **3X**-$110, **6X**-$100. Type will be set to advertiser's layout or *Gear Technology* will set type at no extra charge. **Word Count:** 35 characters per line, 7 lines per inch.

Payment: Full payment must accompany classified ads. Mail copy to *Gear Technology*, P.O. Box 1426, Elk Grove Village, IL 60007. **Agency Commission:** No agency commision on classifieds.

Materials Deadline: Ads must be received by the 25th of the month, two months prior to publication. **Acceptance:** Publisher reserves the right to accept or reject classified advertisements at his discretion.

COMPUTER AIDS

HELP WANTED

BUSINESS OPPORTUNITIES

RELATIONSHIP OF MEASURED GEAR NOISE . . .

(continued from page 45)

With this knowledge, another program was started with a greater number of axles and yielded excellent results, even when comparing single flank transmission errors against subjective car ratings. (See Fig. 9.) From this data it was possible to establish an acceptable range of single flank transmission errors for first and second harmonics of mesh.

Conclusion

Many different types of instrumentation are available for the sound testing of gear noise. However, the procedure used with the instruments is the key to successful application. Relating the frequency of the noise aurally and visually in the data is the most important step in the analysis.

It is possible to apply the above techniques and sort out the facts from mystery. Once this is done, a correlation between noise and transmission error can be established and limits can set on the process for quality control.

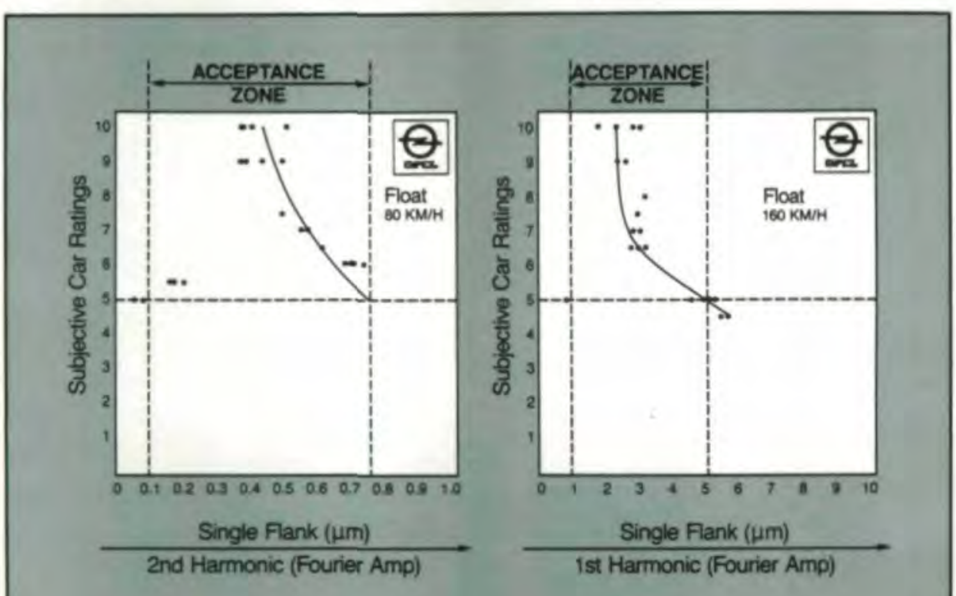


Fig. 9

References:

1. SMITH, R.E. "Identification of Gear Noise With Single Flank Composite Measurement," AGMA Fall Technical Meeting, San Francisco, CA, October 14-16, 1985.
2. PITTS, L.S. "Bevel and Hypoid Gear Noise Reduction," SAE Paper No. 720734.
3. SMITH, R.E. "What Single Flank Measurement Can Do For You," AGMA Fall Technical Meeting, Washington, D.C., October 15-17, 1984.
4. VONDERSCHMIDT. Data from testing done at Adam Opel AG., Ruesselsheim, West Germany.

Acknowledgement: *The author wishes to thank Adam Opel AG., Ruesselsheim, West Germany, and Dr. Vonderschmidt for the use of their test data.*