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TRANSMISSION NOISE TESTING ON MECHANICAL SYSTEMS

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Abstract: Transmission noise remains a serious cause for concern in the automotive industry. End of line noise testing of gearboxes and axles is carried out by some manufacturers. The success of this exercise is critically dependent on whether the results of the end of line tester correlate with measurements and subjective assessments in the vehicle. Achievement of good correlations is a very difficult task and many techniques have been proposed, with varying degrees of success. This paper will review some of these techniques and demonstrate how success can be achieved.

1. INTRODUCTION

Transmission noise is a continuing problem for most manufacturers of gearboxes and axles. Manufacturing engineers are inclined to think that if enough money is spent on the latest gear manufacturing technology the problem will disappear. Unfortunately this is not true. There are many cases on record where a so called “better” gear turns out to be noisier than the old one. It is therefore necessary to test gearboxes and axles for noise when they come off the production line.

It is relatively simple to devise a noise measurement system for the end of the line but it will not necessarily produce a useful result. Many abandoned systems around the industry are clear evidence of the practical difficulties. The transmissions are unlikely to be silent but the noise emitted will be of a level that is acceptable to their vehicle assembly plant customers.

2. TRANSMISSION NOISE TESTING SYSTEMS

Over the years there have been many attempts at producing worthwhile noise testing systems for transmissions. Most have been unsuccessful. One of the few successful systems is Plato (and a predecessor called Caarm). Plato was used to generate the results used in this paper.

The main features are:

a) Arrays of microphones from which spatially averaged noise results are obtained.
b) Tests during acceleration and deceleration over the speed range and torque range in which noise complaints occur.
c) Order locked analysis.
d) Automated extraction and digestion of results to give simple Final answers on a scale of 1 to 10.
e) Same measurement and analysis techniques used for end-of-line testing development test rigs and in-vehicle measurements, thus allowing good correlations between end-of-line and in vehicle results to be achieved.
f) Automatic operation for end-of-line testing.

3. DIFFICULTIES IN DEFINING AN ACCEPTABLE NOISE LEVEL

The definition of an acceptable level is not an easy task. An acceptable level of noise can only be judged subjectively. The subjective result must be translated to an objective value or values to allow a test of acceptability to be defined.

Transmission noise heard in a car is the consequence of the interaction of many mechanical/acoustic systems. Transmission noise heard on a test rig is a consequence of the interaction of another set of mechanical systems; hence transmission noise measured on a test rig is not the same as transmission noise measured in a car. It is therefore necessary to produce a convincing justification for accepting test rig measurements as a reliable indicator of the acceptability of a transmission.

A clear illustration of the problem is given by Figures 1 and 2. Figure I show a test rig measurement of the noise of a transmission. It shows the order tracks of tooth mesh frequency noise of the final drive and speed gear noise of a transaxle transmission. (Order tracks are plots of noise level at a specific order versus speed). The noise level of the speed gear is high relative to the final drive. Figure 2 shows the order tracks for the same transmission measured in a car. There is a very little similarity between these results. Both results are the spatially averaged noise from arrays of five microphones. The final drive noise in a front wheel drive transaxle is often the greatest source of transmission noise.

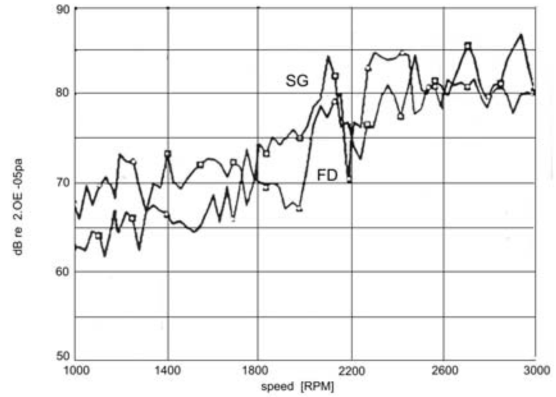


Figure 1- Test Rig Measurement of a Transaxle Noise in Fourth Gear Speed gear (SG) is order 32, Final drive (FD) gear is order 13

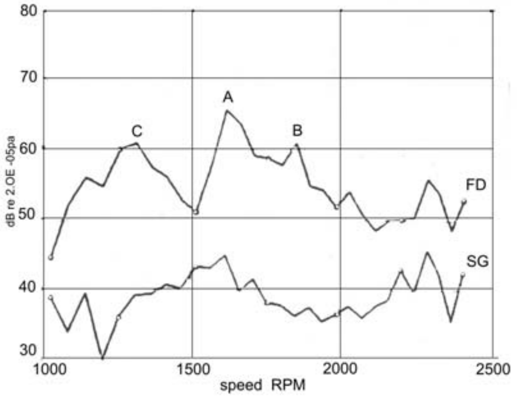


Figure2- In-car Measurement of Noise of Transmission in Fourth Gear Speed gear noise is (SG), Final drive noise is (FD)

On the test rig the casing radiated noise is the main contributor. In a vehicle there is a combination of casing radiated noise and structure borne noise. The airborne noise is attenuated by the body shell and the structure borne noise is modified by its passage through the transmission mountings and the body.

It has been shown that the radiation of airborne noise from a power train is a complex interactive process. Transmission noise radiates from the gearbox casing and from the engine. From this it can be inferred that on a test rig it should be desirable to attach the gearbox to a structure that mimics the structural impedance of an engine. If this is not done it would appear that the gearbox will not radiate casing noise in the same way as it does in a vehicle. Unfortunately engine impedance is very difficult co mimic on a production line test rig, because a fundamental requirement is the ability lo load and unload a gearbox very quickly. Does it matter?

The main objective of any production line test system is lo be able to rank order gearbox noises correctly. To do this successfully it is necessary to test then while accelerating and decelerating at a known level of torque. The speed range should encompass that over which customer complaints occur. For car gearboxes the torque required is low, because that is the condition under which most complaints occur. For heavy commercial transmissions it is necessary to test, under high torque levels.

Experience shows that for end-of-line testing it is not necessary for the rig structure to mimic the impedance of the engine. The relevant differences between individual examples of nominally the same gearbox can be distinguished, although the detail of the noise spectra may not be the same as when tested against an engine.

The Plato software that generated the results in this paper takes account of the fact that there may be small changes in the structural resonant frequencies of the gearbox/test rig assembly due to gearbox casing variations. The main variable is the tooth meshing forces.

An end-of-line test rig may not be a good tool for development testing, though, if it does not represent the engine impedance. To make noise reductions by design changes to the gearbox structure it is desirable to represent bell housing effects correctly. Figure2. 3 and 4 demonstrate how important resonant amplification is when measuring in a car. These figures show the same gearbox noise combination tested in three gears in a car. The figures show order tracks of final drive tooth mesh noise. Many resonances influence the final drive noise in each gear, but it can be shown that the same resonances affect the noise in each gear.

In third gear (Figure 3) final drive noise appears to increase with speed. In fourth gear it peaks at 1610 revolutions per minute (rpm). In fifth gear the noise peaks at 1200 rpm and above 1400 rpm becomes relatively insignificant, compared with the peaks at lower speeds. Comparison of these three graphs shows that the main resonant peaks marked A.B and C occur at frequencies of 315, 390 and 445 Hz in all gears. These frequencies can be calculated from the speeds at which the peaks occur and the orders of the final drive and speed gear noise components.

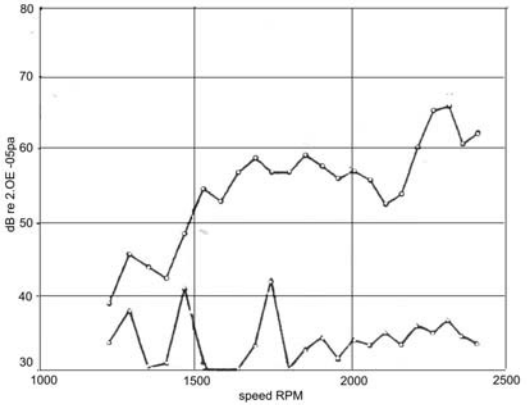


Figure3- In-car Measurement in Third Gear

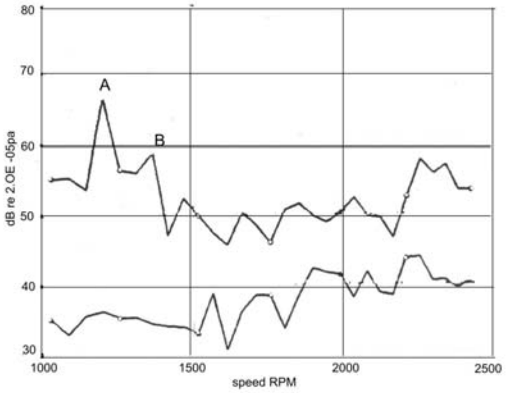


Figure4- In-car Noise in Fifth Gear

An alternative presentation of the data from the Plato software allows the frequencies to be read off directly using cursors to define the data points of interest. In the car the speed gear noise and first harmonic of final drive order are insignificant by comparison with the fundamental final drive noise, whereas on the test stand the first harmonic is relatively much higher. This suggests that resonance A in the car may involve vibration transmission paths between the gearbox and the car which provide vibration isolation at frequencies above resonances. At speeds where the first harmonic forcing function is significant the isolating effect of the resonant systems comes into effect and suppresses the higher frequency noise heard in the car.

4. TEST RIG INFLUENCES

Comparing fourth gear noise results in the car (Figure 2) with those on the test rig (Figure 1) shows that speed gear noise is relatively higher on the test rig than it is in the car, for reasons discussed above. This does not prevent a valid comparison between transmissions lo rank order their noise levels. However, one feature of the test rig results that could cause problems is not apparent on Figure I. It only becomes apparent when a large number of results are overlaid as in Figure 5. The potential problem area is around 1600 rpm where all transmissions show a large increase in a noise over a narrow speed range. This is not the normal behavior of transmissions on a good test rig. It is likely that this peak results from a lightly damped resonance of* the test rig, excited by vibration generated in the transmission. Where possible, features like this should be eliminated, but if that is not possible, the software will still learn the behavior of good and bad transmissions in response to this feature and in most cases will still be able to correctly rank order the transmission for noise.

A constant frequency noise in the vicinity of the test rig can also produce interference on the order tracks. This is usually easy to pick out on a waterfall plot of the order spectra. If the interfering noise is very loud it will prevent the transmission noise being assessed at that frequency but will not prevent the software from effectively rank ordering the transmission noise at other frequencies, If the noise is loud and varying in amplitude while remaining constant in frequency the only solution is to reduce the noise to a level well below the transmission noise, or lo avoid testing at speeds where interference occurs.

Some test rigs produce order locked noise themselves. This does not give any problems when an order locked analysis system is used, provided the rig noise does not occur at the same order as the transmission noise. Some of the results quoted in this paper were measured on a test rig which had an order locked noise problem. The rig generated noise was so close to the Final drive noise that the rig operators had never been able to do a subjective test of final drive noise, which was a severe problem because final drive noise was the worst component in a car. The separation between rig noise and final drive noise was only 1.5 orders and the separation between the First harmonic of rig noise and speed noise in fourth gear was only two orders. Despite this the order locked analysis software had no difficulty in distinguishing gearbox noise from rig noise, with an order resolution of 0.25 orders.

5. TECHNIQUES FOR ALLOWING FOR THE DIFFERENCES BETWEEN IN.CAR AND TEST RIG NOISE

Many techniques have been proposed to allow for the differences between lest rig and in car results when assessing the test rig results.

Examples are:

a) To apply an acoustic transfer function to the test rig results. This is derived by measuring the noise of a gearbox on the test rig. then testing the same gearbox in a car and measuring its noise.

b) To apply a vibration on rig to noise in car transfer function derived using a similar method.

Method (a) has many practical difficulties. A major difficulty is where around the rig you measure the noise and where in the car do you measure the noise. Any system that uses single microphone results in these situations will introduce a high level of uncertainty into the rig to car transfer function. This is because of the variability of the gear mesh noise from position lo position around the gearbox and from position lo position within the car. The variability with microphone position on the test rig is caused by several effects:

- The directivity of noise emission from a gearbox varies with frequency and hence speeds.
- The interference effects of the reflected noise from the test rig and the direct noise from the gearbox varies with frequency and microphone position.
- The interference effects of the reflected noise from the test rig and the direct noise from the gearbox varies with frequency and microphone position.
- The effects of sound reflections within the test room or lest area vary with frequency and microphone position.
- The sound level at tooth mesh frequency measured at any position in an enclosed space varies with air temperature, even if the vibration level of the surface of the source remains constant.

The above effects are not trivial. Figure 6 shows an example of the range of variation of sound level at tooth mesh frequency over five microphone positions. All the microphones were at the same distance from the gearbox and all measured simultaneously. The difference between positions is as high as 20 dB. The air temperature effects are also significant if the air temperature changes more than about 3°C.

An additional temperature effect is the temperature of the gearbox. Most transmission noise complaints in cars occur when the transmission has warmed up, with an oil temperature usually in the range 70 to 100°C.

The noise of some transmissions changes considerably as the temperature rises, but on an end-of-line test is it impossible to allow time for the transmission to warm up. Filling with hoi oil does not solve the problem because it is likely to introduce a different temperature distribution through the gearbox components from that achieved by more gradual warming when driving.

Another problem in deriving an acoustic transfer function between car and test rig is the variability between different examples of the same car. Up to 12 dB difference has been found at tooth mesh frequencies between vehicles, all Fitted with the same transmission. The vehicles were all of apparently the same build specification. When the comparison is increased, in scope to include different variants of the same basic vehicle type the differences can become even greater. Over the speed ranges in which the transmission is subjectively noisy it can be seen that different variants exhibit different resonances that amplify the transmission noise. These vehicle influences are the problems of the vehicle plant rather than the transmission plant. The transmission plant has achieved its objective if it can demonstrate that all its transmissions are quieter than an agreed limit of acceptability. The limit of acceptability must take into account the differences between vehicles.

The derivation of a representative or realistic acoustic transfer function that can be applied to test rig results to allow for the car is therefore very difficult, if not impossible.

Measurement systems that attempt to use gearbox vibration as an indicator of gearbox noise emission appear to have even greater problems. Systems of this type usually attempt to deduce gearbox noise emission from one or two accelerometer positions. It could be argued that structure borne noise transmission through the gearbox mountings is a major contribution to noise inside a vehicle. Therefore, it is argued, one or more accelerometers at these positions should give a good representation of the noise transmitted to a vehicle. However, it is argued, one or more accelerometers at these positions should give a good representation of the noise transmitted to a vehicle. However, the force applied to the vehicle through the mounting is not unidirectional. It is a force vector which is liable to vary in amplitude and direction as the speed changes. A simple accelerometer cannot repress it the vector adequately. Triaxial accelerometers would be better but would introduce considerable complication in their mounting and computing the results. In addition it would be impossible to account for the forces transmitted into the engine via bell housing.

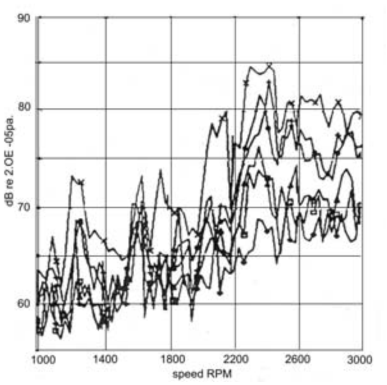
Even if it were possible to derive a representative acoustic transfer function between the test rig and in vehicle the transfer function is likely to be highly variable with speed and gear mesh frequency. Applying this transfer function to the noise measured on the test rig will produce a complex result, which still has to be interpreted to decide whether a gearbox is acceptable. For production inc use some form of automated interpretation would be necessary.

An alternative strategy is required. That strategy must include some way of comparing the objective measured results with the subjective rating schemes used by human testers. Experienced testers rate gearbox noise within a discrimination of half a grade, but they cannot convey what this means in decibels. To complicate matters the grade is usually derived from the testers subjective impression over a range of speeds. Experienced observers can usually discriminate between Final drive noise and speed gear noise, but there are occasions when 'audio confusion' can occur, due to the frequencies of two simultaneously meshing gear pairs being close together. It then becomes impossible for a human to diagnose which gear is noisy. An order locked analysis system does not suffer from “audio confusion”.

A strategy that has been used successfully in a number of evaluations over the past eight years is the targeting and grading system incorporated in the Plato transmission noise measurement system.

Derivation of targets is an integral part of setting up a Plato system for end-of-line testing. Targets are the boundaries between acceptable and unacceptable results based on order tracks. Targets are generated for each of the gear noise orders of interest. On a typical transmission there would be a minimum of four targets per gear lever position when the gears arc loaded on the drive side and four when loaded on the overrun or coast side. These would relate to the tooth mesh orders and First harmonics of speed gear and Final drive gear. In many cases additional harmonics and side bands are also targeted. The targets will be differently shaped for each order, each selected gear, each direction of loading and each variant of a gearbox type.

The process of producing a target is First to test a collection of transmissions using the Plato system. For the moment assume that all the transmissions have been deemed to be acceptable for noise by subjective evaluation in vehicles. For each order of interest the computer overlays its collection of order tracks, conceptually as on Figure 5.



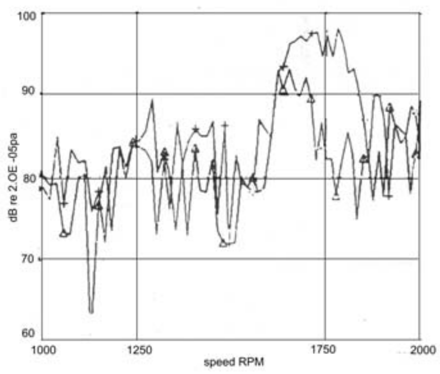


Figure5- Test Rig Results From Six Gearboxes

Figure6- Extremes of noise levels at order 50 from 5 microphones during transmission noise test

It then generates the envelope below which all the acceptable results fall. This is the target for that order. It is important that this target has a shape which is typical of the order tracks which are to be compared with it later. The process described above achieves this objective. The target will consist of 100 to 200 noise level data points covering the speed range of interest for that particular order.

Having calculated a target it is now possible to grade against this target. To do this the computer produces a series of curves parallel to the target and spaced, typically, at 1.5 to 2 dB intervals above and below the target. The zones between the curves in this array are labeled I to 10, with the target being the boundary between zones 5 and 6, say. To test an order track from another transmission against a target it is overlaid on the array of target and grade lines. The First test is to check whether the result is noisier than the target at any speed. If so it is obviously a "fail" result. The second test is to select the speed at which the result exceeds the target by the greatest amount. This point defines the grade by the zone in which the point falls. This process is repeated for each of the selected orders, giving a table of grades showing the overall result for all the aspects of transmission noise that the Plato system has been asked to evaluate. There are additional traps in the software to ensure that the grades are not dictated by stray noise peaks that could not have come from the transmission.

The grade table contains pass/fail information for the whole test and also contains diagnostics information in the case of failures.

An ideal world situation is described above. It is often not possible to obtain a collection of known good transmissions when setting up a production test stand. A workable set of targets can be set up using a randomly selected collection of transmissions, on the basis that the worst 5 or 10% of this collection are noisier than desirable and the production process should be improved to eliminate transmissions like these. The software provides tools to rank order the noise of the collection and weed out the noisiest. Target generation and grading then proceeds as usual.

An arbitrary interval between grades, such as the 2 dB used above, is possible on a production test, but not when the rig results have to correlate with in-car objective results and subjective grading. By testing a number of transmissions on the test rig and in vehicles and by correlating the range and standard deviation of grades achieved in each case, consistent grading structures can be derived for objective tests and for subjective results. This technique has been used successfully to show that transmissions can be rank ordered for noise and graded on a test rig without knowing the vehicle transfer functions. It has also been shown that transmission noise can be rank ordered on the road in the same order as on a test rig, provided the differences between individual examples of vehicles are recognized. It has also been shown that the rank ordering is the same as that attributed by human observers, provided the noise being measured is distinguishable by the human observers.

6. CONCLUSIONS

A successful end-of-line noise test system must produce simple but meaningful results. These results must allow the rank ordering of transmissions for noise and must distinguish reliably between unacceptable and acceptable transmissions, whose noise levels at the orders of interest may differ by no more than I1 to 2 dB.

Noise at tooth mesh frequency measured in cars has a different variation with speed from that measured on test rigs, but this does not prevent the test rig giving reliable indications of the relative noise levels of transmissions.

There is no point in trying to incorporate vehicle transfer functions into the test rig analysis. Different examples of the same vehicle, all tested with one transmission give variability in tooth mesh order noise that is as great as the difference between good and bad transmissions on the test rig

Order locked noise measurement on test rigs coupled with automated analysis of the results continues to give good results. It allows for successful comparison between subjective and subjective results. It has allowed millions of transmissions to be successfully noise tested at the end of the production line to noise limits spread between the transmission and vehicle assembly plants.

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