DIESEL ENGINE GEAR TRAIN NOISE

Zengxin Gao[1], Kari Saine[1], Magnus Wollström[2], Ulf Carlsson[3]

1 Wärtsilä Finland Oy
Järvikatu 2-4, P.O. Box 244
FI-65101 Vaasa
zengxin.gao@wartsila.com
kari.saine@wartsila.com

2 Lloyd's Register Group – ØDS Canada
Magnus.Wollstrom@lr-ods.com

3 Kungliga Tekniska Högskolan, Sweden
ulfc@kth.se

1 INTRODUCTION

In this investigation, the noise inside and outside of the engine cam gear cover has been studied. The engines under test are Wärtsilä 32 engines, with 320 mm cylinder bore, at nominal speed 750 rpm and idle, 25%, 50%, 75% and 100% load conditions.

A schematic picture of the gear train with indicated gear teeth numbers and real pictures of gears on both gas and diesel engines are shown in Figure 1:

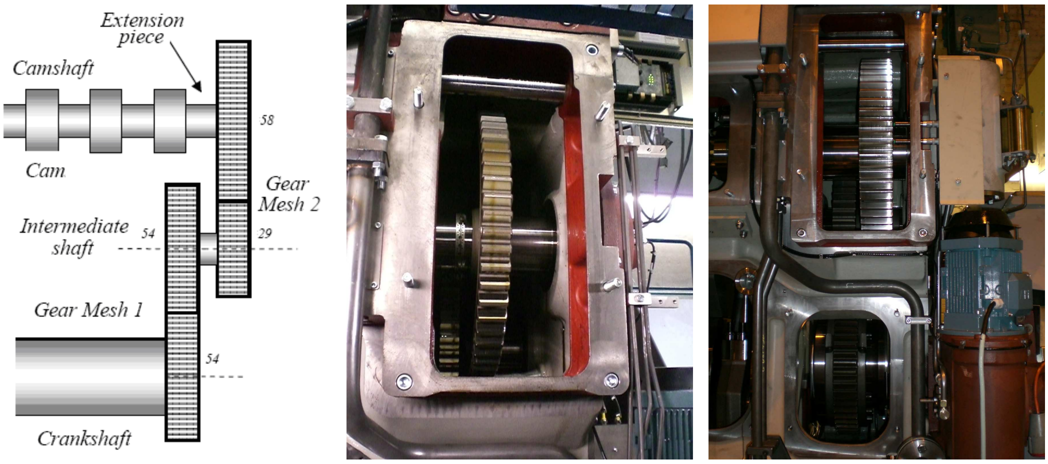

Figure 1 Left, schematic picture of the gear train system; Middle, gas engine cam gear; Right, diesel engine gear train.

2 MAIN CAUSES OF GEAR NOISE

A. *Caused by the bearing misalignment, position errors, machining or process errors of gear shape and tooth shape, worn tooth, temperature variation, etc.;*

B. *Transmission Error caused by stiffness variation resulting in dynamic mesh forces;*

The vibration excitation and resulting noise generated by an involute gearing, with proper lubrication to minimize friction, is minimal but not zero. Vibrations will always occur since the teeth and bodies of real gears are elastic, thus the loaded gear teeth are no longer involute because of deformation when the gears are transmitting torque. Therefore stiffness variation is generated which will lead to transmission error causing dynamic mesh forces. Besides, load variation caused by the change of the number of meshing teeth will also result in stiffness variation, Figure 2 Left.

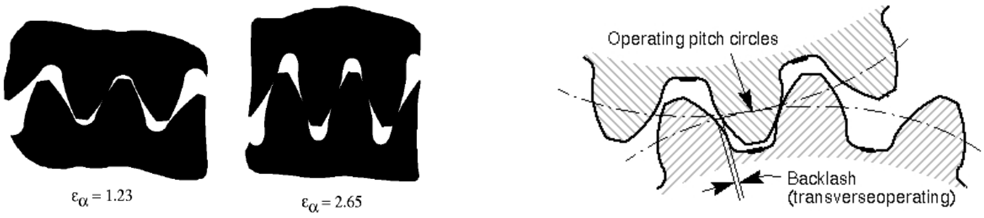

Figure 2 Left, Gears with different numbers of teeth in contact, ε_α is the transverse contact ratio [1]; Right, Gear teeth backlash [2].

C. *Caused by impact of the rattling gear teeth generating rattling noise;*

The gear rattling is also called the gear hammering or impact. The reason why running gear can impact each other on teeth is because of the existing of backlash which can be defined as a rotational arc clearance formed between a pair of mounted gears, Figure 2 Right.

The rattling noise mostly generated by the speed or load fluctuation on shafts. It is predicted beforehand that the Wärtsilä engine gear train noise is mainly caused by gear impact since the fuel injection force applied on the camshaft will generate a large shaft torque variation.

3 THE MECHANICAL FUEL INJECTION

The measured engines in this paper are all equipped with mechanical fuel injection system. For mechanical injectors, the increased injection pressure can lead to significant increase of the camshaft torque variation, Figure 3.

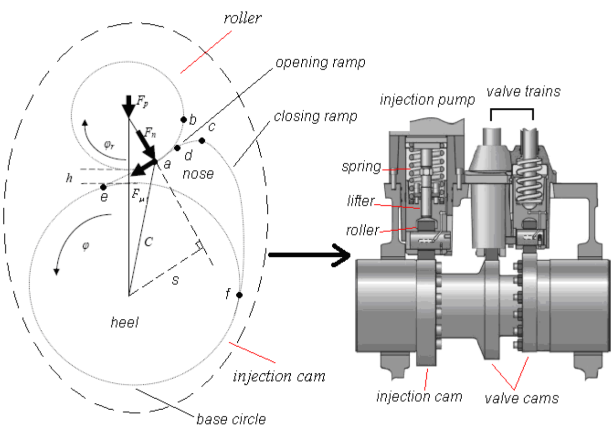

Figure 3 Camshaft piece with part of the driven injection pump and the valve trains [3], the contact profile between the injection cam and the roller being magnified on the left.

As shown in the Figure 3, when the roller runs on the opening ramp, the force F_n will generate a positive torque on the camshaft as a load that intends to block the camshaft rotation, and when the roller is on the closing ramp, the injection pump then gives the camshaft a negative torque that actually helps drive the camshaft rotation. Thus, during one period of fuel injection, the torque applied on the camshaft from the injection pumping varies between positive and negative periodically.

4 MECHANISMS OF ENGINE GEAR TRAIN HAMMERING NOISE

Because of the camshaft torque variation and the existing of gear backlash, gear hammering happens. At first, the angular speeds of the two gears are ideally the same and the gear teeth are in mesh with each other, Figure 4 Left-A. When one injection process is over, the torque on the camshaft will turn to negative. Then the angular speed of the cam gear will be faster than the driving gear and teeth separation starts, Figure 4 Left-B. During this period the cam gear teeth will pass through the backlash and collide with the non-working side of the driving gear teeth, Figure 4 Left-C. When the next injection comes, the cam gear rotation is decelerated, which means the cam gear will pass through the backlash, Figure 4 Left-D, and impact with the working side of the driving gear teeth again, Figure 4 Left-E.

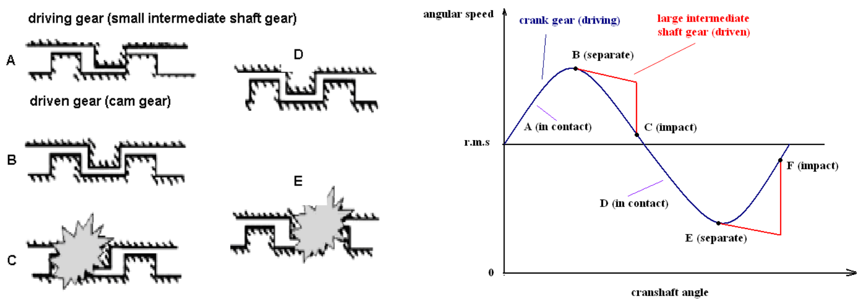

Figure 4 Left, cam gearing teeth impact [4]; Right, crank gearing pair speeds comparison.

Moreover, there is also torque variation on the crankshaft due to the periodical combustion process. The crank gearing teeth impact process is similar with the cam gearing. Figure 4 Right is given with the simplification that: 1st the impact on either tooth side of a gear occurs only once for each one meshing period; 2nd there is static load on the intermediate shaft.

The gear impacts on cam gear and crank gear influence each other through the intermediate shaft. Thus the teeth impact of the engine gear train system is so complex that hard to predict. Since the impact is of impulse nature, the gear hammering noise should locate in a broad frequency range.

5 THE COMPENSATED SPL MEASUREMENT SYSTEM

A pressure transducer is used and a plywood gear cover is made as the mounting. Meanwhile, the vibration on the transducer has been measured simultaneously by an accelerometer and compensated during the sound pressure calculation, Figure 5.

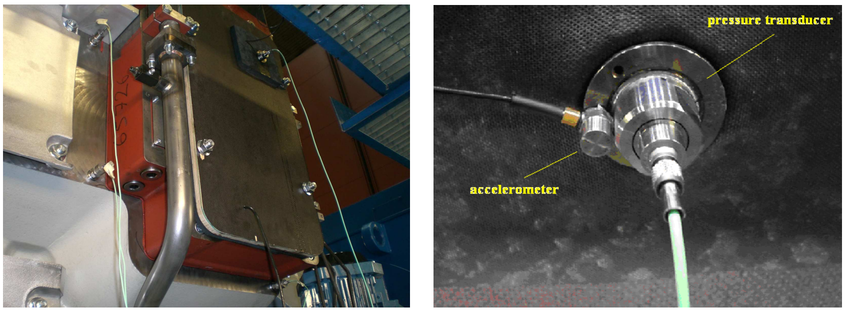

Figure 5 Test setup for the inside sound pressure measurement. The plywood cam gear cover with rubber on both sides, and the pressure transducer with accelerometer.

To achieve a better reliability, a pressure transducer is used instead of a microphone. The acceleration on pressure transducer has also been measured since the transducer is sensitive both to pressure and acceleration. The vibration generated signal is then subtracted. It has been concluded that $115 dB/m/s^2$ is a good estimate for the transducer vibration sensitivity [5]. Therefore the equally square value of the sound pressure accepted by transducer caused by vibration is:

$$p_{vib}^2 = 10^{k/10} \cdot a^2 \cdot p_{ref}^2 \qquad (1)$$

where $k = 115 dB/m/s^2$ is the acceleration sensitivity, a is the acceleration and $p_{ref} = 2 \times 10^{-5} Pa$ is the reference sound pressure. Then the compensated SPL that we are really interested in is calculated as:

$$SPL_{comp.} = 10 \cdot \log((\frac{p_{tr}}{p_{ref}})^2 - 10^{k/10} \cdot a^2) \qquad (2)$$

where p_{tr} is the total pressure signal perceived by the transducer.

6 MEASUREMENT RESULTS

1) Sound Power Radiated by Covers (based on intensity scanning method)

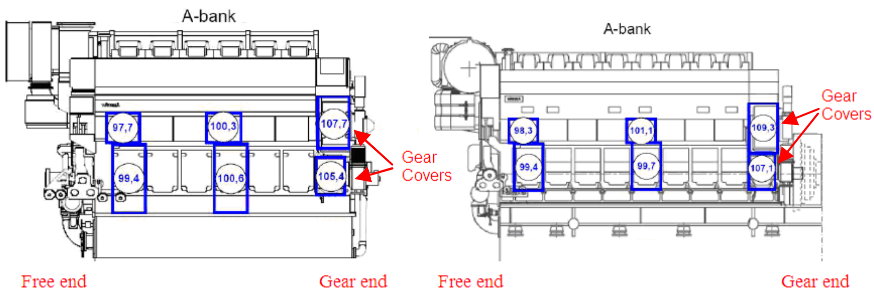

Figure 6 A-weighted sound power levels for some of the operating side covers on W6L32 (left) and W8L32 (right), nominal speed, 100% load. 100-10kHz.

From Figure 6, the sound power level over the gear covers is the highest for both engines. Therefore the engine block vibration level at the gear end must also be the highest.

2) Engine Block Vibration

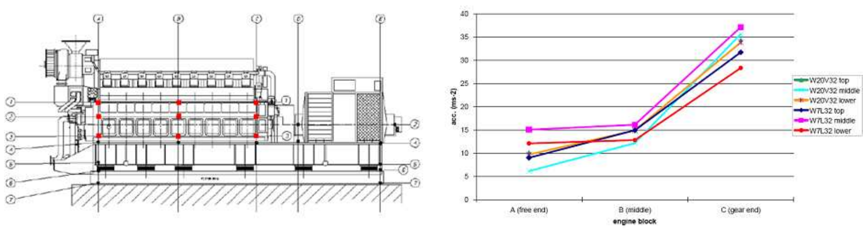

Figure 7 Left, defined measurement positions on the operating side of engine block, red dots; Right, 0-2kHz overall results of engine block vibration, 100% load.

Reasonably, in Figure 7, engine block vibrates more at gear end than at free end and middle part. The excitation of the engine block vibration is mainly contributed from the shaft bearings which transfer a lot of vibration from shafts. The vibration of shafts is generated mainly from: 1st, impulsive piston movement from crank shaft, 2nd, fuel injection pumping force applied on camshaft and 3rd, the gear train vibration on all shafts. Considering the 1st and the 2nd causes of vibration has the same effect on the free end, middle part and the gear end, the author claims that the higher vibration level at gear end is from the gear train vibration.

3) Sound Pressure inside the Cam Cover

First, after the transducer vibration being compensated, the sound pressure level of W9L32 (diesel) and W9L34SG (gas) engines is plotted in one-third octave band in Figure 8:

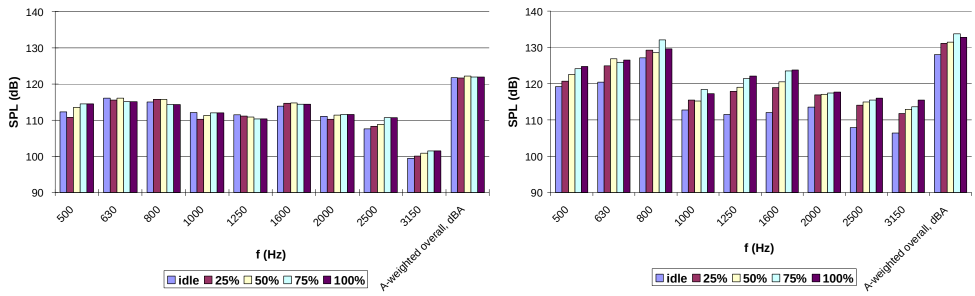

Figure 8 W9L34SG (left) and W9L32 (right) one-third octave band sound pressure level inside the cam gear cover at different load conditions.

The load increase has an influence on the cam cover inside noise of the diesel engine but no influence for the gas engine. The author claims that it is because for a diesel engine, the fuel pumping pressure increases with load increase, so the camshaft torsional vibration becomes larger and the gear train vibration is more intensive, therefore more noise is generated. Gas engines without fuel injection pump do not have such load variation influences.

Further, the narrow band noise spectra inside cam gear cover are plotted in Figure 9:

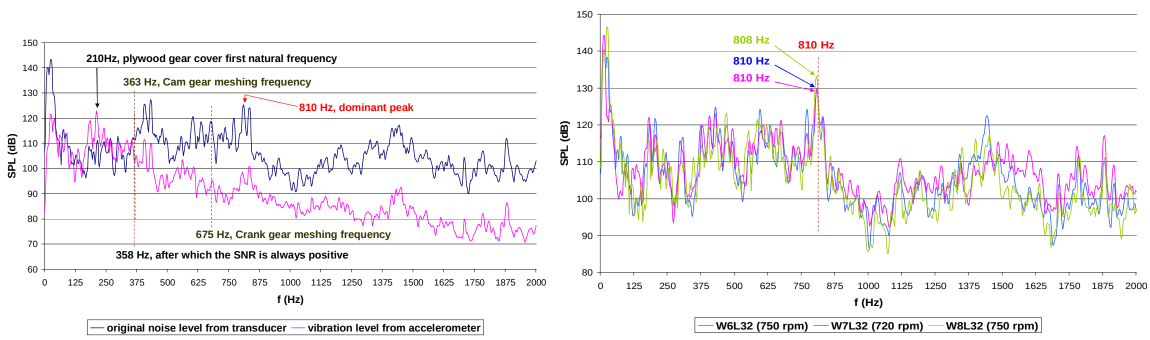

Figure 9 Left, W9L32 cam cover inside noise level and transducer vibration level; Right, three other In-Line engines noise level. (100% load)

Surprisingly, the noise at gear meshing frequencies does not peak up in Figure 9 Left, which indicates that the broad band noise caused by gear hammering is so intensive that it has covered the noise caused by gearing stiffness variation. Besides, a resonant noise around 810Hz is found. This resonant noise is not found in the result of the broad band sound power level of the structure-borne noise over the cam gear cover. It is filtered out by the cam gear cover.

7 SIMULATION RESULTS

A Wärtsilä program [3] based on Matlab has been studied and converted to be applicable to W9L32 that has been measured in this work. The Simulated W9L32 cam gear meshing force with ten times magnified camshaft torque at 100% load condition, two crankshaft rotations, is plotted in Figure 10:

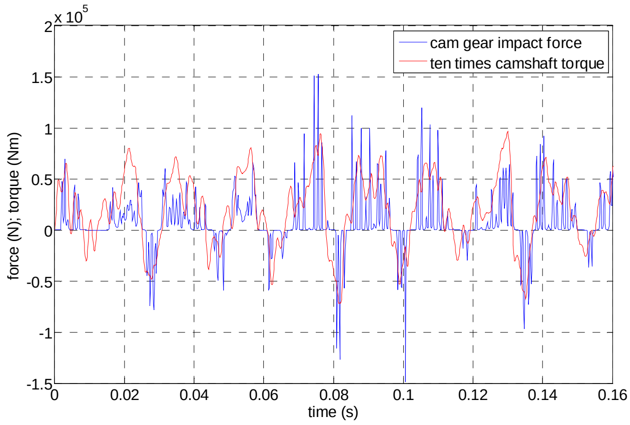

Figure 10 W9L32 cam gear meshing force with ten times magnified camshaft torque at 100% load condition, two crankshaft rotations.

At the place where there are small peaks on the curve of the camshaft torque, the gear hammering force is intensive, which indicates that it is the gear hammering that drives the gear train and the gear meshing teeth are for most of the time out of contact.

8 CONCLUSIONS

In order to simplify the gear noise mechanism, Figure 11 has been drawn. Red colour is original excitations of gear train noise, the blue colour is the vibration transmission path and the green colour is the generated noise.

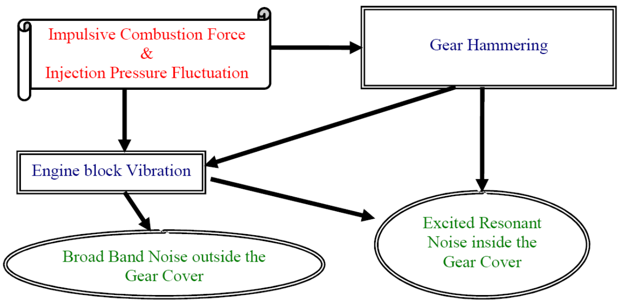

Figure 11 The basic noise generation mechanism with the excitation (red), transmission (blue) and radiation (green) clarified.

All in all, for diesel engines, because of the impulsive fuel injection pumping pressure and the impulsive combustion force, there is torsional vibration on both camshaft and the crankshaft. Gear hammering dominates in the gear train noise generation mechanism. Gear impact will aggravate engine block vibration at the gear end, which makes the gear covers radiate more broad band structure-borne noise along the engine body. Besides, the gear hammering is also one of the most important excitation of a resonant noise inside the cam gear cover.

9 FUTURE WORK AND IMPROVEMENT

To get a better understanding of gear hammering, the following work is suggested:

a) Measure the acceleration on the bearings in the direction of the tooth mesh force and the mobility of the bearings at the same positions as used for the acceleration measurements, so that an indication of the teeth meshing forces can be obtained.

b) Use the difference in instant revolution speeds between the intermediate shaft and the camshaft as another measure to visualize the gear hammering phenomenon.

c) Vibration level on both the cam and crank gear covers and on the engine structure close to covers should be measured in several positions.

d) Sound power over gear covers should be measured in narrow band analysis.

For significant gear hammering noise reduction, one should consider introducing additional compliance in the gear train while maintaining cam to crank timing [6], for instance, devices which could effectively places a nonlinear, tuned torsional spring between the rotating shaft and gear. Another option could be fuel system vibration damper.

Besides, scissors gear which can eliminate the backlash, and thus gear hammering, could also be considered. Gear covers could also be changed to the ones with less radiation efficiency.

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