FUEL INJECTION PUMP PHASING EFFECT ON GEAR-TRAIN IMPACT NOISE OF DIESEL ENGINES

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Fuel injection pump phasing is one of the most effective methods to reduce gear impact noise in heavy-duty diesel engines. It is well known that pressurizing fuel in the injection pump requires non-uniform torque, which contributes to the speed fluctuations of the engine during its operation. These fluctuations lead to propagation of high levels of impact noise from the engine. Fuel injection pump phasing is a procedure that adjusts the fuel injection timing of the fuel injection pump relative to the crankshaft. Adjusting the injection timing provides reduction of torque fluctuations and can thus be used to control gear impact noise. In this paper, numerical and experimental studies are carried out on a heavy-duty diesel engine to investigate how fuel injection pump phasing may affect the occurrence of gear train impact noise. In both numerical and experimental studies, different phase angles are analysed to determine the best and the worst phase angles for gear impact noise. The so-called Impact Impulse Method is used in the numerical study to quantify the relative change of gear impact noise level as a function of phase angle. Experimental investigations, including vibration and acoustic measurements, are carried out on a heavy-duty diesel engine in a semi-anechoic engine test chamber. Vibration and acoustic responses, partially caused by gear impacts, are measured and processed at different pump phase angles and critical resonance frequencies are detected. Broadband characteristic of the gear impact noise is observed in Campbell diagrams. Both numerical and experimental results obtained in this investigation show that fuel injection pump phasing can significantly change the gear train impact noise as well as the overall engine noise level.

Keywords: gear impact noise, pump phasing

1. Introduction

Gear trains are utilized in heavy-duty diesel engines since they allow transmitting higher power and load while minimizing durability risks compared to other timing drive options such as chain and belt drive systems. However, occurrence of gear impact noise is inevitable in gear drive systems and this type of noise in gear trains is one of the significant engine noise contributor in heavy-duty diesel engines. Gear impact noise is a broadband type of noise, resulting from impacts between gear teeth. Moreover, such impacts may cause damage or fatigue problems in the system.

Internal combustion engines generate non-uniform torque output during their engine cycles due to the fundamental principles of the combustion process. Thus, speed and torque fluctuations of the crankshaft occur during the engine operation. In heavy-duty engines, some of the power generated by the engine is transmitted from the crankshaft to the camshaft with several gears on the gear train, hence all the members of the gear train are affected from these fluctuations and the resulting impact forces between gear teeth.

Optimization of fuel injection pump phasing is recommended as the most effective way to reduce the gear train impact noise in diesel engines [1-4]. Sahip [5] showed that fuel injection pump phasing is a very effective tool for reducing dynamic loads on the engine timing system and the best timing position of fuel injection pump gear can be determined by searching the lowest dynamic loads throughout all load cases. Esmaeli and Subramaniam [1] pointed out that increasing fuel injection pressures in diesel engines and the type of fuel injection system had significant effects on overall gear train noise level. Crocker et al. [2] indicated that increase in fuel injection pressures leads to torque fluctuation during engine cycle and, as a result, gear impact forces and gear impact noise can increase. Wilhelm et al. [3] also considered torque fluctuations of fuel injection pump and camshaft in the gear train as the significant contributor on gear impacts. They expressed that torsional vibrations on gear train members lead to impacts between gears and these vibrations are affected by the phase difference between the engine and gear train components such as fuel injection pump, valve train and crankshaft. Moreover, they [3] suggested that natural frequencies of gear train members can be excited by the impacts between gears. Gao et al. [4] studied on overall gear train noise of a large diesel engine, which includes both gear meshing and impact noise. Their important finding is that gear impacts create noise and vibration on gear train members due to the torque fluctuations of fuel injection pump. Apart from experimental studies, Singh et al. [6] theoretically studied non-linear dynamics of a geared system. Mathematically, loosing tooth contact phenomenon is explained with time-varying mesh stiffness within gear backlash. There are also other studies on the non-linear dynamics of gear train systems in the literature. In summary, it is considered that time-varying mesh stiffness affects the dynamic behaviour of gear train systems [7-9].

The main aims of this paper are to describe briefly the background theory of gear impacts and to show the fuel injection pump phasing effect on gear train impact noise in heavy-duty diesel engines. To meet these goals, both experimental and numerical studies are conducted on a heavy-duty diesel engine comprising a gear drive system with spur gears.

This paper is organised as follows. The importance of the problem and a short literature review are introduced in the first section. Definition of gear impact noise and phasing are presented mathematically with their background theory in the second section. Numerical studies are presented using impact impulse method and a gear train of a heavy-duty diesel engine is analysed so as to assess the effect of fuel injection pump phasing on the gear train impact noise level in the third section. Noise and vibration tests in the engine dynamometer are carried out and the test results are described in the experimental studies part in the fourth section. Finally, important findings and conclusions are discussed in the last section.

2. Theoretical Background

2.1 Gear Impact Noise

Gear noise is classified into two main categories as gear meshing and gear impact noise which is referred to as gear rattle noise in the automotive industry. Gear impact noise is a broadband noise, independent of rotational speed and it can be seen in a wide frequency range. Loosing tooth contact within gear backlash due to external excitations such as torque fluctuations and torsional vibrations can cause backward and forward relative motion between gear teeth [10], leading to impacts between gear teeth, which in turn result in impact noise.

Due to the working principles of internal combustion engines, some level of torque fluctuations inevitably exists on the crankshaft during the engine cycle. While transmitting the power from the crankshaft to the camshaft, the torque fluctuation is also carried through the gear train members. Crankshaft and drive components such as fuel injection pump change the torque on the gear train, which results in heavy impacts between gear teeth as well as occurrence of gear impact noise. Moreover, increase in the fuel injection and combustion chamber pressures can directly influence the level of torsional vibrations on the gear train of diesel engines [1].

2.2 Mathematical Models of Gear Impacts

Mathematical relationship between the drag torque and gear wheel inertia torque determines whether the gear impacts exist or not [11]. Theoretically, impacts between gear teeth occur due to the speed fluctuation within the gear backlash. When the angular acceleration of the driven gear wheel becomes sufficient to create higher inertia torque than its drag torque, gear impacts can occur. So, the impact occurrence criteria can mathematically be written as [11];

$$J\dot{w} > T_{drag} \tag{1}$$

Here, J and $\dot{w}$ represent moment of inertia of driven wheel and angular acceleration of the driven wheel, respectively and T_{drag} represents the drag torque acting on the driven wheel. The so-called drag torque here is the torque applied to the system by the peripheral components such as power assisted steering, fuel injection pump, air compressor etc. Power take-off can generate drag torque in gear trains. As can be seen from Eq. (1), impact occurrence criteria can be rewritten in terms of critical angular acceleration term, suggesting that gear impact starts to happen [11] when;

$$\dot{w}_{critical} = \frac{T_{drag}}{J} \tag{2}$$

From Eq. (1) and Eq. (2), it is clearly seen that impacts between gear teeth occur above a critical acceleration value.

2.3 Gear Contact Dynamics

Contact forces between gears can be calculated with gear contact dynamic analysis in order to assess gear impacts. Gear researchers have recently proposed several gear contact dynamic models in the literature. Singh et. al. [6] presented an updated non-linear model as shown in Fig. 1. Loosing tooth contact phenomenon within backlash and gear mesh stiffness variation during the contact period are accepted as the main non-linear factors in gear contact dynamics. To model this phenomenon, a time-varying mesh stiffness with a backlash function is employed between gear teeth at the gear mesh. Dry friction damping at the gear mesh, transmission error and gear errors are also known as some of the other non-linear factors.

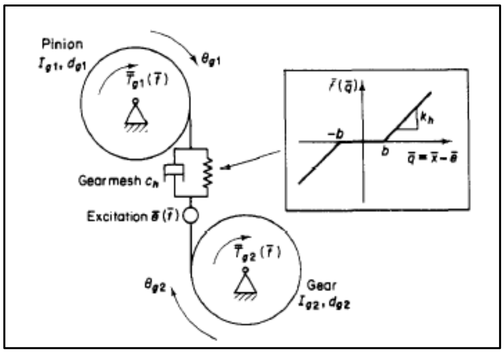

Figure 1: Gear contact dynamic model [6].

As seen in Fig. 1, gear contact is modelled with a time varying mesh stiffness, mesh damping and meshing error. Gear meshing force (contact force) F_m is expressed as [6];

$$F_m = c_m \frac{dq}{dt}\ k_m q \tag{3}$$

where c_m and k_m represent mesh damping and mesh stiffness of gear pair, respectively, and q is the relative displacement between two gears, which is written as [6];

$$q = r_{b1}\theta_1 - r_{b2}\theta_2 - e(t) \quad (4)$$

Here, θ_1 and θ_2 are angular displacements of the gears, r_{b1} and r_{b2} are base circle radius of the gears and $e(t)$ represents the transmission error excitation.

2.4 Fuel Injection Pump Phasing

Fuel injection pump phasing is a procedure that adjusts the fuel injection timing of the fuel injection pump relative to the crankshaft. Physically, it is achieved by changing the timing between fuel injection pump plunger and crankshaft piston. During the engine operation, as the fuel pump consumes time-varying power, fuel injection pump causes torque fluctuations in drag torque hence high levels of torque variations occur between the timing gears and fuel injection pump gear [12]. Consequently, these excessive torque fluctuations can cause impacts between gear teeth and propagation of impact noise.

Mathematically, as an approximate approach, torque variations of the crankshaft and fuel injection pump can be can be assumed as a sinusoidal wave and they can be expressed as;

$$T_c = A_c \sin(w_c t + \theta_c) + T_{c0} \quad (5)$$

$$T_f = A_f \sin\left(w_f t + \theta_f\right) + T_{f0} \quad (6)$$

where T_c and T_f are crankshaft and fuel injection pump torque respectively, w_c and w_f are the crankshaft and fuel injection pump torque frequency, θ_c and θ_f are the phase angles and T_{c0} and T_{f0} represent the mean values . In machine dynamics, turning moment [13] on the crankshaft is also described as;

$$T_c = F_p \times r\left(\sin\theta + \frac{\sin 2\theta}{2\sqrt{n^2 - \sin^2\theta}}\right) \quad (7)$$

where F_p is piston effort, r is radius of crank, n is ratio of the connecting rod length and radius of crank and θ is angle turned by the crank from inner dead centre. The net torque is expressed as;

$$T_{net} = T_c - T_f - T_o \quad (8)$$

Here, T_o represents the torque required by other components such as power assisted steering gear pump and power take-off gear. Fuel injection pump and other components consume power hence their torque terms have negative signs in Eq. (8).

Noise and vibration consideration of fuel injection pump phasing demands maximum possible cancellation of the torque fluctuations. Ideally, the impacts on the gear train can be eliminated by setting the torque fluctuations to zero. In practice, timing between fuel injection pump and crankshaft torque curve can be shifted with phasing so as to minimise the torque fluctuations. Gear impacts may increase at some phase angles because of the summing of the torque fluctuations. On the other hand, they can be minimised when the maximum torque cancellation is achieved at optimum phase shifting. In summary, the phase shifting operation can lead to higher or lower gear impact noise hence requiring phase angle optimisation.

3. Numerical Study of Fuel Injection Pump Phasing

3.1 Impact Impulse Method

Impact impulses at the gear meshes are calculated in order to assess gear impact noise level relative to a reference level. They can be calculated by evaluating the definite integral in Eq. (9) where contact forces between gears and acoustic relevant contact time (ARCT) are utilized [14]. In this equation, I is the impact impulse for a gear mesh and F is the contact forces between gears.

$$I = \int_{ARCT} F dt \tag{9}$$

AVL Excite multi-body dynamic software also uses this method to quantify gear impacts. According to AVL Excite Timing Drive guideline [14], low contact force and velocity value are assumed to be zero under specified threshold values. The time when the force is peaked is considered as the acoustic relevant contact time [14].

3.2 Geartrain Model in AVL Excite Timing Drive

A gear train model of a 12.7 litre heavy-duty diesel engine is built for impact impulse analysis. The model included mechanical elements such as shafts, gears, bearings and rotational excitations in AVL Excite software. All elements are connected to other elements using their input-output characteristics and inertia properties of individual elements are modelled as lumped masses in this multi-body dynamic analysis software. Material and geometry properties are also defined for each element. Measured engine speed data is used as an input for rotational excitation. Negative torque demands of fuel injection pump and camshaft loads are additionally defined to the gear train model. For gear impact analysis, constant meshing stiffness is used instead of varying meshing stiffness [14]. To compute forces, torques and displacements of gear train members in time domain, Predictor / Corrector method [15], a kind of systematic integrations is employed.

3.3 Numerical Analysis of Fuel Injection Pump Phasing

Nine different phase angles starting from 0 to 96 degrees are examined in the software to obtain the corresponding total impact impulse values by summing up individual impact impulse values of gear meshes. Timing of fuel injection pump torque curve is shifted for each iteration with respect to engine torque peak time hence fuel injection pump phasing is achieved in software simulations.

In Fig. 2, the total impact impulse result of the worst and the best cases are presented with respect to the engine speed. The best and the worst phase angles are predicted as 12 and 72 degrees, respectively.

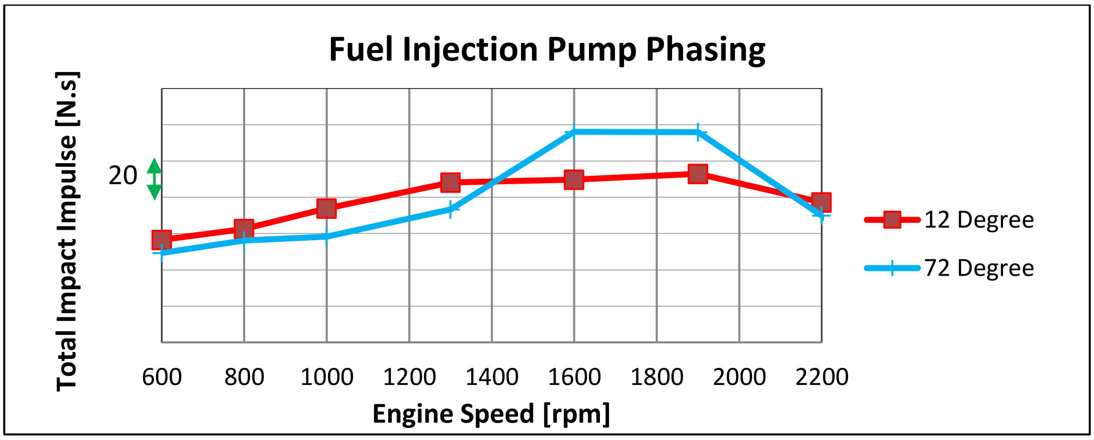

Figure 2: Fuel injection pump phasing effect on total impact impulse.

Close inspection of the behaviour of the total impact impulse values at different engine speeds in Fig. 2 reveals that there is a nodal point at about 1400 rpm and it can be said that the impact impulse behaviour changes based on this nodal point. It is seen that, at speeds greater than 1400 rpm, 72 degree phase angle shows higher impact values compared to that of 12 degree. In contrast, at speeds lower than 1400 rpm, 12-degree phase angle yields higher impact value than 72-degree phase angle. These results obtained via simulations clearly show that fuel injection pump phasing affects impact impulse values which in turn affects the gear train impact noise. Therefore, it is evident that fuel injection pump phasing can be used to minimise gear train impact noise.

4. Experimental Study of Fuel Injection Pump Phasing

4.1 Engine Dynamometer Noise & Vibration Tests

A 6 cylinder 12.7 litre heavy-duty diesel engine without the transmission unit is tested in a semi-anechoic chamber using the acceleration and acoustic transducers. The tests are carried out on the heavy-duty diesel engine in full load conditions. Sound pressure levels are estimated using the average of three measurements.

For the engine noise measurements, a measurement procedure described in DIN 45635 is utilised in semi-anechoic chambers. According to DIN 45635 [12], the microphones are located 1 meter away from the outermost part of the engine and centred to the whole engine surface. Four microphones located at engine left side, right side, front side and top side are employed to calculate the overall engine noise level in the semi-anechoic chamber. The microphone locations are shown in Fig. 3.

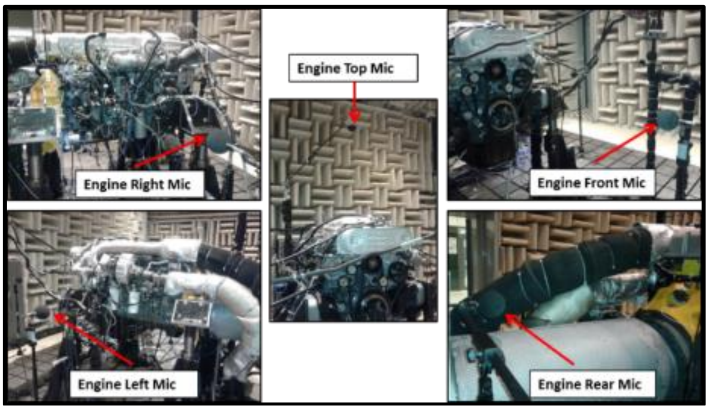

Figure 3: Microphones locations.

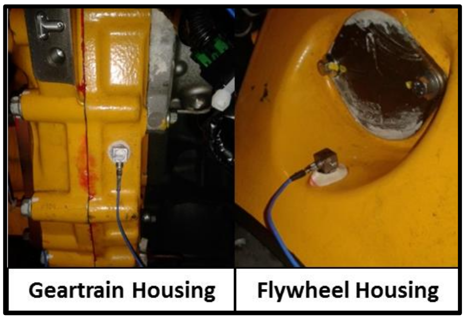

Figure 4: Accelerometer locations.

Apart from four microphones, the fifth microphone, called rear microphone here, is also used in order to make more detailed analysis of gear impact noise since gear train is located at the rear side of the engine. The rear microphone is located 0.8 meter away from the outermost part of the engine.

To calculate average sound pressure level of an engine in semi-anechoic room, engine left, right, front and top microphone data are used. Average sound pressure level formula is expressed as [12];

$$L_{P_{average}} = 10log_{10}\left[\frac{1}{N}\sum_{i=1}^{N} 10^{\left(L_{P_n}/10\right)}\right] \tag{10}$$

Here, N is the total number of the microphone positions. L_{P_n} is the sound pressure level of each microphone.

Gear train housing and flywheel housing are considered as the best acceleration measurement locations on the engine so as to analyse gear train impact noise. Two accelerometers located on flywheel and gear train housing are shown in Fig. 4.

Gear impact noise is expected to be seen at higher frequencies as a broadband noise. The impact frequencies of the gear train are observed between 1 kHz to 10 kHz. Moreover, gear impacts may have contributions at other frequencies owing to the nature of hammering process.

4.2 Fuel Injection Pump Phasing Noise and Vibration Tests

In the experiments, nine different phase angles starting from 0 (baseline) degree to 96 degrees are examined by changing the assembly position of the fuel injection pump with respect to the crankshaft in order to see the phasing effects on gear train impact noise. The phase angle is set by turning the fuel injection pump gear in anti-clockwise direction with a phasing tool.

Phasing tests are carried out under engine full load condition. The best and the worst phase angles for gear train impact noise is determined as 12 and 72 degrees, respectively, based on the average of 4 microphone data. As can be seen in Fig. 5, the maximum sound pressure level difference between the best and the worst case is clearly separated from each other, allowing one to set the optimum pump phasing with very high level of confidence. It is believed that combustion noise has a minor effect on the change of overall engine noise level since no significant change in the engine torque, common rail pressure or cylinder pressure is observed between the 12 and 72 phase angles. In the light of all microphones result, it can be concluded that the largest sound pressure level difference is observed at engine rear side that shows the significant effect of fuel injection pump phasing on the gear train impact noise.

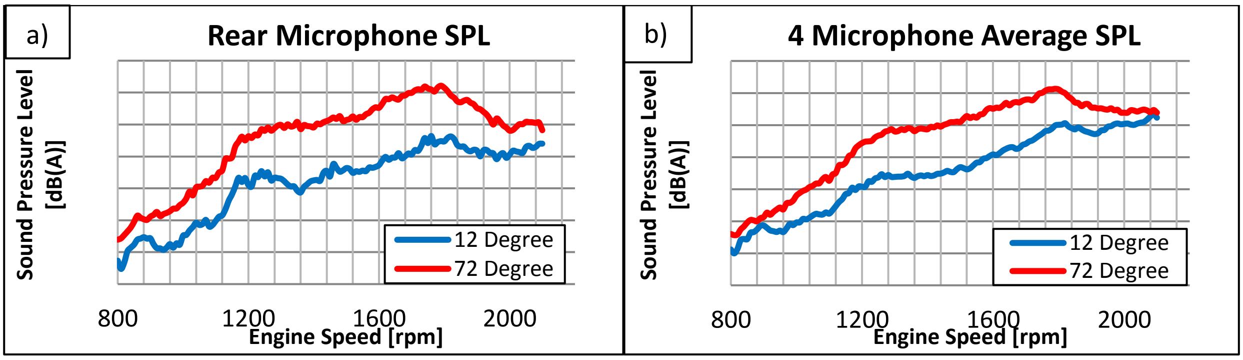

Figure 5: Fuel pump phasing noise contributions, a) rear microphone, b) the average of four microphones.

Measured vibration data from flywheel housing and acoustic data from engine rear microphone at different phase angles shows the change in vibration and sound pressure levels so it could be deduced that fuel injection pump phasing has direct effect on the gear train impact noise. Moreover, the results of the analyses of the microphone and accelerometer signals reveal that running the engine at different fuel injection pump phase angle changes the signal amplitudes at resonance frequencies.

As seen in Fig. 6, Campbell diagrams are plotted using engine rear microphone and flywheel housing accelerometer signals for each phase angle from 0 degree to 96 degree. The engine speed from 800 rpm to 2100 rpm is shown in the diagrams. Rear microphone data is shown between 1 kHz and 6 kHz whereas flywheel housing accelerometer data is shown between 1 kHz and 10 kHz. Both microphone and accelerometer measurements reveal the phase angle effect at resonance frequencies, which effect is particularly seen between the worst and best phase angle. Moreover, gear impact frequencies can be observed up to higher frequencies from 1 kHz to 10 kHz in each Campbell diagram. Consequently, fuel injection pump phasing may provide noise improvements in a wide frequency range by determining the best phase angle.

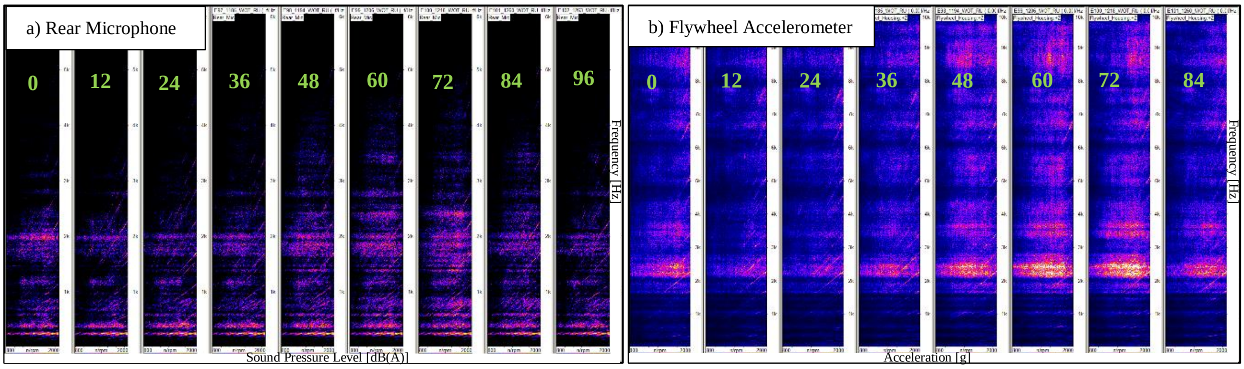

Figure 6: Campbell diagrams, a) using rear microphone, b) using flywheel housing accelerometer.

5. Concluding Remarks

In this paper, the effect of fuel injection pump phasing on gear train impact noise of a 12.7 litre heavy-duty diesel engine is investigated. Both numerical and experimental studies show the strong effect of fuel injection pump phasing on the gear train impact noise. The Impact Impulse Method is used in the numerical study to predict the total impact impulse values. Then, the variation of the total impact impulse is calculated for different values of fuel injection pump phase angle. These results are used to predict the best and the worst phase angles as 12 and 72 degrees, respectively.

Experimental investigations comprised vibration and acoustic measurements on the same engine in a semi-anechoic engine test chamber. The engine is run at full load under various fuel injection pump phase angle. Campbell diagrams corresponding to various fuel injection pump phase angle are obtained using both vibration and acoustic measurements. Experimental results fully confirmed the predicted values of the best and the worst fuel injection pump phase angles. Phase angle effect at resonance frequencies is also clearly observed in Campbell diagrams. Both numerical and experimental results show that fuel injection pump phasing can significantly change the gear train impact noise as well as the overall engine noise level.

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