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Development of Vibration Test and Analysis Methods for Diesel Engine Belt System

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ABSTRACT

The engine belt is the critical part of the engine which transfers crankshaft rotational movement to the pulleys. There are several types of belt failures. One of the root causes of the belt failure is the vibration. In this study, the belt vibration of a heavy duty diesel engine has been investigated. Firstly, belt vibration has been quantified with the help of displacement measurements on the belt in lateral direction. Additionally, belt noise measurements have been performed to make further investigations. Pulley torsional vibrations of two different engines were measured and results were compared. Furthermore, system finite element model has been created to do modal and random frequency response analysis by using FEA (Finite Element Analysis) methods. Crank-pulley angular speed power spectral density (PSD) test values were used as an input at the finite element model (FEM) and lateral displacement was calculated on the belt with the help of PSD analysis. Then, FEM model was correlated with test data by tuning belt elasticity module so that a good starting point has been achieved to make further iterations on the model. This study comprises both test and analysis methods and comparison between measured test results and analyses.

Keywords: Belt, torsional vibration, PSD analysis
I-INCE Classification of Subject Number: 40

1 INTRODUCTION

The belt is the one of the important parts of the engine so that transfers rotational movement of the crankshaft to the other components such as alternator pulley, fan pulley, compressor, etc... There are very kind of belt quality criteria such as wearing, breakage, noise, lateral movement and

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vibration. Even small failures on the belt can cause reducing of the system performance and belt vibration is the main key to understand engine belt dynamic behavior.

In this study, it is aimed to make basic assessment for the belt vibration. Belt vibration is investigated in detail by using comprehensive test and analysis methods. After initial measurements, belt dynamic behavior is defined and improvement possibilities are examined to support design phase before production for the future projects.

A considerable amount of reserch has been conducted on a method predicting belt vibration at the development stage of FEAD (Front End Accessory Drive) in order to reduce lateral movement of the belt and a huge number of papers have been published dealing with resonance and vibrations in drive belts.

Actual transversal vibration is an event that is influenced by fluctuations in engine speed and which fluctuates cyclically. The spectrum of transversal vibration is constituted of multiple frequencies centering on natural frequencies. According to literature, the belt lateral resonance is maximized at a specific engine speed because of the frequency of the lateral vibration produced by fluctuations in engine speed. If the frequency of the excitation force generated by the engine are identical with belt natural frequencies,the belt is excited by multiple frequencies. [1]

Belt vibration produces fluctuations in amplitude results from changes in engine speed, and will produce radial spectra centering around the natural frequency of belt vibration. The natural frequency of the vibration of a moving belt can be expressed using the following equation [1]:

$$f_n = \frac{1}{2L}\left(c_0 - \frac{v^2}{c_0}\right) \qquad (1)$$

$$c_0 = \sqrt{\frac{T}{\rho}} \qquad (2)$$

where
f_n: Natural frequency of lateral vibration
L: Span of belt
v: Velocity of belt
c_0: Lateral wave propagation speed
T: Belt tension
ρ: Belt mass per length

Eq. (1) shows that when engine speed increases, the natural frequency of belt vibration will decline because the velocity of the belt is proportional to engine speed. Figure1 shows a diagram of the relationship between engine speed and frequency for belt vibrations that produce fluctuations in amplitude based on Eq. (1). The solid line in the center of the graph shows the natural frequency, while the dotted lines show components of belt vibration produced by fluctuations. The graph also shows the distribution of radial frequencies centering on the natural frequency. [1]

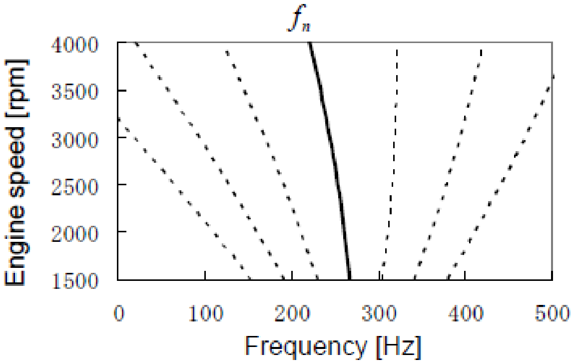


Figure1. Radial spectrum of belt lateral vibration [1]

To predict the vibration response of a system the dynamic characteristics of the belt, such as the Young's modulus and the damping factor, must be accurately identified. Because of the viscoelastic behaviour of the rubber material, its dynamic material properties, which depends on many environmental and operating conditions, but mainly on the static pre-load, vibration amplitude, temperature and frequency are difficult to define. From the theory of viscoelasticity it is known that at least two parameters are needed to completely define the mechanical behaviour of an isotropic viscoelastic material. Usually these two parameters are the Young modulus and the Poisson's ratio of the viscoelastic material. [2] The relationship between the Young's modulus, Bulk modulus and Poisson's ratio is given as: [3]

$$E = 3K(1-2v) \qquad (3)$$

where
E:Young's modulus
K: Bulk modulus
v: Poisson's ratio

Young's modulus of rubber at the natural frequency is given as: [3]

$$E = \frac{tensile\ stress}{tensile\ strain} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0\Delta L} \qquad (4)$$

where
E: Young’s modulus (modulus of elasticity)
F: Force applied to the object
A_0: Original cross-sectional area throuh which the force is applied
ΔL: The amount by which the length of object changes
L_0: Original length of the object

In that study, the belt lateral displacement is investigated depending on the belt Young’s modulus (elasticity modulus).

Meckstroth, Deneszczuk and Skrobowski show a relation between belt noise and vibration in their studies. Accessory belt “chirp” noise is a major quality issue in the automotive and truck industry. Chirp noise control is often achieved by very tight pulley alignment in industry. This study offers an explanation for such occurrences. [4]

2 FEAD BELT SYSTEM CONFIGURATION

Current examined engine FEAD belt system components, which is named as configuration-1, are tabulated in Table1 and shown at Figure2. Dimensions are given as proportional according to new design, which will be given in section 6.2 and Table3. There are alternator pulley, tensioner pulley, fan pulley, crank pulley and idler on the belt path. Additionally, "reference" engine is selected to define the target level for belt vibration. The reference engine has same basic properties with the configuration-1 engine to make a correct comparison between them.

Table 1 - Configuration-1 FEAD Belt System Parts

FEAD System Parts	Configuration-1
Flywheel inertia	1
Belt	Current
Crank Pulley Diameter (1)	1
Fan Pulley Diameter (2)	1
Tensioner Pulley Diameter (3)	Slot position: Max
Alternator Pulley Diameter (4)	1
Idler (5)	1

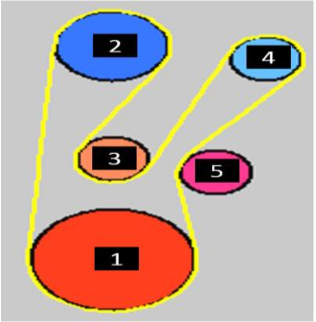


Figure2. Configuration-1 FEAD Belt System

3 TEST INSTRUMENTATION

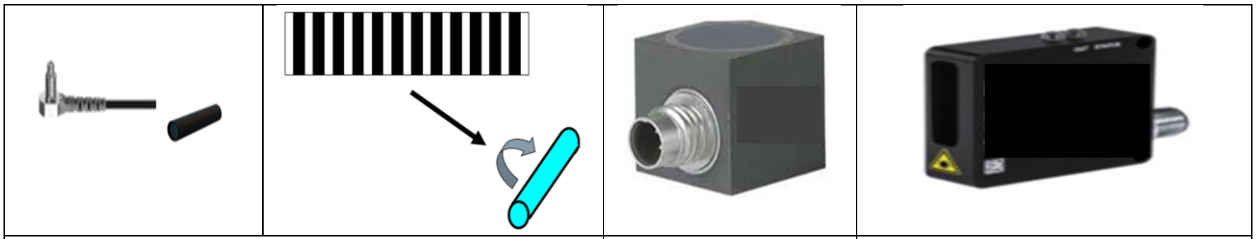
"Reference" engine and "configuration-1" engine FEAD belt system dynamic behaviors are compared in that study by considering belt vibration. Measured engine FEAD system components, used sensor types and measured quantities have been summarized in Table2. Tractor configurations are selected almost same to make correct comparison between them.

In reference engine, alternator and crank pulley angular velocities are measured by using fiber optical sensors. Zebra tapes were used during measurements to get sufficient vibration data. Fan pulley velocity could not be measured because of insufficient working place on the pulley. In addition, belt lateral displacement is measured by using a laser displacement sensor. A displacement sensor is placed in front of the belt laterally and 4cm away from belt. Alternator pulley, crank pulley and belt vibrations are measured at operational conditions which contains all speed ranges of engines as unloaded. Also, FRF test has been performed by using an impact hammer to understand belt modal behavior. Selected force input point is excited only at lateral side of the belt. At the end of the Tier3 engine test, torsional vibration of the alternator and crank pulley have been measured. Moreover, belt lateral displacement is measured together with pulleys synchronously. Finally, the natural frequency of the belt is detected with an experimental modal test method. Used sensor pictures during measurements are shown at Figure3.

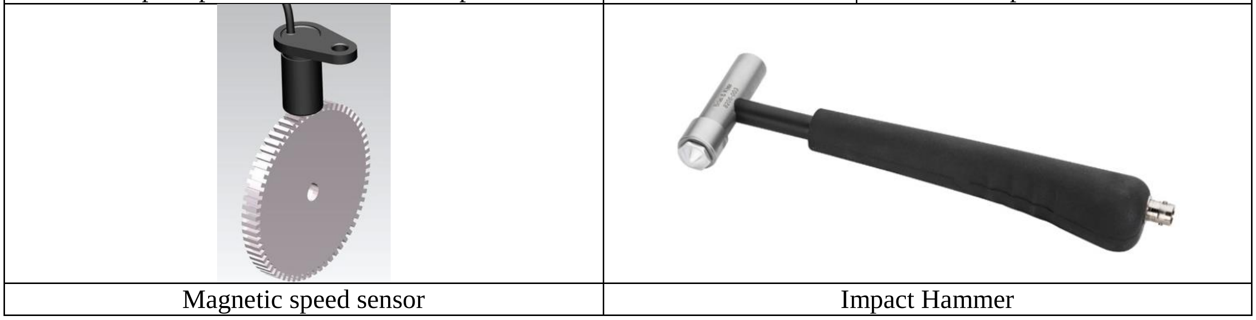
In the configuration-1 engine, fan pulley torsional vibrations are measured instead of alternator pulley. Alternator pulley could not be measured because of insufficient working place. Crank pulley torsional vibrations are measured by using crank gear teeth with magnetic speed sensor. Fan pulley torsional vibration is measured again with optical sensors.

Table 2 - Measurement Details of Compared Tractors with Tier3 and Tier4 Engine

Engine	Measured Part	Sensor Type	Measured Quantity
Configuration-1	Fan pulley	Optical sensor (Zebra tapes were used)	Angular velocity (Torsional Vibration)
	Crank gear	Magnetic speed sensor	
	Belt	Laser displacement sensor	Lateral Displacement
	Belt	Impact Hammer/ Force transducer	FRF (Belt resonance)
Reference	Alternator Pulley	Optical sensor (Zebra tapes were used)	Angular velocity (Torsional Vibration)
	Crank pulley	Magnetic speed sensor	
	Belt	Laser displacement sensor	Lateral Displacement
	Belt	Impact Hammer/Force transducer	FRF (Belt resonance)



Optic speed sensor and zebra tape | Accelerometer | Laser displacement sensor



Magnetic speed sensor | Impact Hammer

Figure3. Used sensor pictures during tests

4 INVESTIGATION OF THE TEST RESULTS

4.1 Belt Lateral Displacement Results

Belt lateral displacement is measured depending on the engine speed at loaded and unloaded conditions on the engine dyno test rig. It has been seen that displacement values do not change in according to engine load significantly. Configuration-1 engine belt lateral displacement is measured 19 times more according to reference engine. (Figure4 and Figure5).

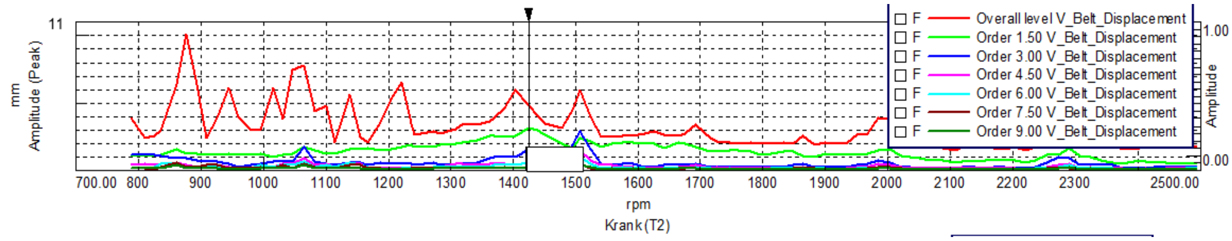


Figure4. Reference Engine Lateral Displacaments and Order Contributions (Neutral Runup)

(Values are normalized)

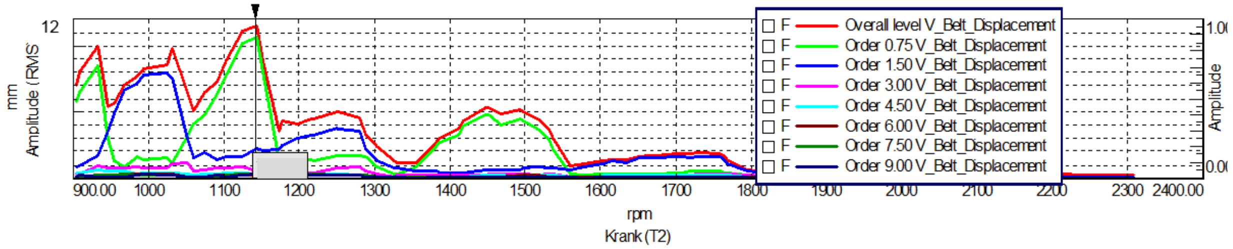


Figure5. Configuration-1 Engine Lateral Displacements and Order Contributions (Neutral Run-up) (Values are normalized)

Reference and configuration-1 engine belt displacements are compared at unloaded condition by considering the frequency content (Figure6, Figure7). It is has been seen that there is higher displacement below 50 Hz in the configuration-1 engine. Especially, 0,75th order contribution to the overall level is highlighted in Figure7. Also, order overall levels are shown in Figure8. Generally, 1,5th order contribution is expected in 3cyl engine dominantly and 0,75th order could not be linked directly with the engine firing order at 3 cylinder engines. The reason of the order contribution of 0.75th order will be investigated at the following section.

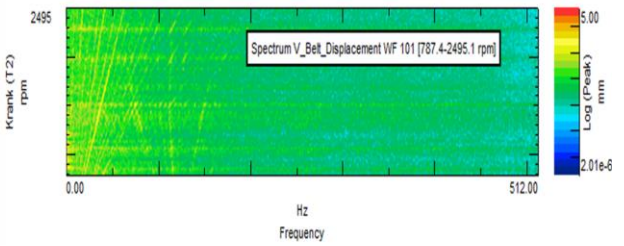


Figure6. Reference Engine Lateral Vibration Frequency Content

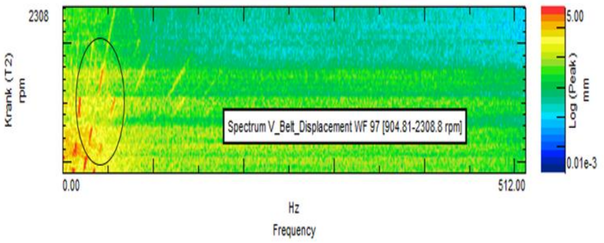


Figure7. Configuration-1 Engine Belt Lateral Vibration Frequency Content

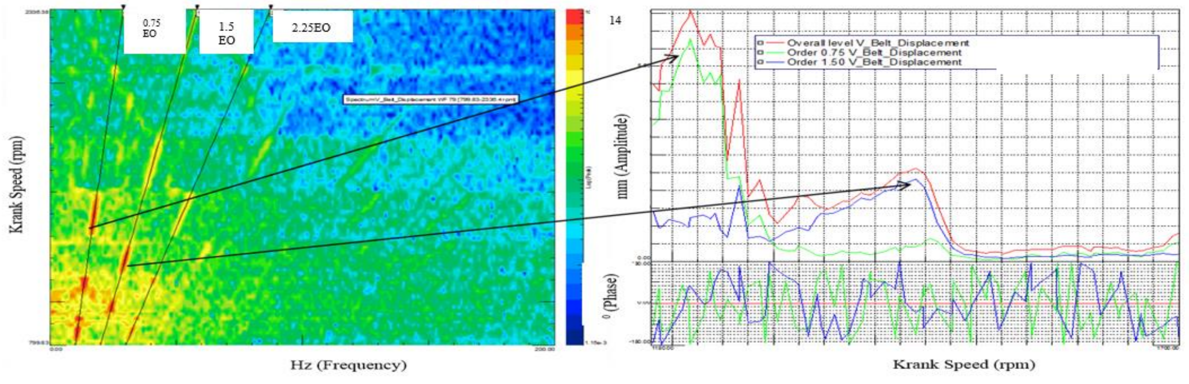


Figure8. Matching up belt displacement orders with overall level displacements

(Values are normalized)

In the configuration-1 engine, belt noise is not observed subjectively. For further investigation of the belt system, belt noise is measured in neutral run-up condition with microphone. Belt noise and vibration measurements are correlated and dominant noise contribution is not seen between noise and vibration measurements (Figure9).

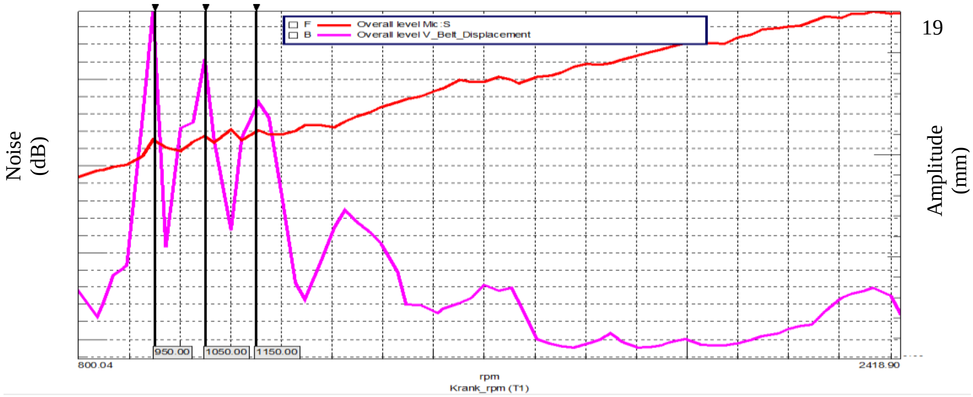


Figure9. Correlation between belt noise and vibration (Values are normalized)

4.2 Configuration-1 Engine FEAD Belt System Operational Deflection Shape Investigation

Fan pulley, crank pulley angular speeds and belt lateral displacement are measured simultaneously during tests. Additionally, phase information of measured quantities is matched with instantaneous movement in the system. It has been observed that there is 180^0 phase difference between the fan and crank pulley during system working at 0.75th order. It can be the one of the reasons for higher displacement on the 0,75th order. 0,75th order movement is visualized at Figure10. 0.75th order dynamic behavior will be linked to the engine dynamics at the following section.

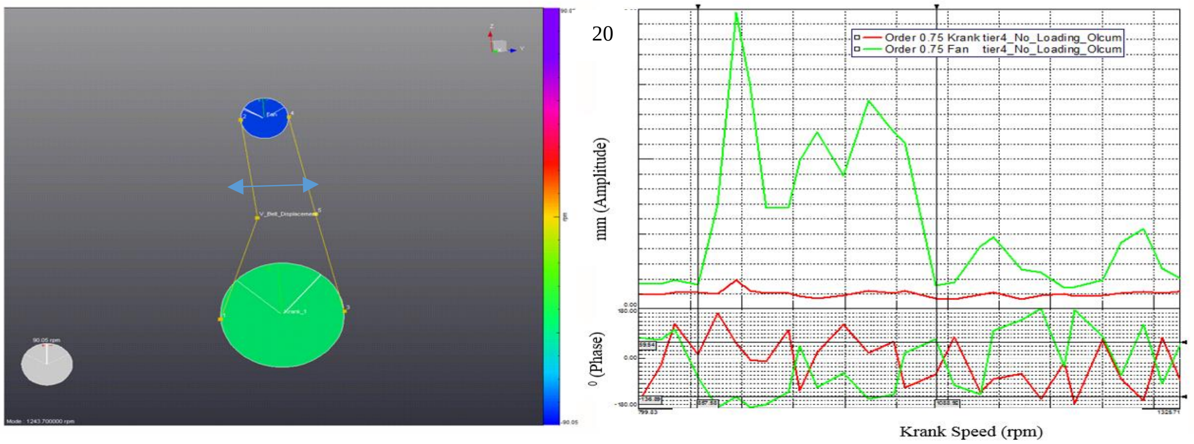


Figure10. *0.75th order animation (Neutral Run up)*

(Values are normalized)

5 FINITE ELEMENT ANALYSIS OF THE TIER4 ENGINE FEAD SYSTEM

5.1. Random Frequency Response PSD (Power Spectral Density) Analysis

Random frequency response analysis is used when a structure is subjected to a non-deterministic, continuous excitation. Random response analysis requires input, which are the complex frequency responses from frequency response analysis and power spectral density functions of the non-deterministic excitation source. The complex frequency responses are generated by modal frequency response analysis. [5]

In this analysis, measured crank pulley angular speed PSD values at the neutral run up condition are used as input in the simulation model (Figure11). Input and output points are shown in Figure 12. Belt displacement is calculated depending on the PSD input on the simulation model (Figure 12). Belt elasticity modulus in simulation model is tuned to catch frequency correlation with test. Corrected elasticity modulus of the belt is taken as 5200N/mm^2. Poisson ratio is taken as 0.47 and the damping value is taken as 8% in the simulation model. To achieve same displacement amplitudes in the model, damping value is tuned. Correlated belt elasticity modulus is used at the modal analysis so that rotational mode of the system is appeared with appropriate belt elasticity modulus in the modal analysis, which is explained at section 5.2. In this way, a verified methodology has been developed to specify the belt elasticity modulus.

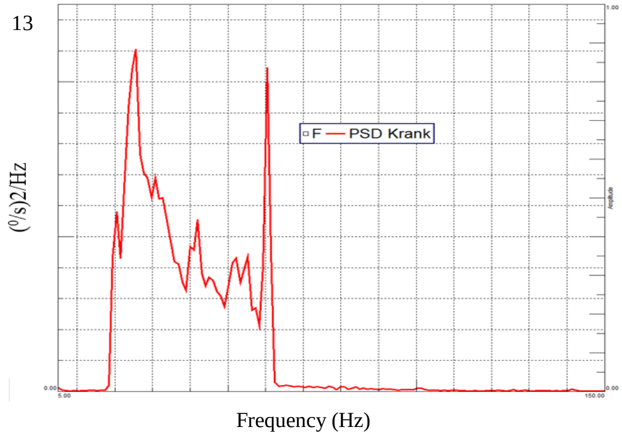


Figure11. Crank speed angular velocity(Test) (Values are normalized)

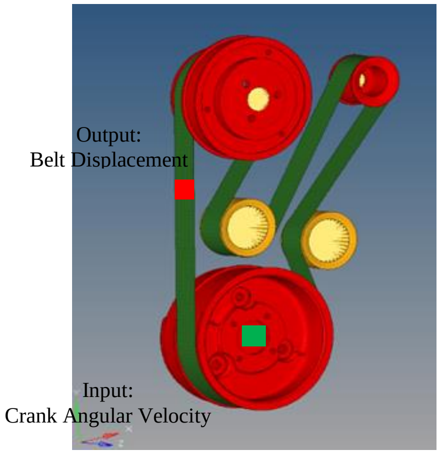


Figure12. Test data input and output point

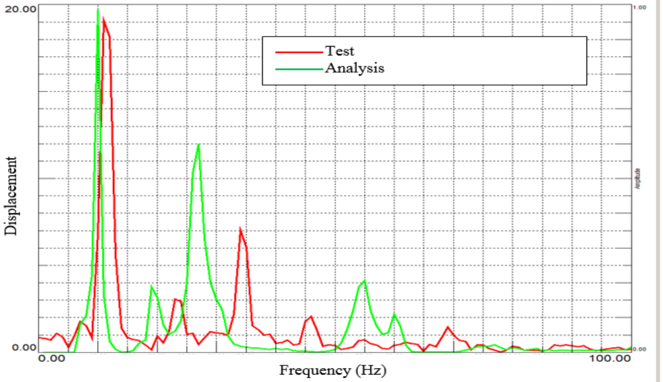


Figure13. Calculated belt displacement and correlation with test (Values are normalized)

When the PSD analysis input examined, it has been seen that PSD amplitude frequency range is between 20-65 Hz in the crank pulley. It means that excitation frequencies coming from engine between this frequency ranges. This range above the 14 Hz frequency which maximum belt vibration is observed. In the PSD output, data (Figure 13), first frequency correlation is achieved perfectly but higher frequency correlation is not perfect as much as first frequency. The reason of this phenomenon is that elasticity modulus of the belt is used same at all frequency ranges. Belt elasticity modulus would be defined depending on the frequency to achieve high frequency correlation.

5.2. Modal Analysis of the System and Correlation with Frequency Response Function Test

Modal analysis is the study of the dynamic properties of systems in the frequency domain. In this study, modal analysis is performed with a finite element model of the pulley-belt system. System rotational and lateral modes have been calculated during analysis. System first rotational mode is calculated as 14 Hz and belt lateral mode is calculated as 112 Hz in the simulation model (Figure14 and Figure15).

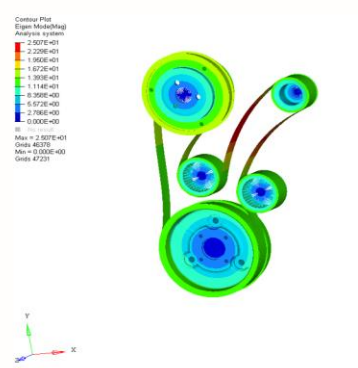


Figure14. Pulley-Belt System Rotational Mode at 14Hz

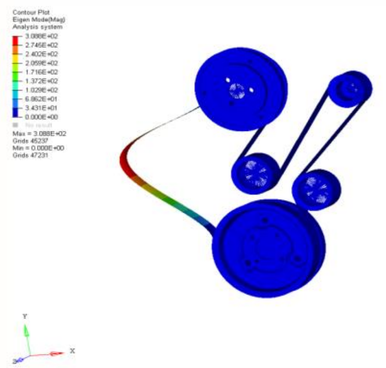


Figure15. Belt Sistem Lateral Mode at 112Hz

Specifying the belt elasticity modulus is challenge in the simulation. Belt elasticity modulus is tuned in FEM (Finite Element Model) to catch the lateral mode that is taken from FRF test. An impact hammer is used to apply a unit force to the belt and belt displacement is measured from across the belt with a laser displacement sensor placed at the belt surface normal during frequency response function (FRF) test (Figure16-Figure17). The belt lateral mode is measured as 116 Hz which is near 112 Hz lateral mode frequency of FEM. The rotational mode of the system could not be measured during test because rotational excitation can not be applied to the system so that only belt lateral mode is correlated.

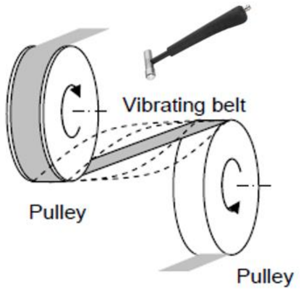


Figure16. *Belt Frequency FRF Test*

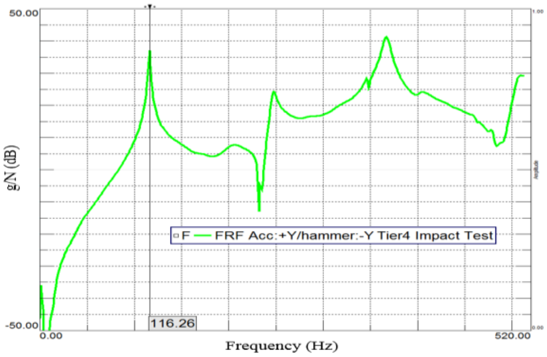


Figure17. Belt FRF Test Results

6 IMPROVED FEAD SYSTEM ANALYSIS AND TEST RESULTS

6.1. PSD Analysis with Bigger Pulley

It has been seen that in accordance with the belt elasticity modulus parameter, the belt lateral displacement changes nonlinearly (Figure 18). In that condition, belt elasticity modulus are seen as important factor on the belt displacement. It was hard to give proposal without test for the FEAD system parameters because of the uncertainty of the belt elasticity modulus in the PSD analysis. A new methodology should be developed to specify the belt elasticity modulus depending on other belt parameters and frequency. It has been understood that if the appropriate belt elasticity modulus has been captured, the belt lateral response changes in an appropriate way. For that reason, bigger alternator and tensioner pulley seems appropriate to use on the FEAD system because of the increasing belt elasticity modulus.

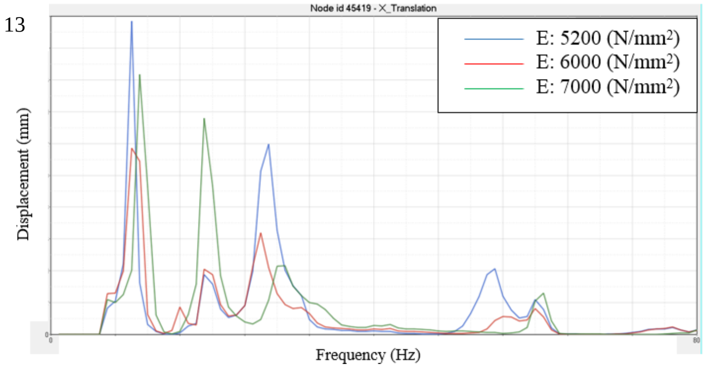


Figure18. Belt lateral displacement results in according to different elasticity modulus values with bigger pulleys (Values are normalized)

6.2. Test Results with Configuration-1 and Configuration-2 Engine

The vibration status of the configuration-1 engine FEAD system is detected with very detailed test and analysis studies which are mentioned at section 4. Configuration-1 and Configuration-2 parts are tabulated as proportional in Table3.Configuration-2 results are shown at Figure19 and Figure20. Crank pulley vibrations are compared for both configurations. As seen

Figure19, crank pulley vibrations are reduced significantly with the higher inertia flywheel. It comes to reference crank pulley vibration levels nearly with configuration-2 flywheel.

Table 3 - Tier3 I3 Engine FEAD System

FEAD System Parts	Configuration-1	Configuration-2
Flywheel inertia	1	1,86
Belt	Current	Current
Crank Pulley Diameter	1	1
Fan Pulley Diameter	1	1
Tensioner Pulley Diameter	Slot Position: Max	Slot Position: Middle
Alternator Pulley Diameter	1	1,27
Idler	1	1,14

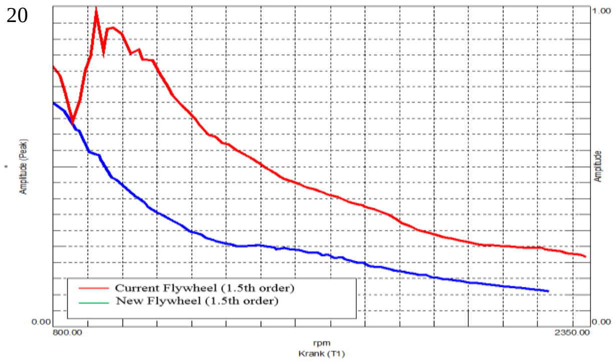


Figure19. Comparision of crank pulley vibrations with the current and high inertia flywheel (Values are normalized)

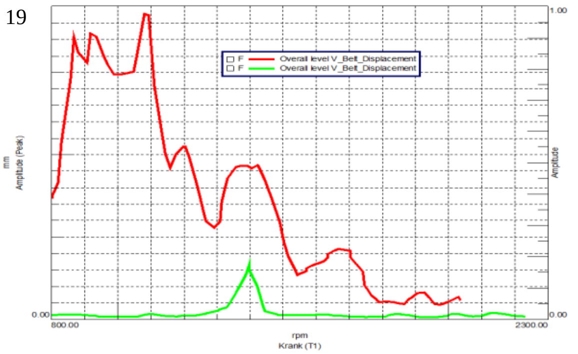


Figure20. Belt lateral displacement with the configuration-2 FEAD design (Values are normalized)

Configuration-1 engine crank pulley vibration comes to reference engine vibration level with higher inertia (Figure19). Also the alternator pulley diameter is increased 1.27 times and idler diameter is increased 1.14 times. The belt length is the same with configuration-1. The belt tensioner position is taken from max to middle to get same tension on the belt because of bigger pulleys. Belt lateral displacement result is seen at Figure20 with the configuration-2 engine parts. At the end of the study, 80% vibration reduction is ensured with configuration-2 engine parts.

The comparison of the belt lateral displacements with 3 different engine FEAD system is tabulated in Table3 comparatively.

Table 4 - Comparison of the different engine FEAD system belt lateral displacements

Configuration	Displacement (Proportional)
Configuration-1 Engine	1
Configuration-2 Engine	0,2
Reference Engine	0,06

7 CONCLUSIONS

In this study, it is aimed to develop basic assessment and development methodology to reduce belt vibration. Firstly, detailed tests have been performed to define the system dynamic behavior. A new simulation method is developed and correlated with test results. At the end of the tests, investigated belt vibration dynamics are explained as following;

- It has been thought that the FEAD belt system 1st rotational mode which is 14 Hz can be linked with the 0.75th order which is dominant between 10-25 Hz in accordance with test results. It means that engine excitations come from between this frequency range from low idle to high idle engine speed and increase the belt vibrations.
- 0.75th order is one of the reflected lateral modes of the belt and coincident with a rotational mode and it causes the increasing of the belt vibrations.

Configuration-1 engine accelerations come to nearly reference engine accelerations with the flywheel which has 1.86 times higher inertia. For further development on the belt vibration, bigger alternator and idler pulleys are used on the system. At the end of the study, %80 vibration reduction on belt is ensured with the improved parts.

It has been thought that these changings effects the belt elasticity modulus and it changes the system first rotational mode. A successful test and simulation methodology has been created and presented in this paper. It has been concluded that a new approximation should be created to detect belt nonlinear elasticity modulus parameters for the future projects.

8 ACKNOWLEDGEMENTS

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