Vibration Damping Optimization using Simulated Annealing Algorithm for Vehicle Powertrain System

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Abstract—The clutch system in a vehicle’s powertrain system controls torque transmission and has vibration damping properties. A vehicle’s clutch system is subjected to high dynamic loads and vibrations, under operational conditions, that need further system analysis. The torque generated from the vehicle’s engine creates vibrations at different levels of frequencies. For this purpose, vibration damping systems have to be designed to make the vehicle work more efficiently. In this study, the 1-D modeling of powertrain system, including metallic clutch damper springs, was subjected to vibration optimization with the Simulated Annealing (SA) algorithm. This novel methodology accelerates the powertrain system vibration optimization and provides assumptions eliminating cost and time in real vehicle testing.

Keywords—clutch damper; simulated annealing; 1-D modeling; damper torque; powertrain system; driving comfort; vibration

I. INTRODUCTION

Clutch damper springs, used in vehicle powertrain systems, are of great importance as they damp engine vibrations during torque transmission (Figure 1). Prominent studies have been carried out on the optimization of the vibration on vehicles. Torsional mode analysis was carried out in [1] investigating the modeling of powertrain systems, including automated transmission. The hydraulic hybrid powertrain system was analyzed in [2] using 1-D modeling. Analysis using 1-D simulation at stiffness levels of the clutch disc damper were studied in [3]. The natural frequency of vehicle components were studied in [4], assuming on optimal weight values. In [5], an analysis on the vibration frequency level of a 3-cylinder engine proposed improvements to the clutch design. The study of a passenger car’s powertrain system modeling determined the clutch damper disc stiffness behavior on driving conditions in [6]. The frequencies of the gearbox vibrations on different gearbox types were analyzed in [7], while in [8] the engine vibrations were analyzed by FFT method. Harmonic investigations were performed on an engine’s behavior in [9], in order to reduce the noise in the power transmission system. The design of transmission gears and the optimization of clutch-damping factors, by applying harmonic analysis, were studied in [10]. The frequency ranges on heavy vehicles were examined by modal analysis in [11]. Optimization algorithms are of high importance in vehicle engineering system design.

This study examines the powertrain system of a gasoline engine vehicle, having 110Nm torque, integrating the Simulated Annealing (SA) algorithm into powertrain system vibration optimization simultaneously with 1-D modeling, providing assumptions and precautions prior to production phases.

II. CLUTCH DAMPER SYSTEM

Clutch damper systems are designed to damp excessive vibration transmission from engine to gearbox. The clutch damper disc can be observed in detail in Figure 2. Metallic damper springs, located in the clutch disc, enable damping under driving conditions. Damper spring’s stiffness value is the sum of the stiffness of each spring ($k_{\text{equivalent}}$). The importance
of the stiffness behavior can be observed on the model analysis of the powertrain system [6]. Damper torque is applied on the clutch disc to get damper torque capacity which has high importance on the powertrain system optimization. Damper torque’s graph indicates an hysteresis, due to the internal friction which has effect on the dampening ability (Figure 3). Figure 4 shows the loading and unloading phases of the clutch damper disc in operational condition. In this study, the clutch disc assembly can be compressed up to 6.5° radial travel.

III. MODELING OF THE POWERTRAIN SYSTEM

The powertrain system model belongs to a specific type of passenger vehicle. Simcenter AMESim was utilized to analyze the model (Figure 5). The metallic spring was selected from the library of AMESim. The stiffness value 16Nm/°, according to the results of experimental disc measurements, was provided as input to the model interface (Figure 6). Figure 7 contains the sample output graph for the analyzed 1-D modeling. The vibration was taken from the gearbox model part. The selected values on this graph were used for the vibration optimization using the SA algorithm integrated in AMESim. The gearbox in the powertrain system is important in displaying the dampening effects of the clutch system. In case the target dampening is not obtained from the clutch system, mechanical damages may occur in the powertrain system.

IV. SA ALGORITHM INTEGRATED WITH 1-D MODELLING

SA algorithm is designed to perform a global search, preventing the convergence to locally optimal solutions, by allowing movement to the worst solutions through the Boltzmann factor, simulating the annealing process of metals.
Its name comes from the simulating the behavior of metals in the annealing process, in which the metal is heated and kept at stabilized temperature while slowly cooling. The optimization process starts by generating a random initial solution, while SA allows movement resulting in solutions that are worse (uphill moves) than the current solution in order to escape from local minima. Each iteration of a new current solution leads to the decrease of the current temperature in the ratio of the Boltzmann probability factor enables the algorithm to take worst results in the range of the Boltzmann probability equation, while the global minimum is searched and finally found.

\[ \text{Boltzmann factor} = \frac{1}{e^{\left( \frac{F(\text{New}) - F(\text{Old})}{T} \right)}} \]  

The optimization is performed by a system programmed in Python integrating the SA algorithm and AMESim analysis. Figure 8 shows the process of each main iteration. Figure 9 describes the algorithm of the Python script. At first, the function code of the AMESim 1-D modeling is defined. Then, AMESim function run code is loaded. After that, the algorithm initializes X0, T0, k, N, M, and iteration parameters are entered into the algorithm. At the end of the algorithm the best value of F_best, X_best is obtained.

\[ T_{\text{new}} = k \cdot T_{\text{current}} \]  

Uphill moves eliminate each local minimum, while the global minimum is searched and finally found.

\[ T_{\text{end}} = T_{\text{initial}} \cdot \left( \frac{k}{k+1} \right)^{\frac{N}{M}} \]

Fig. 10 present the SA algorithm’s flowcart in detail. Spring stiffness value defines the initial search parameter and SA algorithm parameters such as temperature T, cooling ratio k and iteration parameters are entered into the algorithm. At the end of the algorithm the best value of F_best, X_best is obtained.

The result values of each run were very close. Figure 11 shows the graph of the objective function and temperature for an example run. It seems that SA algorithm successfully eliminates local minima and converged to the global minimum point at each run. Moreover, Figure 11 also shows the vibration decrease. The optimum damper stiffness was 15.715Nm/°. SA algorithm inputs have many effective parameters to change search capability. Table II shows a brief vibration analysis values are directly linked to the key parameters of the SA algorithm. Therefore, in case the key parameters of the algorithm change, the obtained values are expected to change. This case needs detailed analysis in SA algorithm parameter variations.

| Run   | X (Nm/°) | Objective Function (rad/s²) |
|-------|----------|----------------------------|
| 1     | 15.749   | 86                         |
| 2     | 15.854   | 92                         |
| 3     | 15.801   | 89                         |
| 4     | 15.715   | 84                         |
| 5     | 15.732   | 85                         |

Table I shows the obtained minimum vibration results on the gearbox. X represents the clutch damper stiffness level and optimum vibration values for each run are exhibited.

V. SIMULATION RESULTS

Fig. 8. Python script integrating AMESim and SA algorithm

Fig. 9. AMESim integrated SA algorithm

Fig. 10. SA algorithm - vibration minimization through SA and AMESim
This method saves cost and time on the optimization of the 21%, using the optimum clutch damper spring stiffness value. Vibrations in the gearbox were decreased by and used with 1-D modeling for torsional vibration optimization of a vehicle’s powertrain system, designed for a middle segment vehicle having an 110Nm torque gasoline engine. Excessive vibrations are making the driving experience uncomfortable, while unwanted oscillations result in mechanical damages. New generation optimization algorithms presented in order to find optimum design parameters that reduce the vibration level. The SA algorithm was developed and used with 1-D modeling for torsional vibration optimization. Vibrations in the gearbox were decreased by 21%, using the optimum clutch damper spring stiffness value. This method saves cost and time on the optimization of the vibration dampening in a powertrain system.

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Table II. COMPARISON RESULTS OF BASE VS OPTIMUM DESIGN

|                  | Base design | Optimum design |
|------------------|-------------|----------------|
| X (Nm°)          | 16          | 12.715         |
| Objective Function (rad/s) | 105     | 84             |

Fig. 11. SA algorithm: Objective function vs temperature graph