

New Hybrid Genetic Algorithm for Pitch Sequence Optimization of CVT Variator Chain

Kenji Tsutsumi, Yoshitaka Miura, and Yusuke Kageyama
Nissan Motor Co., Ltd.

Arata Miyauchi
ESTECH Corp.

ABSTRACT

A CVT variator chain system is superior in transmission efficiency to a belt system because of its lower internal friction. However, a chain produces more noise than a belt due to the long pitch length of contact between the pulleys and rocker pins. This study focuses on optimization of the pitch sequence for reducing chain noise. The previous pitch sequence was suitably combined of links of different lengths to improve noise dispersibility for reducing chain noise. First, the object function was defined as the reduction of the peak level of 1st-order chain noise combined with a well-balanced the levels on the low and high frequency sides. Interior background noise consisting of road noise and wind noise have the characteristic that they increase as the frequency decreases. Therefore, the object function was aimed at reducing the peak level of 1st-order chain noise by shifting the chain noise energy from the vicinity of the 1st-order band to the low frequency side in consideration of the masking effect of low-frequency background noise. Next, clustering clarified the characteristics of the pitch sequence design space as a multimodal space. Finally, "Hybrid genetic algorithm", combining a genetic algorithm and local search was developed in order to search widely and deeply in the multimodal space for global optimal solutions. Hybrid-GA found global optimal solutions from a very large design space of 3^{80} patterns. This pitch sequence was reduced the peak level of 1st-order chain noise by 2.8 dB compared with that of the previous pitch sequence.

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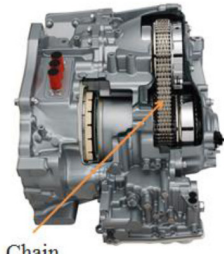
INTRODUCTION

Table 1 compares the relative advantages and disadvantages of variator chain and belt systems [1-2]. A CVT variator chain system is superior to a belt system in terms of transmission efficiency because it has less internal friction. However, because of the long section (pitch length) of contact between the pulleys and rocker pins, a chain has a structural disadvantage with respect to noise and vibration.

Principal measures taken against chain noise include shortening the pitch length (shorter pitch) and changing the link pattern (pitch sequence). However, there is a limit to how much the pitch length can be shortened because it affects torque capacity and chain strength.

Therefore, in this work attention was focused on improving noise and vibration performance by optimizing the pitch sequence while minimizing the impact on torque capacity and chain strength. The previous pitch sequence suitably combined links of different lengths to improve noise dispersibility, thereby reducing the peak level of 1st-order chain noise [3].

Table 1. Comparison between chain and belt systems

	Chain system	Belt system
Structure	 Chain	 Belt
Transmission efficiency	+	Reference
Noise	-	Reference

In this study, the frequency characteristics of interior background noise were used to shift chain noise energy near the 1st-order band to the low frequency side with the aim of reducing the peak level of 1st-order chain noise. The pitch sequence was optimized by using a genetic algorithm and local search (Fig. 1).

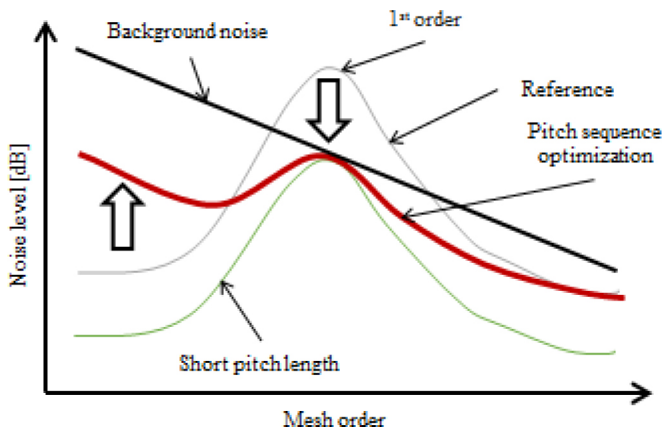


Figure 1. Concept for improving chain noise

THEORY

Evaluation Method for Pitch Sequence

Figure 2 shows the pitch sequence that served as the reference for optimization. The x-axis shows the pin number and the y-axis shows the ratio of two pitch lengths (long/short). As shown in the figure, the previous pitch sequence consisted of two types of pitch lengths.

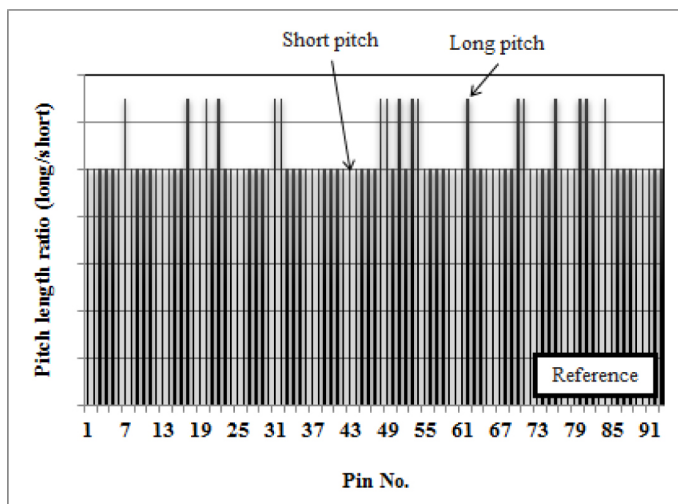


Figure 2. Pitch sequence

The frequency characteristics of the pitch sequence were evaluated with the following method.

1. The pitch sequence is converted to an excitation force waveform expressed in a time history.
2. A frequency analysis is performed on the excitation force waveform for one revolution of the chain as one cycle. The results of a Fast Fourier Transform (FFT) analysis of the frequency characteristics of the excitation force waveform produced by the reference are shown in Fig. 3.

3. An evaluation is made of the frequency characteristics of the excitation force level.

The region of the 1st-order mesh is defined in a range of ± 20 mesh orders in relation of the orders of the 1st-order mesh band that is determined by the number of rocker pins in the chain. In relation to the center of this region, a low frequency area and a high frequency area are defined on either side.

As indicated by the reference pitch sequence, the frequency characteristics of the excitation force for improving the dispersibility of chain noise (Fig. 3) showed that the peak level of 1st-order chain noise was the highest. The most important point for improving noise and vibration performance is to reduce this peak level of 1st-order chain noise.

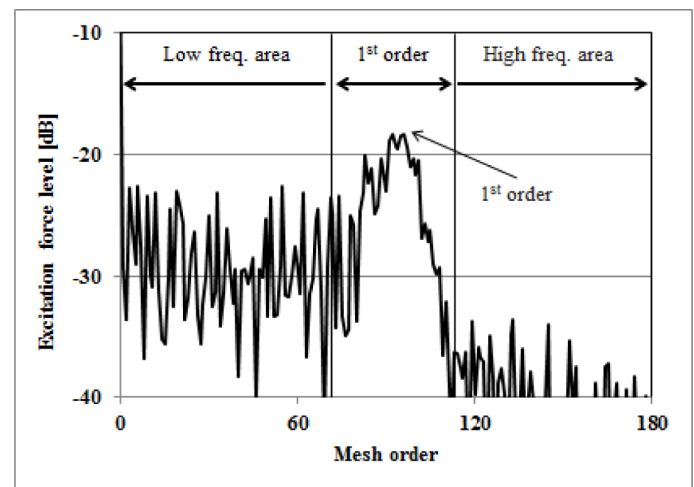


Figure 3. FFT analysis result of pitch sequence

Object Function for Optimization

As shown in Fig. 4, target levels (upper and lower limits) were defined for the frequency characteristics of chain noise in order to evaluate whether the frequency characteristics of the excitation force induced by the pitch sequence were good or poor. If the frequency characteristics of chain noise were contained within the target range, the pitch sequence was judged to be good; the amount extending outside the target range was evaluated as the nonconforming quantity q in Eq. (1) below.

$$q \equiv \sum_{i=0}^n [\{ \min(A_i - L_i) \}^2 + \{ \max(A_i - L_i) \}^2] \quad (1)$$

where the symbols were defined as noted below. The nonconforming quantity q was used as the object function for optimization and the aim was to minimize q .

- A_i : excitation force level of the i^{th} order
- L_i : value of the lower line (lower limit value) of the i^{th} order
- U_i : value of the upper line (upper limit value) of the i^{th} order

The upper and lower lines (U_i , L_i) used for minimizing the nonconforming quantity q were defined as follows:

1. Low frequency area

On the low frequency side, the background noise of the vehicle interior is dominant, so relative deterioration of the vibration characteristics is allowed. In actuality, the results of background noise measurements in an actual vehicle show that the noise level increases with decreasing frequency (Fig. 5). The aim of the optimization exercise was to shift the chain noise energy from the vicinity of the 1st-order band to the low frequency side and to use the above-mentioned masking effect of the interior background noise against chain noise. For that purpose, the upper line of the low frequency side was set high relative to the reference, and the lower line was also set with the aim of shifting the chain noise energy.

2. 1st order band

The target reduction for the peak level of 1st-order chain noise was defined as an equivalent reduction of -3 dB by shorter pitch by one class (e.g., 8□7 mm pitch). The upper line was defined at -3 dB below the reference.

3. High frequency area

Interior background noise is low on the high frequency side, so no masking effect for chain noise can be expected. For that reason, the peak chain noise level of the reference was selected as the upper line on the high frequency side with the aim of keeping the noise level from becoming worse than the reference.

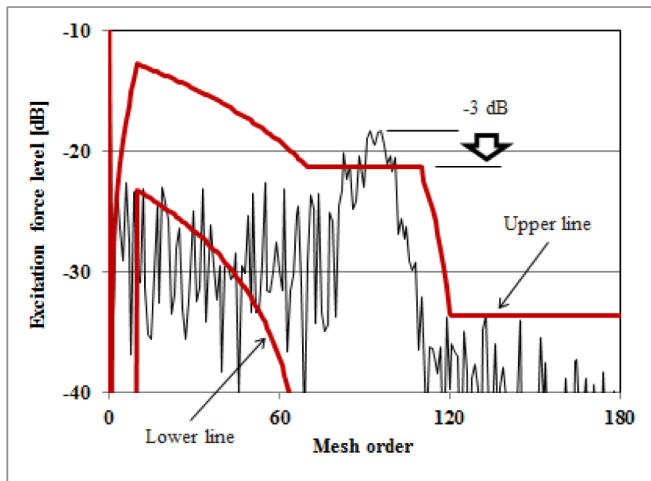


Figure 4. Object function for pitch sequence

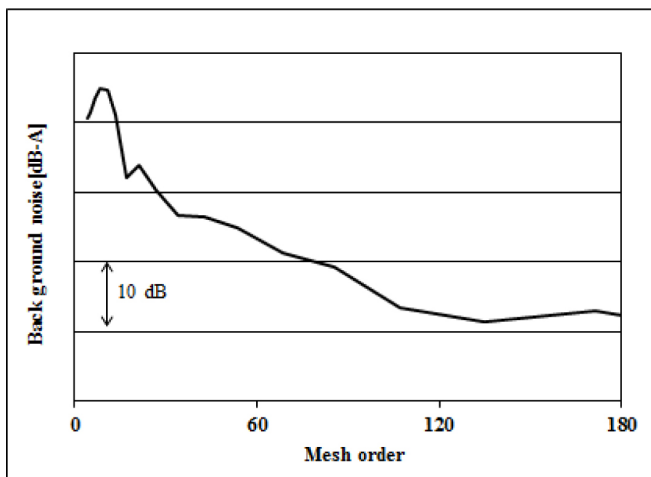


Figure 5. Frequency properties of the background noise (Nissan C-class sedan, vehicle speed 20 km/h, Interior noise)

Preliminary Survey for the Choice of the Optimization Method

As the first step, a preliminary survey was conducted in which Isight 5.9, a general-purpose optimization software tool made by Dassault Systems Simulia, was used to optimize the pitch sequence [4]. Four optimization methods in which Isight is implemented were used in the survey, namely, Multi-island Genetic Algorithm, Downhill Simplex, Pointer and Adaptive Simulated Annealing. The pitch sequence in this preliminary survey was composed of three pitch lengths—short, medium and long. The pitch ratios were medium/short = 1.2 and long/short = 1.3.

Figure 6 shows the optimization results obtained for the pitch sequence with the four methods. The peak level of 1st-order chain noise obtained with Multi-island GA was below that of the reference for the first 2000 evaluations. Subsequently, the peak level was not reduced even though the number of evaluations was increased. Presumably, that is because the optimization converged to a local optimal solution and was not able to find a global optimal solution [5]. Except for the Downhill Simplex method, the peak level of 1st-order chain noise decreased with all the other optimization methods. However, the amount of reduction in the peak level relative to the reference was small, so the effect of optimization was limited. Accordingly, optimization in a wider design space is necessary in order to obtain a pitch sequence for significantly improving the frequency characteristics.

Moreover, the relationship between the pitch sequence and the frequency characteristics of chain noise, which was the target of this study, showed strong nonlinearity and discontinuity. Just changing one pitch length from short to long markedly changed the frequency characteristics of chain noise over the entire frequency range. Based on the foregoing results, it was concluded that, as the first step, the design space of the pitch sequence must be made clear and that a method must be developed for optimizing the pitch sequence over a wide range and in accordance with its features.

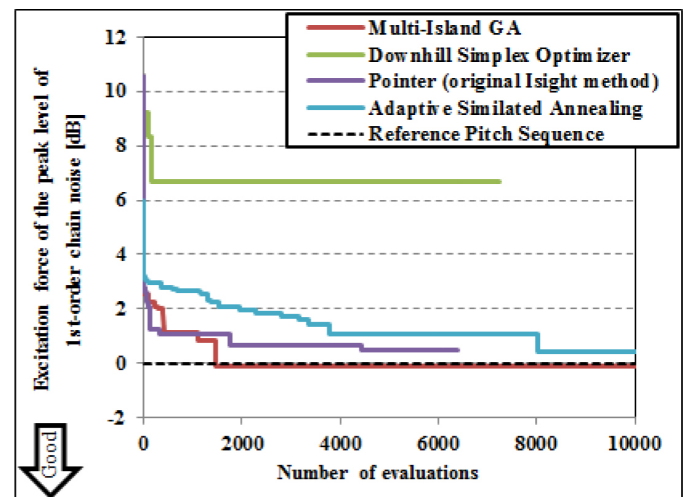


Figure 6. Optimization results for pitch sequence by using current methods