Establishment of Evaluation Method for Rattle Noise of Steering Gear for Column Type Electric Power Steering (C-EPS®) System

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Due to increased environmental awareness, "quiet vehicles" such as hybrid cars are driving the market and quietness is increasingly being demanded of column type electric power steering (C-EPS) systems. At the same time, increasing market globalization requires dealing with a wide variety of rough road conditions, which are frequently observed in emerging countries. In this paper, the causes of rattle noise in C-EPS manual steering (MS) gears will be touched on and a quantitative method of evaluating such noise generation proposed. Utilizing a neural network as a means of predicting rattle noise has made it possible to design an MS gear optimally suitable for the vehicle.

Key Words: *rattle noise, manual steering gear, electric power steering, evaluation method, neural network*

1. Introduction

Installation of column type electric power steering (C-EPS®) started originally with light vehicles and recently has been expanding to medium and large vehicles because of higher motor output being possible and having the advantage of easy mounting. Also, because of increased consciousness of environmental issues, "quiet vehicles" such as hybrid vehicles or electric vehicles have been gaining popularity in the market, and therefore quietness is increasingly demanded in C-EPS®. Furthermore, suitability for various rough road conditions frequently observed in emerging countries is also demanded in line with rapid globalization of the market.

During driving on rough roads, rattle noise may emanate from the manual steering gear (MS gear), a main component of C-EPS®, as a result of reverse input from the road surface. Appearances of C-EPS® and MS gear are shown in **Fig. 1**. One factor causing rattle noise is considered to be teeth contact noise between the rack and pinion. This can be controlled by making the backlash of the MS gear small. However, there is concern that such may cause driving stability to deteriorate due to friction increase, etc. In other words, it is important in designing the MS gear that both driving stability and quietness be considered in order to maintain the most appropriate balance. So far, in regard to rattle noise evaluation, there has been no definitive judgment criterion except evaluation by subjective rating done inside the vehicle.

This paper introduces a method for predicting rattle noise in the C-EPS® MS gear in the design stage and recommends optimal design specifications for the MS gear per vehicle.

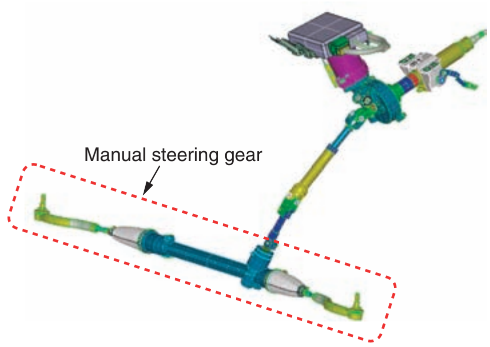

Fig. 1 Structure of C-EPS system

2. Factors Causing MS Gear Rattle Noise

The MS gear rack & pinion structure is shown in **Fig. 2**. MS gear rattle noise occurs by collision caused by pinion movement due to clearance with the supporting bearings during rack & pinion engagement component force generation resulting from reverse input from the road surface, or by teeth contact caused by rack separation from the pinion. Accordingly, in order to reduce the occurrence of rattle noise, it is important to reduce the movement of the rack & pinion. To this end, the three points shown below can be considered.

- To reduce the force causing rack & pinion separation
- To reduce rack & pinion displacement
- To provide force in advance to suppress rack & pinion movement

As representative factors influencing these points, gear tooth specifications, part clearances, spring loads, etc. are considered. Furthermore, as this problem is influenced by forces from road surfaces, it is necessary to consider reverse input load on the rack also as one factor. These multiple factors work in combination to determine the level of MS gear rattle noise, and therefore in order to quantitatively acquire each factor's extent of contribution, a bench evaluation has been carried out as shown below.

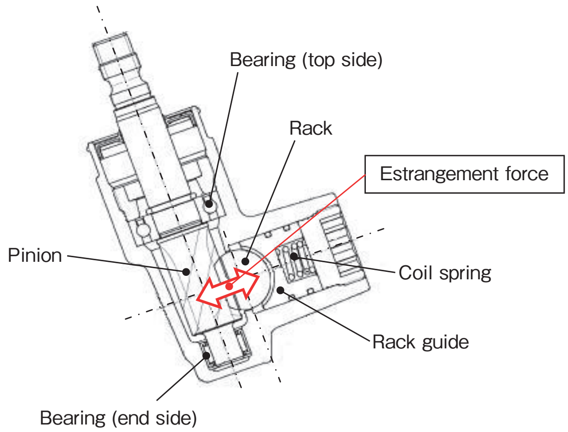

Fig. 2 Structure of rack and pinion

Several levels of samples were prepared for each factor influencing rattle noise in order to confirm how the MS gear vibration acceleration fluctuates by carrying out bench evaluation. As an example, the relation between the pinion axial rigidity and the vibrating acceleration rate is shown in **Fig. 4**. The higher the pinion axial rigidity, the less the vibration acceleration of MS gear becomes. Also, on "Specification A" and "Specification B," for which the conditions of other factors are different, the sensitivity of the pinion axial rigidity against vibrations is different, and the interactions on each factor are recognized.

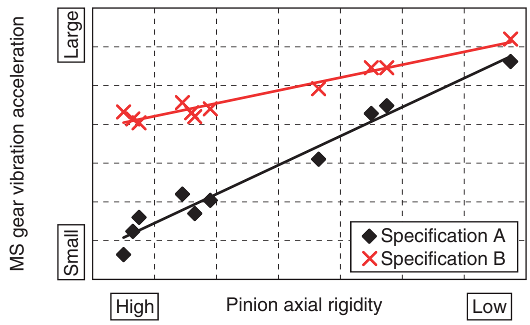

Fig. 4 Relation between pinion axial rigidity and vibration of MS gear

3. Bench Evaluation Method on Rattle Noise

As a bench evaluation method for rattle noise had already been established, this method was used. By providing load oscillation simulating reverse input when driving on rough roads to the rack, the vibration acceleration on each MS gear part has been measured. Here, simulated inertia from the steering wheel is provided to the pinion end. An outline of the evaluation method is shown in **Fig. 3**. In evaluating MS gear rattle noise during driving on rough roads, measuring the MS gear vibration acceleration is easier and more accurate for quantification than measuring actual sound pressure. This is because when driving on rough roads, the vehicle ambient noise is higher than the rattle noise, and therefore it is difficult to extract and quantify only the noise emanating from the MS gear.

4. Prediction of Rattle Noise

First, the method of predicting MS gear rattle noise is explained. Determination of the magnitude of MS gear rattle noise, that is, vibration acceleration, is not by a single factor but rather by multiple factors interacting, as already stated. Therefore, it has been determined to express the MS gear vibration acceleration with the objective function in which plural factors have been made to be variables based on accumulated past data.

4. 1 Utilization of Neural Network

In this paper, regarding the method of formulating the objective function as a function of multiple variables, the radial base function (RBF) network[1], which is one neural network, has been used. The RBF network consists of a three-layer structure as shown in **Fig. 5**. There is a middle

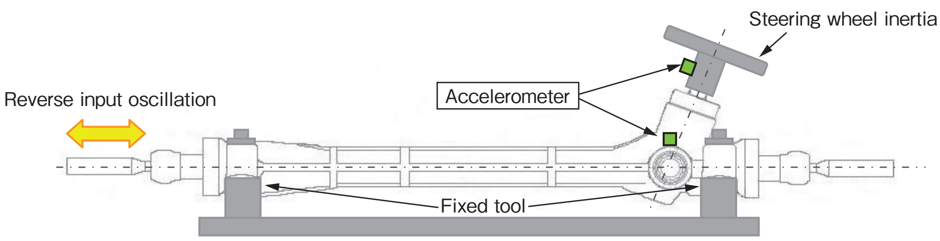

Fig. 3 Evaluation method

layer between the input layer and the output layer where nonlinear conversion is made. In the RBF network, it is possible to define output information as a function of the input variable after learning this from given actual measurement data and to formulate with the smooth linkage between the actual measuring points. The reason why the RBF network is used this time is that it has been considered to be difficult to make better prediction with the linear multiple regression equation, because the vibration acceleration of MS gear and each factor are not maintained always with a linear relationship and the interactions between the factors are also recognized.

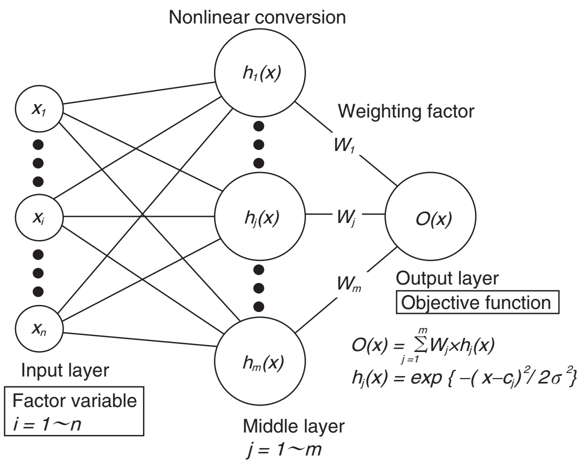

Fig. 5 Neural network model

4. 2 Formulation of MS Gear Vibration Acceleration

Accumulated actual measurement data based on bench evaluations so far have been made the learned data in the RBF network, and the MS gear vibration acceleration has been formulated as the function having variables including design factors such as gear specifications. In **Fig. 6**, a prediction result of actual measurement points and a prediction result of the RBF network and, for the purpose of comparison, prediction results of the linear multiple regression are shown as examples. The horizontal axis is rack axial force, one of the factor variables, and in "Specification A" and "Specification B," the level of other factor variables differs. While a RBF network prediction result of a smooth curved line passing through actual measurement points is obtained, it can be understood as per the prediction result of the linear multiple regression that the interaction cannot be considered and accuracy is bad. By formulating the MS gear vibration acceleration, as it is possible to predict the MS gear vibration acceleration even on the point which is not an actually measured point, it is possible to estimate MS gear vibration acceleration when the factor variable has fluctuated.

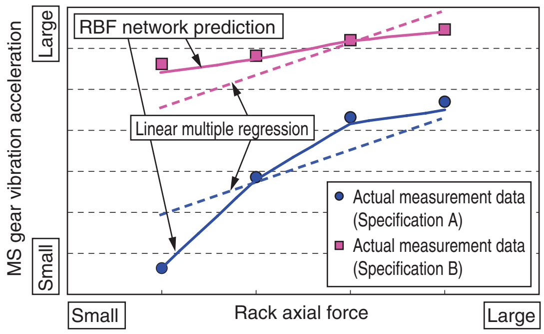

Fig. 6 Prediction result of vibration acceleration

5. Establishment of Evaluation Method by Utilizing Predictions

5. 1 Structure of Rattle Noise Evaluation Method

Here, this section describes the rattle noise evaluation method by utilizing the prediction method stated above. **Figure 7** shows the structure of the evaluation method. First, with the input conditions such as gear specifications, clearance of each part, bearing rigidity and spring specifications, MS gear vibration acceleration is acquired from the RBF network based on actual measurement data in the past. Next, with consideration of being differently audible depending on vehicles under the same bench vibration acceleration, the threshold value of the vibration acceleration as the basis of judgment has been determined based on the actual results in the past.

As an example, on seeing the differences between a gasoline vehicle and a hybrid vehicle, the hybrid vehicle is quieter when driving at low speed and, therefore, the threshold value of the vibration acceleration is set with the small value. When the predicted vibration acceleration exceeds the established threshold value beforehand, it is judged that the rattle noise occurs and, then, the design specification shall be reviewed again. The suitability of the prediction is verified by carrying out the bench evaluation and the vehicle evaluation for confirmation after making the judgment of passing. Furthermore, the information acquired anew from the actual machines can be fed back to the data base as the learned data and therefore the accuracy of prediction has been improved as the number of measurement increases.

5. 2 Utilization Example of Evaluation Method

Finally, an example of utilizing this evaluation method is explained. This is a case study on "Specification A" focused on measures for the rattle noise, "Specification B" oriented on cost, and "Specification C" balanced by both specifications. In summing up the result of prediction of MS gear bench vibration acceleration using this method, a map of the vibration acceleration can be made as per **Fig. 8**. With this, the relation between the MS gear design specification and vibration acceleration can be

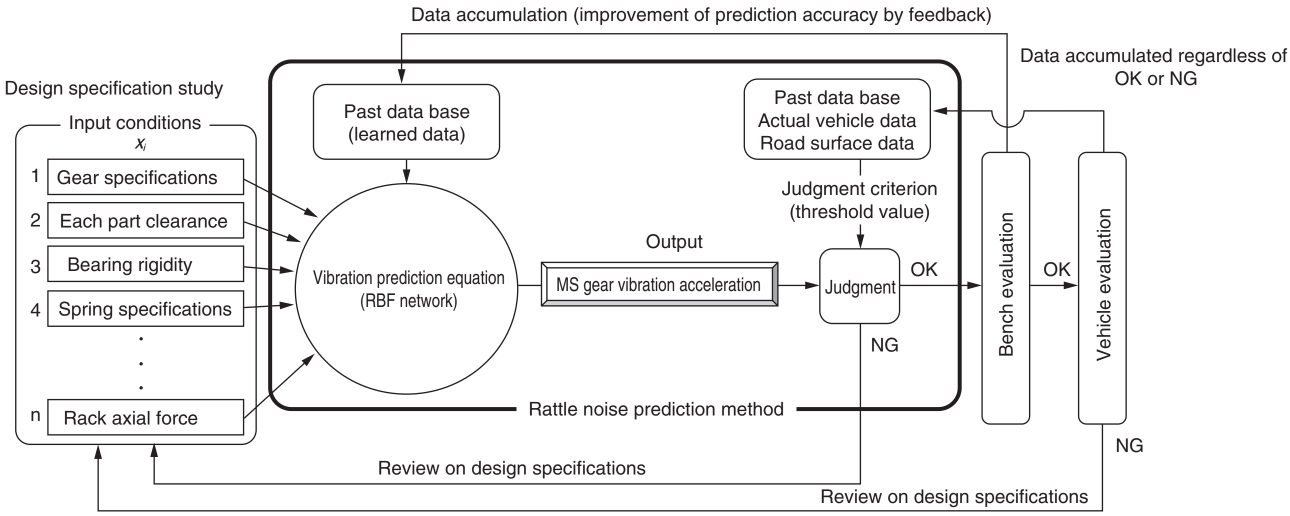

Fig. 7 Model of evaluation method for rattle noise of MS gear

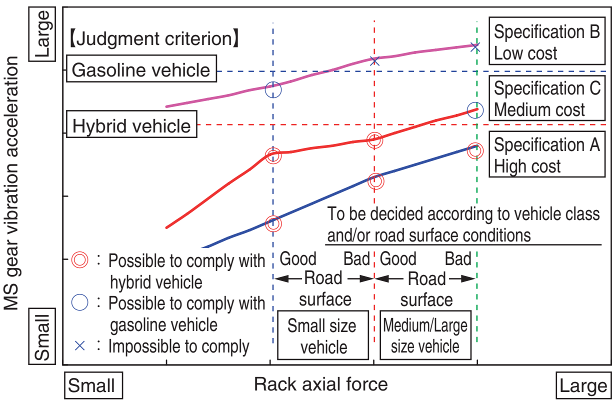

Fig. 8 Map of predicted rattle noise

visually acquired. With "Specification A," it is estimated that rattle noise does not occur at all even with a hybrid vehicle and therefore it is recommendable for all vehicles. However, due to high cost, there is no versatility. And then, with consideration of the road conditions assumed from vehicle classes and destinations, the magnitude of the rack axial force as an outside force has been added to the judgment criteria. For example, by restricting the destinations under better road conditions, small size gasoline vehicles generate a low magnitude of vibration owing to small rack axial force loaded on the rack and, therefore even with "Specification B" having merits on cost, it is estimated that the rattle noise does not occur. Then, for the medium size gasoline vehicle for areas under severe road conditions and the small size hybrid vehicles, it can be recommended that "Specification C" is the optimal specification.

6. Conclusion

This report described an evaluation method of MS gear rattle noise for C-EPS®. Also, by changing the objective functions and factors, this method can be widely applied on the various noise predictions and evaluations. So far, the noise evaluation of C-EPS® has been liable to rely on the subjective rating within vehicles, but taking this study as a foothold, JTEKT will further develop more accurate prediction methods and ensure optimal designing in the initial stages of development.

Reference

1) T. Yahagi, M. Hagiwara, T. Yamaguchi: Neural network and fuzzy signal processing, CORONA PUBLISHING (1998) 36.

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