Technology Introduction

Method for Reducing Jig Resonance Using Modal Analysis

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1 Introduction

With the recent widespread adoption of battery electric vehicles (BEV) and hybrid electric vehicles (HEV), automobiles have become much quieter. As the background noise in the vehicle cabin has decreased, the noise from peripheral components has come to the fore, which is expected to lead to even more stringent requirements for lower NVH [Note 1)]. It is now essential to pursue noise and vibration reduction in product development through sophisticated NVH evaluation.

The conventional test bench evaluation approach, in which the product is installed in a test jig assembly, makes it difficult to identify the inherent NVH characteristics of the product because resonance occurs between the product and the jig assembly. We have established a design method using modal analysis to eliminate the jig resonance in order to identify the vibration mode during actual operation. This paper introduces the method.

Note 1) An acronym for noise, vibration, and harshness.

2 Product Introduction

With the popularity of electric vehicles, the demand for electric oil pumps used to cool/lubricate the main engine motor and battery has increased. Electric oil pumps with integrated mechanical and electrical systems are finding wider applications due to their independence from engine speed. KYB is developing downsized, high-efficiency electric oil pumps by utilizing its accumulated pump design technology. Fig. 1 shows an example of an electric pump for cooling/lubricating purposes.

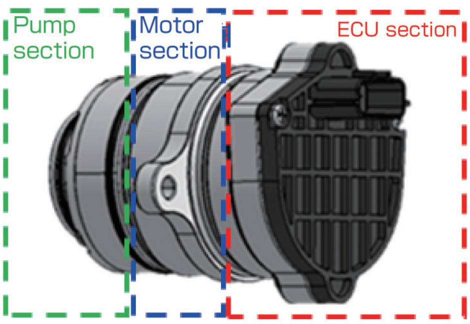

Fig. 1 Electric pump for cooling/lubrication

3 Issues with NVH Evaluation Equipment

Conventional evaluation test equipment provides an environment to evaluate a simulated vehicle. The environment actually includes various disturbances caused by the complex test jig configuration, such as oil agitation by the chain through the belt drive or sprockets, under which the vehicle has been evaluated (Photo 1). These many disturbances in the test jig assembly have made it difficult to evaluate pump NVH alone. In some cases, it was difficult to evaluate the reliability of vibration-reducing parts and to identify variations.

The disturbances can be classified into the following three main types:

[1] Transmission of drive-side vibration caused by chain drive

[2] Air entrapment in the pump due to the agitation of the hydraulic oil

[3] Resonance of test jigs

Based on the idea that the elimination of these disturbances would make it possible to evaluate the pump NVH alone, we made new NVH evaluation equipment consisting mainly of a direct-drive type performance tester (Photo 2). By replacing the conventional chain-drive type with the direct-drive type, two of the above three disturbances [1] and [2] were eliminated, but disturbance [3] (resonance of test jigs) remained. The reason for this is that the pump runs at

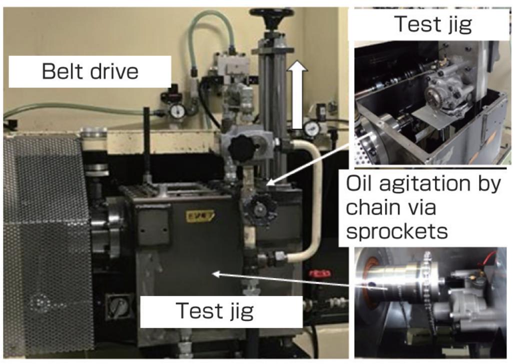

Photo 1 Conventional belt-drive type evaluation equipment

variable speeds according to the flow demand to generate vibrations over a wide range of frequencies from several Hz to several kHz, which is likely to cause resonance with the natural frequency of the jigs. Once resonance occurs, the vibration of the pump will increase significantly, making it difficult to determine the pure NVH characteristics of the pump. We then established a modal analysis technology to prevent the resonance of the test jigs and designed a test jig assembly that eliminates the resonance.

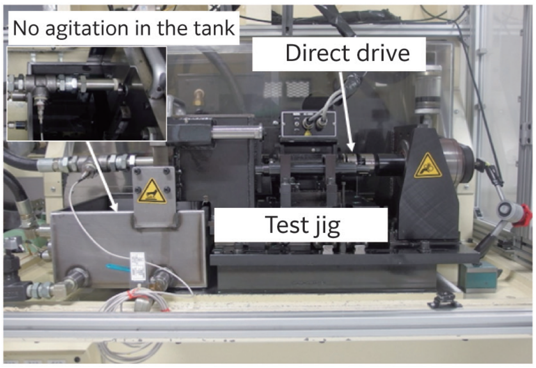

Photo 2 Direct-drive type evaluation equipment

4 Determining Resonance Frequency and Identifying Resonant Test Jigs

4. 1 Determining Resonance Frequency of Test Jigs

The color map in Fig. 2 shows the result of pump NVH evaluation using the direct-drive type evaluation equipment. The horizontal axis shows the frequency, and the vertical axis shows the pump speed. The color represents the magnitude of the pump vibration. The radial lines represent the rotational order components of the pump. The red-framed area with large vibration in a certain frequency band independent of pump rotation is the frequency band where the test jig resonance occurs. Two resonance frequency bands are observed: 1.3 kHz to 1.6 kHz and 3.5 kHz to 4.5 kHz. Resonance occurs when the natural frequency of one (or more) of the test jigs around the pump matches one of the rotational order components of the pump[Note 2], thereby influencing the pump vibration.

Note 2) Order components of pump rotation

A phenomenon that occurs once in the period of one revolution of the pump is the 1st-order component of the pump rotation. Its nth multiple is called the nth-order component.

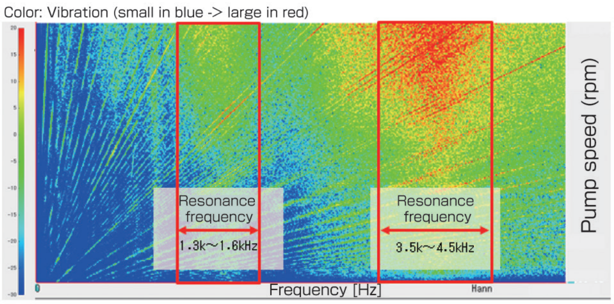

Fig. 2 Color map of pump NVH evaluation

4. 2 Subdividing the Test Jig Assembly

To identify resonant jigs, we subdivided the test jig assembly into nine jigs including the pump (Fig. 3).

We installed a three-axis accelerometer on each jig and the pump to identify resonant jigs by experimental eigenvalue analysis and to measure and analyze frequency responses during acceleration. We conducted two patterns of measurement and analysis, i.e., operational modal analysis and experimental modal analysis, to improve the accuracy of experimental eigenvalue analysis and to try to identify resonant jigs with higher accuracy.

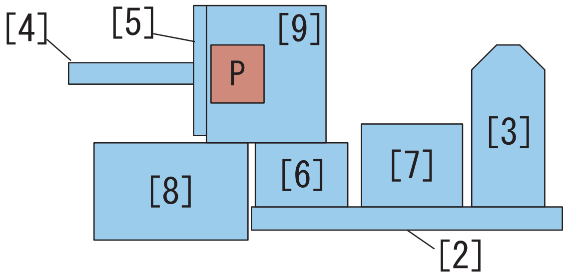

Fig. 3 Test jig assembly divided into nine jigs including pump

4. 3 Operational Modal Analysis

Operational modal analysis is a vibration mode analysis approach to pump NVH evaluation. Measurements can be made under actual test conditions to obtain analysis results that reflect the actual environment. We measured the power spectrum[Note 3] and the cross spectrum[Note 4] of the

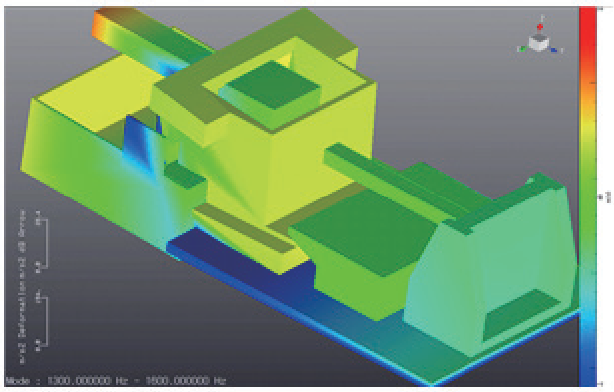

Fig. 4 Test jig vibration mode in 1.3 kHz to 1.6 kHz

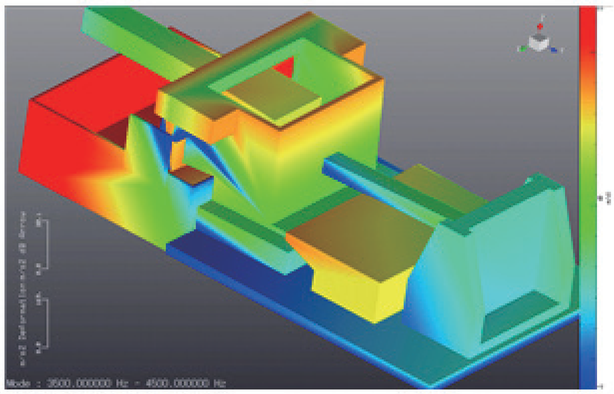

Fig. 5 Test jig vibration mode in 3.5 kHz to 4.5 kHz

test jigs and visualized the vibration mode in the resonance frequency bands as shown in Figs. 4 and 5. Like the color map, these figures use color to represent the magnitude of vibration: large vibration is indicated by red.

Note 3) Power spectrum: The signal power is divided into each specific frequency band and the resulting power for each frequency band is expressed as a frequency function. This is called the power spectrum.

Note 4) Cross spectrum: The frequency components of the spectrum of two signals are multiplied by each other and averaged. The result is called the cross spectrum.

4. 4 Experimental Modal Analysis

Experimental modal analysis is a vibration mode analysis approach based on the frequency response function obtained from excitation tests. We conducted an excitation test on the pump installed with the test jigs and on the same pump alone. This is because the vibration mode of the pump may depend on whether the pump is with the test jigs or alone.

Based on the results of the actual and experimental modal analyses, Table 1 shows the test jigs whose natural frequencies may be within the resonance frequency band. We comprehensively reviewed these analysis results and determined that the red-framed test jigs Nos.7, 8, and 9 required resonance improvement.

Table 1 Identified resonant jigs

Jig No.	Operational modal analysis	Experimental modal analysis	
	Jig ass'y	Jig ass'y	Jig alone
No. 2	×	○	×
No. 3	×	×	×
No. 4	×	×	×
No. 5	×	×	×
No. 6	×	×	×
No. 7	○	○	○
No. 8	○	○	○
No. 9	○	○	○

○: The natural frequency may be within the resonance frequency band.
× : The natural frequency is unlikely to be within the resonance frequency band.

5 Optimization of Test Jigs

5. 1 Procedure for Improving Test Jigs

After identifying resonant jigs, we attempted to modify the geometry, material, and/or other factors of these test jigs to change their natural frequency. Alternatively, we tried to increase the rigidity of these jigs to reduce the vibration level (inertance). To reduce cost, we also tried to design an efficient test jig that did not involve complex geometry. These modified jigs were analyzed with a FEM software program called ANSYS® and subjected to modal analysis by simulation. Then, we prospected the natural frequencies of the test jigs with different geometries.

However, for test jigs with low rigidity, the modal analysis produced many calculation results of the natural frequency, resulting in less accurate analysis. To improve the accuracy, low-rigidity jigs were subjected to experimental modal analysis to determine the vibration mode with actual measurements before improving them. Fig. 6 is a flowchart showing the improvement procedure. The analysis approach to be selected depends on the rigidity of the test jigs. The final jig geometry was checked by simulation modal analysis to see if it had given an improvement. If insufficient improvement was found we modified the jig geometry and repeated the process until the goal was achieved. After the simulation modal analysis verified the achievement of the goal, the test jig was manufactured and subjected to experimental modal analysis, and the effect of the improvements was verified by actual measurement.

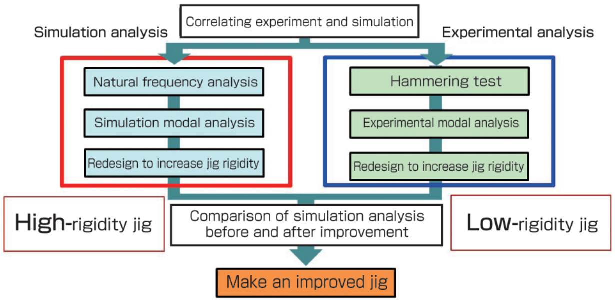

Fig. 6 Improvement flowchart

The goal of the improvement was set as a 50% reduction of the inertance of the test jig in the direction of the pump discharge over the resonance frequency band. The following section explains the improvement procedure in detail.

5. 2 Correlation of Experimental and Simulation Modal Analyses

In order to increase the accuracy of experiment and simulation modal analyses in the flowchart of Fig. 6, the two analysis approaches must have correlation [Note 5)] with each other. As a target test jig for correlation, we selected the No.5 jig with relatively simple geometry and high rigidity (Fig. 7).

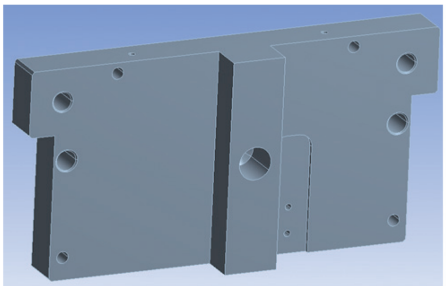

Fig. 7 Geometry of No.5 jig

Fig. 8 shows the frequency response data obtained from the experimental and simulation modal analyses before ensuring correlation. According to these pre-correlation waveforms, the natural frequency is almost the same between the experimental and simulation modal analyses, but their inertance is quite different. This was due to

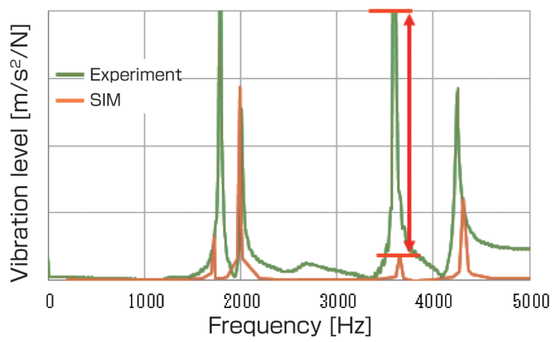

Fig. 8 Pre-correlation frequency response

differences in analysis conditions between the experimental and simulation modal analyses. Specifically, the probable causes include:
- Jig support methods
- Excitation and response positions
- Attenuation ratio setting for simulation modal analysis

We then tried to reestablish the correlation by harmonizing the test environment and conditions as well as the analysis parameters. Fig. 9 shows the frequency response after the correlation was restored by harmonizing the conditions. Comparing the post-correlation figure with the pre-correlation figure, the natural frequency as well as the inertance values between the experimental and simulation modal analyses are in better agreement. In this way, a high correlation between the experimental and simulation analyses was achieved, and a highly accurate analysis was implemented.

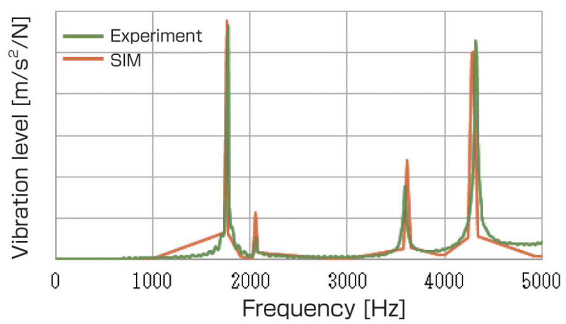

Fig. 9 Post-correlation frequency response

Note 5) Correlation: Refers to the relationship between two variables or phenomena in which they vary rhythmically together to some degree.

5. 3 Simulation Verification of Vibration Modes

Fig. 10 visualizes the vibration mode in the resonance frequency band from 3.5 kHz to 4.5 kHz. The figure shows a wave-like vibration mode in the lateral direction of the test jig. In particular, both sides of the upper end vibrate strongly. This means that increasing the rigidity of the upper part of the jig will hopefully reduce the resonance. If the simulation modal analysis has produced many natural frequency calculation results, the jig may have low rigidity, which means that the accuracy of the simulation analysis has been reduced. In this case, the analysis approach must be changed to experimental modal analysis.

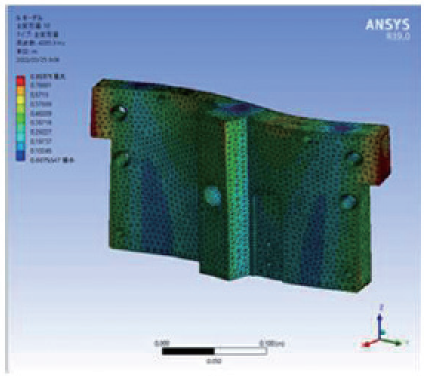

Fig. 10 Vibration mode analysis of No.5 jig

5. 4 Experimental Verification of Vibration Modes

We conducted experimental modal analysis on the No.9 test jig, which had shown low rigidity in the simulation modal analysis. Fig. 11 visualizes the vibration mode in the resonance frequency bands of 1.3 kHz to 1.6 kHz and 3.5 kHz to 4.5 kHz. Like the color map, this figure uses color to show the magnitude of vibration: large vibration is indicated by red. In both frequency bands, the analysis showed that resonance occurred due to insufficient rigidity of the open side and back side. Therefore, modifying the test jig to have higher rigidity of these two sides will hopefully reduce the resonance. In particular, the figure shows that it will be effective to increase the rigidity along the diagonal line from the upper right corner of the open side.

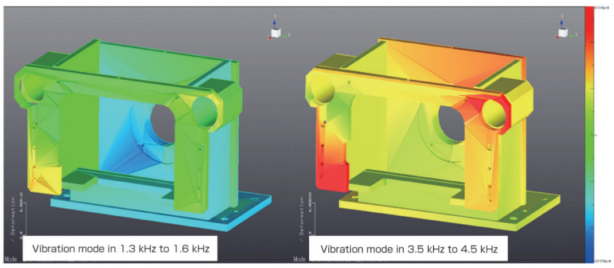

Fig. 11 Vibration mode analysis of No.9 jig

5. 5 Improving Jig

In order to reduce the inertance in the resonance frequency band from 3.5 kHz to 4.5 kHz of the No. 5 jig identified in Section 5.2, we studied to improve the geometry to suppress the deformation in the vibration mode. Considering the availability and cost of machining during jig manufacturing and the operability during testing, which are very important in jig design, we decided to add lateral ribs to the No.5 jig as shown in Fig. 12.

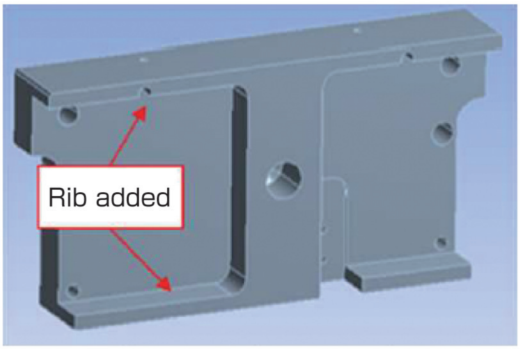

Fig. 12 Improved jig

5.6 Analysis of Improved Jig Model

We compared the frequency response between the original and improved jigs using simulation modal analysis. The improved jig showed 64% lower inertance than the original. At this point, the goal of a 50% reduction in inertance was achieved. With a further goal of reducing inertance while taking into account analysis variations, we repeatedly changed the rib height and width to find a rib geometry that satisfied both inertance reduction and cost requirements. Fig. 13 shows the final geometry and Fig. 14 shows the frequency response results with 97% inertance reduction.

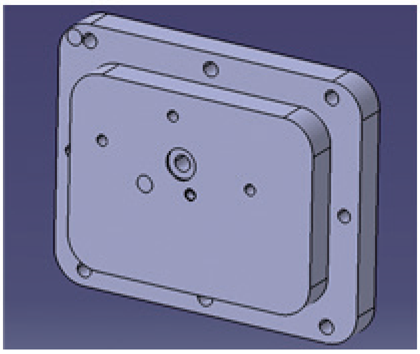

Fig. 13 Final geometry of No.5 jig

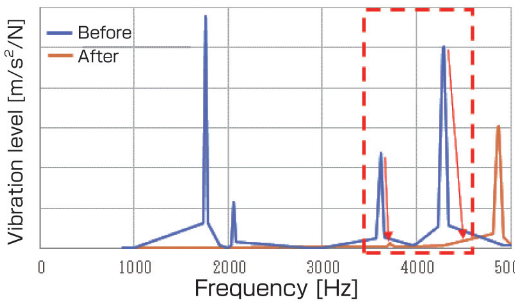

Fig. 14 Simulation comparison of frequency responses before and after improvement

5.7 Verification of Modified Jigs through Experimental Modal Analysis

From the improved jig model, we proceeded to the jig design and manufactured the improved jig. The improved jig, whose resonance had been reduced by simulation modal analysis, was subjected to experimental verification. Compared to the expected inertance reduction rate by simulation, the actual inertance reduction rate in the experimental measurement was 93%, which was almost the same as the result of the simulation analysis. Thus, a high correlation between experiment and simulation was again verified. Fig. 15 shows the frequency response of the improved jig obtained by experiment and simulation.

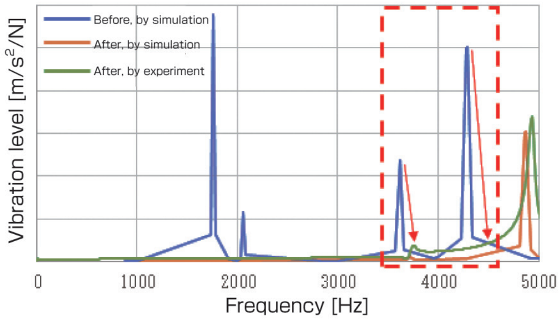

Fig. 15 Comparison of frequency responses of improved jig between experiment and simulation

Next, the frequency responses of the original and improved jigs obtained by experiment modal analysis are shown in Fig. 16. The inertance of the improved jig was 93% lower than that of the original jig. It was verified that the natural frequency and inertance of the improved jig obtained by simulation modal analysis were almost equivalent to the actual measurements.

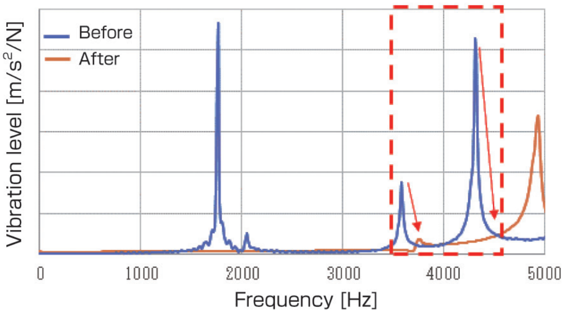

Fig. 16 Experimental comparison of frequency responses before and after improvement

5.8 Geometry of Test Jig Assemblies Before and After Improvement

Fig. 17 shows the geometry of the original and improved test jig assemblies. We reduced the resonance and changed the complex jig configuration to a simple one to reduce the number of jigs, and successfully manufactured a high-rigidity, low-cost jig assembly.

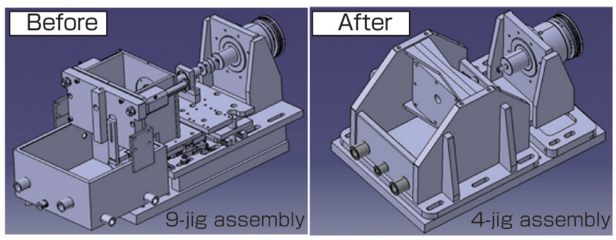

Fig. 17 Test jig assemblies before and after improvement

6 Verification Results of the Improved Jig Assembly

Fig. 18 shows the results of the NVH evaluation of the pump on the original test jig assembly and on the improved assembly with resonance prevention measures. According to the color map, the improved assembly does not show any resonance in the frequency band from 3.5 kHz to 4.5 kHz, which was one of the resonance frequency bands of the original assembly, and the order component vibration of the pump rotation can be clearly found in the frequency band from 1.3 kHz to 4.5 kHz, which was the other resonance frequency band. These results show that the resonance of the test jig assembly has been improved and all the disturbances that can affect the pump have been eliminated. Therefore, highly accurate pump NVH evaluation is now possible.

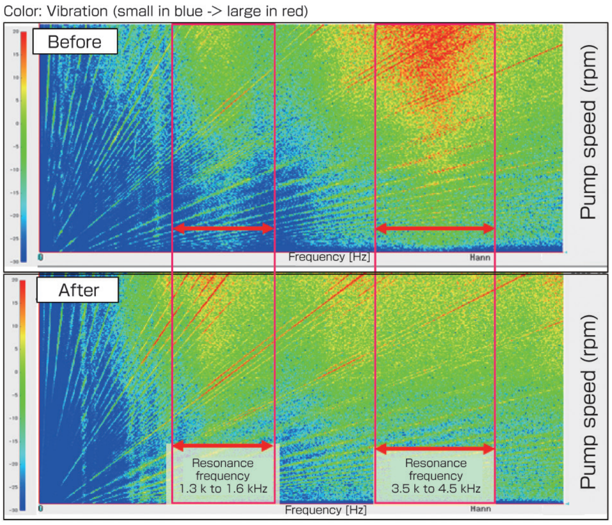

Fig. 18 Results of pump NVH evaluation before and after improvement

7 Future Prospects

NVH evaluation is indispensable for the development of automotive parts. As vehicles continue to become quieter, establishing an environment for highly accurate NVH evaluation is a top priority. The analysis methods and technical knowledge obtained in this activity can be extended to other products, thereby improving the accuracy of product NVH evaluation. It is also expected that we will reduce the trial and error in evaluation and the man-hours required to find the cause of abnormal vibration by designing and manufacturing a test jig assembly with improved resonance with the product at the design stage of the assembly. We are also committed to using this approach effectively in the development of electric pumps, which are required to be much quieter.

8 In Closing

This paper has presented our activity to address the resonance improvement of test jigs using modal analysis. In addition to conventional experimental and simulation modal analyses, we have introduced operational modal analysis to successfully visualize the vibration mode of the jig assembly under actual NVH evaluation conditions. This has identified the resonant jigs and the resonant parts of the jigs, resulting in higher analysis accuracy. By establishing a high correlation between experimental and simulation analyses, we were able to improve the resonant jigs with high accuracy. This activity has clarified the process of resonant jig improvement. Hopefully, even more accurate test jig analysis technology will be accumulated. It is important for us to make efforts to further improve the accuracy and to improve the new NVH evaluation technology day by day.

Finally, we would like to take this opportunity to express our sincere gratitude to those who have provided guidance and cooperation in building the modal analysis technology.

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