

Prediction of Fatigue Strength of Motorcycle Exhaust System Considering Vibrating and Thermal Stresses

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ABSTRACT

A method applicable in the design stage to predict fatigue strength of a motorcycle exhaust system was developed. In this prediction method, a vibrating stress, thermal stresses, stresses resulting from the assembling of the exhaust system components and a deterioration of fatigue strength of materials originated from high temperature were simultaneously taken into account. For the prediction of the vibrating stress, flexible multibody dynamics was applied to get modeling accuracy for vibration characteristics of the entire motorcycle and the exciting force delivered from engine vibrations. The thermal conduction analysis and the thermal deformation analysis based on finite element method (FEM) were applied for the prediction of thermal stresses in the exhaust system components. The temperature distribution on the surfaces of the exhaust system components is required for calculations of the thermal stresses. The heat transfer analysis, which was composed by combing a one-dimensional (1D) engine cycle simulation and an air flow simulation around the vehicle by 3D-CFD, was used for the estimation of temperature distributions. To validate the developed method, the correlations between the simulations and the actual measurements were analyzed for the vibrating stress, the temperature distribution, the thermal stresses and the fatigue safety factor. High correlations were yielded between them proving the validity of the new method.

CITATION: Kuribara, H., Horikawa, H., Teraguchi, T., Nagata, T. et al., "Prediction of Fatigue Strength of Motorcycle Exhaust System Considering Vibrating and Thermal Stresses," *SAE Int. J. Engines* 9(1):2016.

INTRODUCTION

Recently, due to advancement of CAE analysis technology and increased computer processing speed, the use of CAE in the development of motorcycles and automobiles is increasing. However, it is difficult to obtain necessary analysis accuracy when a structural body is composed of a number of parts or when a part is affected by a number of physical phenomena. One of such a physical phenomenon difficult to analyze by simulation is the fatigue strength of an exhaust system of a motorcycle.

The vibrating stress and the thermal stress occur simultaneously in the exhaust system components of a motorcycle. At the same time, the fatigue limit of material lowers along with an increase of temperature. It is necessary to simultaneously take into account such physical phenomena for simulation of fatigue strength of exhaust system components.

In the conventional product development process, the fatigue strength of an exhaust system component was evaluated in three stages.

The first stage is the design. In this stage, the fatigue strength was evaluated according to the vibrating stress and the thermal stresses estimated by FEM analysis. However, there were the following three issues. The first issue was that the frequency response analysis was used for estimation of vibrating stress. The frequency response analysis is a linear analysis. Accordingly, an appropriate modeling

was not performed for parts having non-linear stiffness characteristics such as a rubber bush or gasket, which were used to support exhaust system components, or the exciting force resulting from engine vibrations. The second issue was that an appropriate boundary condition for estimation of thermal stresses was unobtainable. The data representing temperature distribution in the exhaust system are required to estimate thermal stresses. However, there was no technical means to estimate temperature distribution. Accordingly, the temperature distribution data taken from a similar motorcycle were used as the boundary condition. The third issue was that the vibrating stress and the thermal stresses were independently evaluated. For proper evaluation, the thermal stress and the vibrating stress should be superimposed, and evaluated on the fatigue limit diagram.

The second stage is the measurement of performance of a prototype motorcycle on a dynamometer. In this stage, the fatigue strength was evaluated by the stresses those were measured by strain gauges. The strain gauge allows simultaneous measurement of the thermal stress and the vibrating stress. The allowable temperature of a general strain gauge, however, is lower than the maximum temperature of the exhaust system components. So, an accurate measurement at a high-temperature part therefore was difficult.

The third stage is the durability test using prototype motorcycle. As mentioned above, the evaluation of durability of an exhaust system in the design stage and the stage of performance measurement on the

dynamometer was inadequate. As a result, the exhaust system components were often damaged during the durability test. Such damage in the durability test causes not only a delay of product development, but also an increase of man hours for the countermeasure. Accordingly, there had been a strong demand for a method that allows prediction of fatigue strength of an exhaust system in the early stage of product development.

There are a large number of past studies on the fatigue strength of exhaust system components. There are several studies on the simulation of fatigue strength in the design stage. (Reference 1, 2, 3) However, such studies concern only on the vibrating stress without taking into account the thermal stress. Meanwhile, there are some studies in which both of the thermal stress and the vibrating stress are considered. (Reference 4, 5). However, such studies are focused on evaluation and improvement of fatigue strength in the stage of tests using prototype vehicle, not yet allowing estimation of stress in the design stage. Studies for an accurate prediction of fatigue strength of exhaust system components in the design stage had not been conducted.

In view of the above, the authors conducted studies with a target at development of a method for prediction of the fatigue strength of a motorcycle exhaust system in a design stage at a practical accuracy. The feature of this project is the attempt for prediction of the fatigue strength of an exhaust system by linking the flexible multibody dynamics, 3D-CFD, 1D engine cycle simulation and the structure analysis by FEM. The recently developed simulation method and the results of validation are reported in this paper.

OVERVIEW OF FATIGUE STRENGTH PREDICTION

Structure of Motorcycle Exhaust System and How Stresses Occur

The structure of a motorcycle exhaust system and how the stresses occur should be explained before explaining the simulation. The overview of a motorcycle and enlarged pictures of areas where the exhaust components are connected to the vehicle body are shown in [Figure 1](#).

The exhaust system of a motorcycle is usually composed of exhaust pipes and mufflers. A gasket is provided where the pipe and the muffler are connected for sealing of exhaust gas and insulation of vibration. The exhaust pipe is attached to the vehicle at the cylinder head and the mount bracket in the main frame. The exhaust pipe is bolted to the cylinder head via flanges. Metal gaskets are provided between the exhaust pipe and the cylinder head. Rubber bushes for mounting are provided between the exhaust pipe and the frame body. The muffler is attached to the frame body via a mount bracket on a seat rail. Rubber bushes are provided between the muffler and the seat rail.

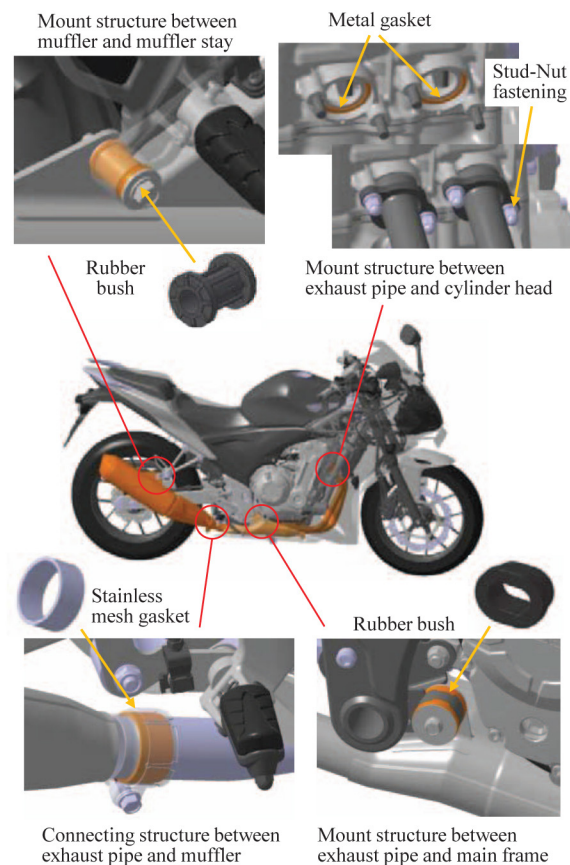


Figure 1. Connecting structure between vehicle and exhaust system in motorcycle

The exhaust system expands due to the passing of hot exhaust gas. Under such conditions, when the thermal expansion is firmly restricted due to the stiffness of frame or engine, a high stress occurs in the exhaust system. To control such a thermal stress, the rubber bush is shaped like an elongated ring with the major axis in the direction the exhaust pipe elongates. The rubber bush in the muffler also has a construction that prevents excessive constraint. Consequently, the stiffness of rubber bush is designed non-linear and differs depending on the direction. Due to the non-linearity, the stiffness in the connecting part changes depending on the thermal deformation and the displacement from the vibrations. Consequently the natural frequency of exhaust system also changes due to the influence of thermal deformation and vibrations.

In automobiles, an insulating device such as a spherical joint or a metal bellows is provided in the part of an exhaust pipe close to the engine to prevent transmission of engine vibrations to the exhaust system. In motorcycles, however, such an insulating device is not provided because it affects the appearance, space layout, and kinetic performance of the vehicle. As a result, stresses resulting from engine vibrations tend to occur in the exhaust system of a motorcycle. Moreover, the natural frequency of an exhaust system when installed in the vehicle often falls somewhere between 50 Hz and 300 Hz, which overlaps with the frequency band of the vibrations occurring from reciprocating system in an engine. Consequently resonating vibrations often occur in the exhaust system, causing a significant lowering of the fatigue strength.

In addition to that, three kinds of thermal stress occur in the exhaust system and lower fatigue strength. One is the stress that occurs from constraint for thermal expansion as mentioned earlier. The second is the stress occurring from temperature distribution in the exhaust system. The third is the stress occurring from the difference of a linear expansion of materials. In the exhaust system components of a motorcycle, stainless steels having various linear expansion coefficient are often welded together to achieve both goals i.e., the production cost and the appearance. Such a construction causes a high thermal stress when hot, and reduces fatigue strength.

The last issue is that the fatigue limit of the material lowers along with an increase of temperature. Especially in the part of the exhaust pipe close to the engine or near the catalyst, the surface temperature becomes higher than 500 degree C. At such a high temperature, the fatigue limit of the material lowers to a half compared to that at a room temperature.

Requirements in Prediction Method

When predicting the fatigue strength of exhaust system components, the structural features and how the stresses occur mentioned in the preceding paragraph should be considered. The authors considered the following requirements for the simulation.

1. Simulation should be able to represent the vibrating stress including under condition in resonation.
 - 1-(a). Dynamic characteristics of major components in a motorcycle including those in the exhaust system should be represented.

- 1-(b). An appropriate damping for each component part is set, and the vibration amplitude when resonating should be correctly represented.
- 1-(c). An exciting force in accordance with operating conditions of an engine should be considered.
- 1-(d). Changes of connection stiffness that depends on the thermal deformation and the displacement from vibrations should be considered.
2. Simulation should be able to represent following three kinds of thermal stresses.
 - 2-(a). Stress occurring from constraint for thermal expansion
 - 2-(b). Stress occurring from temperature distribution
 - 2-(c). Stress occurring from difference of linear expansion of materials
3. The stress occurring from fastening with bolts for assembling the exhaust system should be considered
4. Fatigue safety factors should be calculated simultaneously taking into account the above stresses 1~3. At that time, the lowering of the fatigue limit when the material becomes hot should be considered.

Outlines of Fatigue Strength Prediction Method

As a solution for the issues, the authors have developed the simulation method in which the flexible multibody dynamics, the 3D-CFD, the 1D engine cycle simulation, and the structural analysis are linked. The relationship among the factors affecting the fatigue strength of exhaust system components and the domain each analysis method covers are shown in Figure 2.

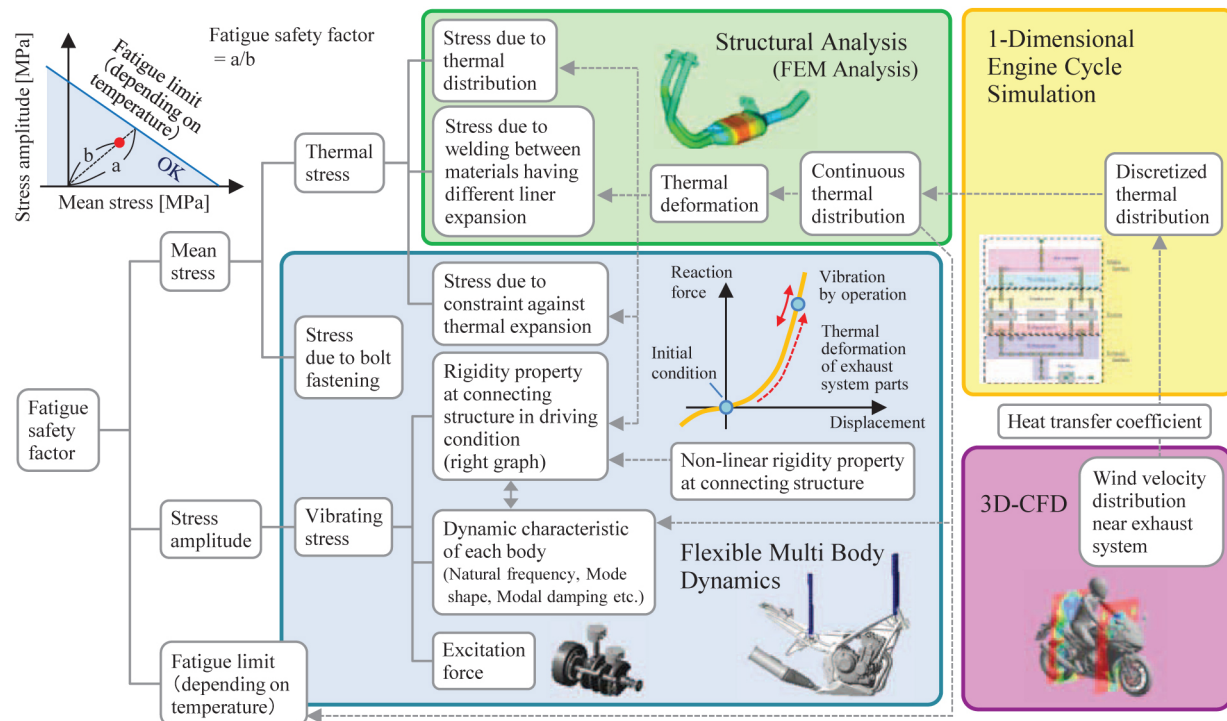


Figure 2. Relationship among factors affecting fatigue strength of exhaust system components and domain each analysis method covers

TEST MOTORCYCLE

The sport-type motorcycle equipped with a 399 cm³ parallel twin cylinder engine was used for the development of simulation. The test vehicle and the engine that is equipped in the vehicle are shown in Figure 3 and its major specifications are shown in Table 1. The engine has a balance shaft to reduce coupling force occurring from the crankshaft having crankpins 180 degree apart. Accordingly, first-order coupling vibrations generated by the rotation of the crankshaft are reduced. The second-order vibrations, however, occur from rotating of the crankshaft. In motorcycles having an engine of this configuration, resonating vibrations tend to occur in the exhaust system due to the second-order vibrations.



Figure 3. Test vehicle and engine that is equipped in the vehicle

Table 1. Specifications of test motorcycle used in verification

Specifications	
Engine type	4 stroke, Liquid-Cooled, Inline two-cylinder
Displacement	399 cm ³
Bore and stroke	67.0 mm × 56.6 mm
Crankshaft type	180 degree crankshaft
Balance shaft type	1st harmonic, 1 shaft
Max. brake power	34 kW at 9500 rpm
Max. brake torque	37 Nm at 7500 rpm
Frame type	Diamond
Engine mount type	Rigid mount

VIBRATING STRESS PREDICTION METHOD

Method Selection

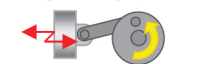
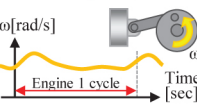
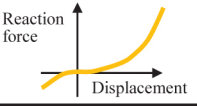
In the field of industry, the frequency response analysis is generally applied for prediction of vibrating stress. In the meantime, as a dynamic analysis method for complex and large-scale vibration systems, the flexible multibody dynamics (FMBD) (Reference 6) is recently used. (Reference 7, 8)

The comparison of analysis capabilities of the frequency response analysis and the FMBD with respect to the function necessary for prediction of vibrating stress in the exhaust system is shown in Table 2. The frequency response analysis is a linear analysis. It is therefore difficult to accurately simulate engine vibrations or non-linear stiffness characteristics in the connecting part between exhaust system components. Meanwhile in the FMBD, the equation of motion

and the geometric constraint equation between the components are coupled, and the body motions and vibration are calculated by the time-history numerical integration. Thereby, dynamics in a reciprocating system and non-linear stiffness characteristics in the connecting part can be directly described in those equations, and correctly solved.

Due to above-mentioned reasons, the authors decided to employ the time history response analysis base on the FMBD.

Table 2. Comparison of analysis capabilities of frequency response analysis and FMBD with respect to function necessary for prediction of vibrating stress in exhaust system

Analysis method		Frequency response analysis	FMBD
Needed function for simulation			
Excitation force	Excitation force by unbalance in reciprocating system 	Applicable Superposition of sinusoidal wave $F = \sum a \sin \omega t$	Applicable Direct modeling
	Variation of rotational velocity of a crankshaft in a engine cycle 	Not applicable	
Dynamic characteristic	Dynamic property of each body 	Applicable	Applicable
	Non-linear rigidity property at connecting structure 	Not applicable Linearization is needed	Applicable Direct modeling

Clarification of Parts That Affect Stresses Occurring in Exhaust System Components

It is considered that the stress of exhaust system components should be affected by a large number of components of a motorcycle. From the standpoint of analysis efficiency, however, it is preferable to have the analysis model composed of less number of parts. The authors therefore conducted experiments to clarify parts that are necessary for estimation of stress in the exhaust system components. Parts are removed one after another from the complete motorcycle. At the same time, changes of the acceleration response and the vibrating stress at various points of the exhaust system are measured. Figure 4 is the picture showing a scene in the experiment. The motorcycle without the front and rear wheels and suspension systems is suspended by soft springs from the ceiling. Thus operating the engine under various conditions, the parts having a significant influence to the stress in the exhaust system components were clarified.