

Establishment of Prediction Method for Fatigue Durability Applied for Exhaust System in Motorcycle by Coupled Simulation of Vibrating Stress and Thermal Stress

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ABSTRACT

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

In this paper, some of the application examples of newly developed method to an early stage of the development process are also presented. Through the examples, it is shown that the application of the new method effectively help designers implement feasible measures for potentially frail areas against fatigue. As a consequence, the new method enhances the efficiency of the development of the exhaust system.

1. 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 practically impossible 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 challenging for analysis 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

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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 cannot be conducted without special technique.

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⁽¹⁾⁻⁽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^{(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.

In addition to that, the examples of applications of

the newly developed method in the product development process are introduced to clarify effectiveness of this simulation method.

2. Overview of Fatigue Strength Prediction

2.1 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 Fig. 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 as shown in Fig. 1 (a). 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

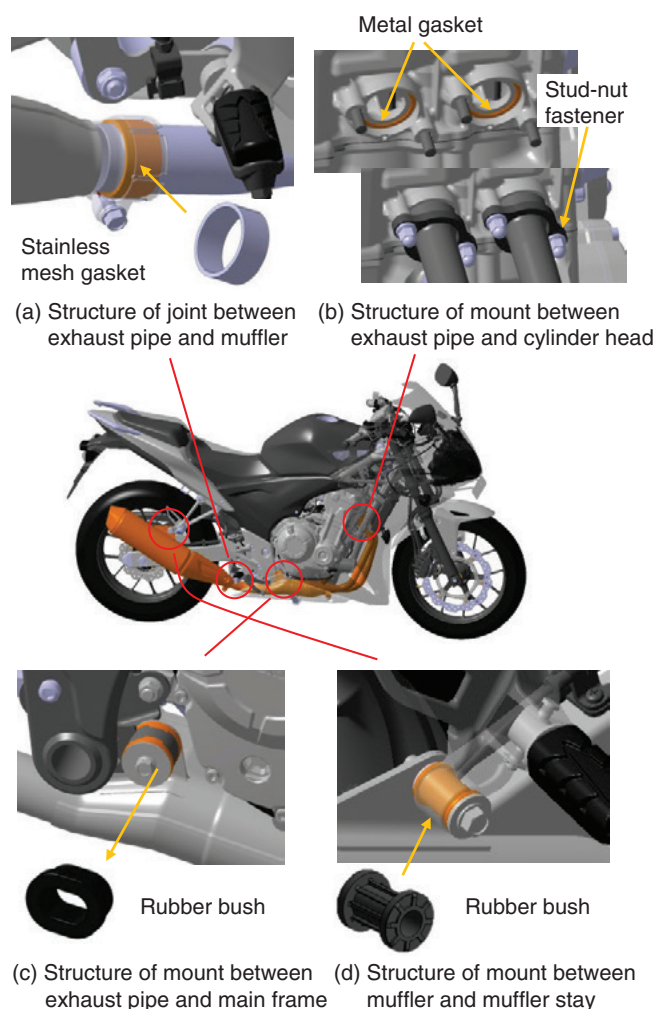


Fig. 1 Connecting structure between vehicle and exhaust system in motorcycle

provided between the exhaust pipe and the cylinder head as shown in Fig. 1 (b). Rubber bushes for mounting are provided between the exhaust pipe and the main frame as shown in Fig. 1 (c). The muffler is attached to the main frame via a mount bracket on a seat rail. Rubber bushes are provided between the muffler and the seat rail as shown in Fig. 1 (d).

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.

2.2. 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 resonance.
 - (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.
- (5) At that time, the lowering of the fatigue limit when the material becomes hot should be considered.

2.3. 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 Fig. 2.

2.4. 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 Fig. 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.

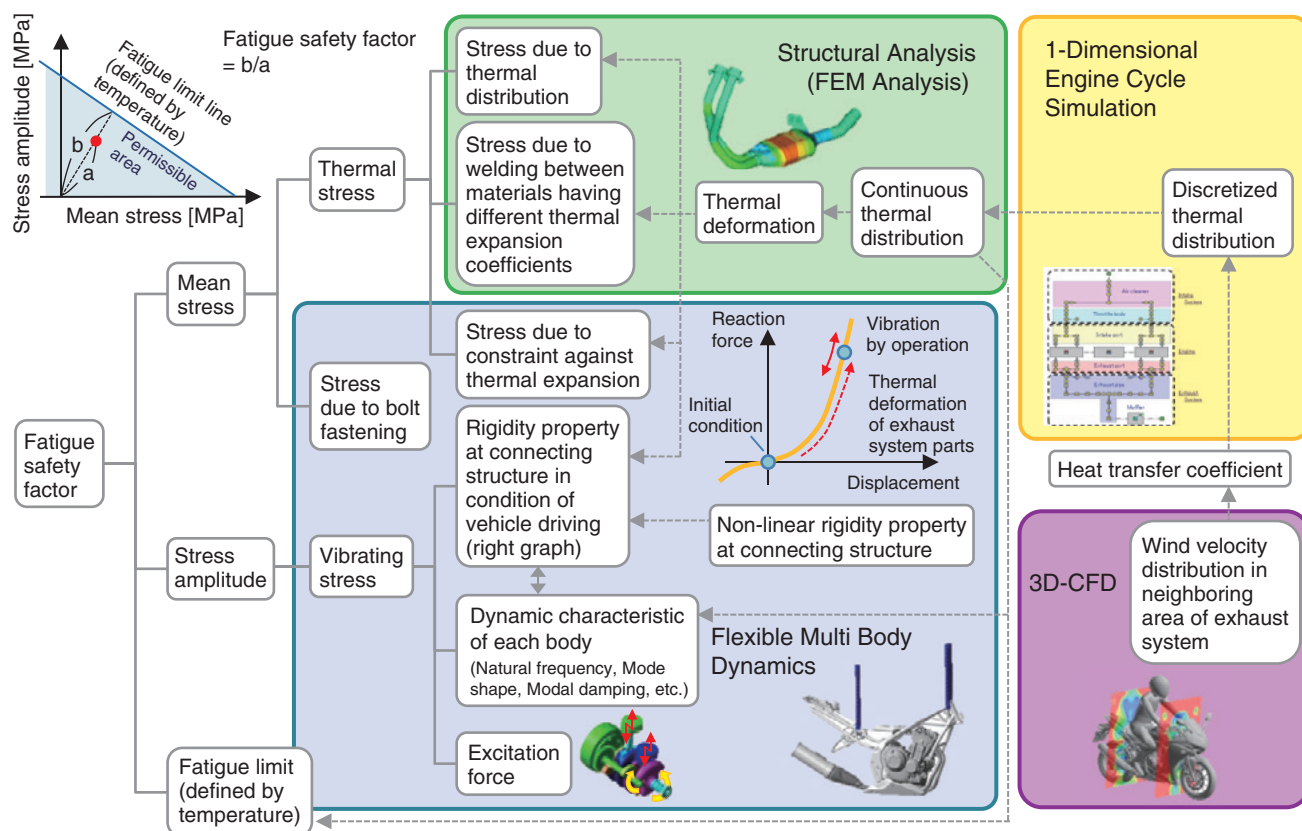


Fig. 2 Relationships among involving factors in fatigue safety factor and regions assigned by four simulation technology

Table 1 Specifications of test motorcycle used in verification tests

Specifications	
Engine type	4 stroke, Liquid-cooled, Parallel twin-cylinder
Displacement	399 cm ³
Bore and Stroke	67.0 mm × 56.6 mm
Crank shaft type	180 deg 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



Fig. 3 Test vehicle and equipped engine

3. Vibrating Stress Prediction Method

3.1. 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⁽⁶⁾ (FMBD) is recently used^{(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 Fig. 4. The frequency response analysis is a linear analysis. It is therefore almost impossible 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 motions and vibration of the components 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.

3.2. 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. Fig. 5 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.

In the experiment, the stress in the exhaust system components was virtually unaffected by the front and rear suspension systems. The resonance frequency of a suspension system is generally around several Hz, which is adequately lower than the resonance frequency of an

exhaust system. In such a case, the two vibration systems can be deemed as independent from each other. The authors therefore concluded that it was not necessary to consider the suspension system in the analysis model. Similarly concluded that it was not necessary to take into account the fuel tank, throttle body, etc.

The authors finally concluded that it was efficient to have the vibrating stress simulation model composed of five parts, which are; the engine, the main frame, the seat rail including the muffler mount bracket, the muffler, and the exhaust pipe.

3.3. Modeling of Dynamic Characteristics of Each Component of Analysis Model

For accurate simulation of the dynamic behavior of an exhaust system, it is necessary to have the natural frequency, the vibration mode shape and the modal damping of each component in the analysis model accurately simulated. In this project, the mode synthesis that allows reduction of calculation time while maintaining accuracy is employed. So, each component is modeled as a dynamic super element that is made from FEM model.

In the FMBD method using super elements, the displacement of the center of gravity point of the elastic body and the modal displacement are calculated. The stress is not directly calculated. Therefore, the stress in the exhaust system components is calculated from the modal displacement and the mode shape.

Meanwhile in the temperature zone where the exhaust system components are in operation, a change of Young's modulus, which is dependent on the temperature, cannot be ignored. Young's modulus in the FEM model was set in accordance with the temperature of each component.

3.4. Modeling of Stiffness Characteristics of Connecting Element

The stiffness characteristics of the connecting element were measured prior to the modeling. As the connecting

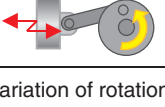
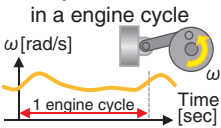
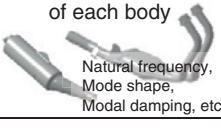
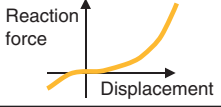
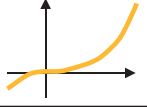
Needed function for simulation		Analysis method	Frequency response analysis	FMBD
Excitation force	Excitation force by unbalanced reciprocating system 		Applicable Superposition of sinusoidal wave $F = \sum a \sin \omega t$	Applicable
	Variation of rotational velocity of a crankshaft in an engine cycle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

Fig. 4 Comparison between frequency response analysis and flexible multibody dynamics regarding demonstration capabilities required for dynamic response representation of exhaust system

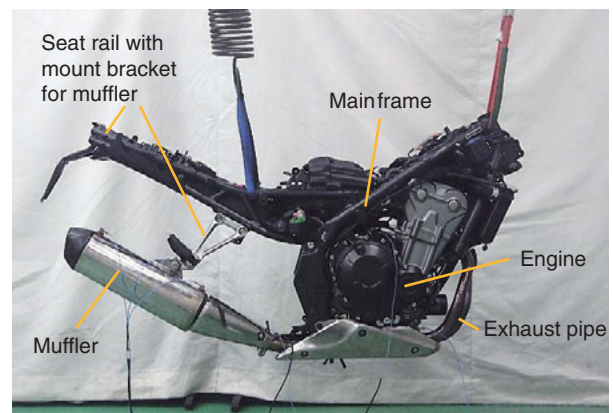


Fig. 5 Photographic view of experimental setting to identify the parts influential to the vibrational stresses on exhaust system in motorcycle

part is always vibrating, the dynamic stiffness was measured rather than the static stiffness.

As an example, the test equipment for measurement of stiffness characteristics of the muffler gasket is shown in Fig. 6. The test equipment is composed of a body and two weights. The body is fixed on the shaking table, and muffler gaskets are installed between the body and the weights. The construction of the areas where the gaskets are installed is same as that of the area where the actual exhaust pipe and the muffler are connected. In the experiment, the shaking table was sweep-accelerated at constant displacement amplitude and the acceleration response of the weights was measured. The input amplitude was altered in six levels. The measured acceleration of a weight is shown in Fig. 7. The input frequency is on the horizontal axis, and the acceleration response of a weight is on the vertical axis. Six lines of various inputs are drawn in the graph. The lowering of resonance frequency of the system along with an increase of amplitude is seen in the graph. The data indicates that the stiffness characteristics of the muffler gasket are non-linear.

In this project, the modeling of stiffness characteristics of the connecting element was conducted using springs and dampers having non-linear characteristics. The spring constant and the damping coefficient were determined using the FMBD model in which the test equipment was simulated. The analysis model is shown in Fig. 8. The body

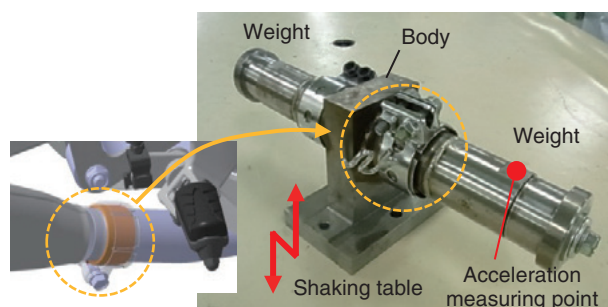


Fig. 6 Measurement of dynamic rigidity of muffler gasket

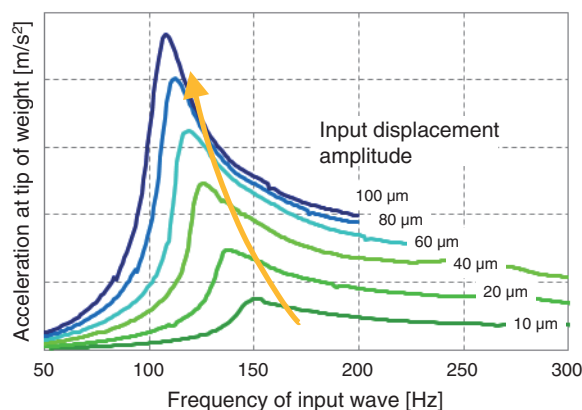


Fig. 7 Response acceleration of tip of weight

and the weights are modeled as super elements. The springs and the dampers are installed between the body and the weights. Using the model, the characteristics of the springs and the dampers were determined in such a manner that the response of weights reproduced the test results.

The acceleration response waveforms of a weight in the analysis model after setting the characteristics are shown in Fig. 9. The use of this model allows simulation of changes of stiffness characteristics in the connecting part that depend on the displacement from vibrations and the thermal deformation. The changes of resonance frequency, which depends on the amplitude of vibration, can also be simulated.

3.5. Excitation Force of Engine

In this project, the reciprocating system is represented by multibody model consists of pistons, piston pins, connecting rods and a crankshaft. Moreover in this reciprocating system model, the changes of pressure in the cylinder within a cycle of reciprocating mechanism are taken into account. In doing so, the motions of the reciprocating mechanism are faithfully simulated, allowing accurate modeling of excitation force of the engine.

3.6. Vibrating Stress Analysis Model

The overview of the vibrating stress analysis model

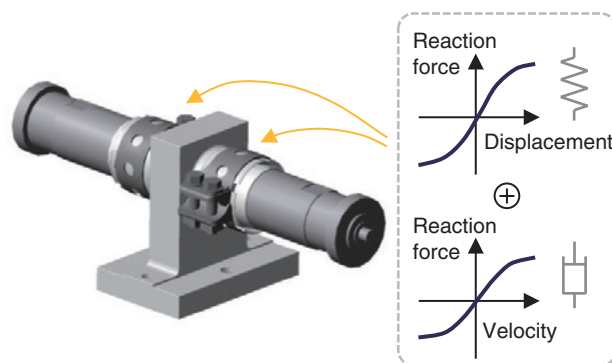


Fig. 8 Flexible multibody model used for setting dynamic rigidity property of muffler gasket

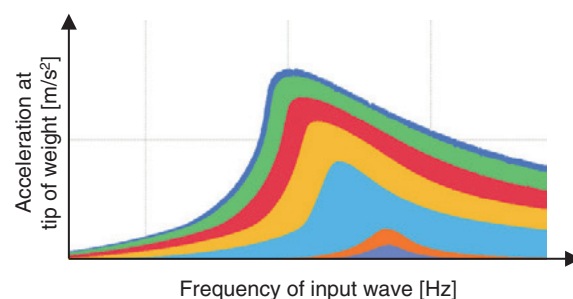


Fig. 9 Response in acceleration measured at tip of weight calculated by flexible multibody model analysis

is shown in Fig. 10. The components of the model are the engine, the main frame, the seat rail including the muffler mount bracket, the muffler, and the exhaust pipe. Those components are connected via non-linear springs and dampers to represent stiffness characteristics of the connecting element. At that time, the bolt fastening force in the position where the exhaust pipe is attached to the cylinder head is also taken into account. A multibody model that represents reciprocating system is incorporated into the crankcase for modeling of the excitation force. The main frame is mounted on the ground via the flexible spring.

The analysis takes approximately 8 hours with the engine sweep-operated from 1000 rpm up to 10000 rpm. This calculation time is allowable when applying it in the design stage.

3.7. Correlation of Entire Behavior of Exhaust System

In the analysis model, it is necessary to allow simulation of not only regional stress conditions but also vibration mode shape in the entire exhaust system. For validation of the analysis model, the correlation was analyzed in the behavior of entire exhaust system when the engine was operating.

The behavior of entire exhaust system was measured with four triaxial accelerometers. The accelerometer locations are shown in Fig. 11. The acceleration was measured while sweep-operating the engine from 1000 rpm up to 10000 rpm.

This motorcycle is equipped with a balance shaft to reduce vibrations of the primary component of crankshaft rotating frequency. Hence the acceleration response of the exhaust system at first order component is small. For the correlation validation, the acceleration response data of the secondary component of crankshaft rotating frequency was used. The acceleration response waveforms acquired from the experiment and the simulation are shown in Fig. 12. In the matrix, the horizontal direction indicates measurement points, and the vertical direction shows the direction of

acceleration. A graph is composed of two parts. The lower graph shows acceleration and the upper graph indicates phase of the vibration. The engine speed is on the horizontal axis. The standard of the phase is the response waveform measured by an accelerometer, which is attached to the engine, in the Z direction. The red lines show measurement and the blue lines indicate the simulation by the analysis model.

It can be understood from viewing of the entire data that the vibrations of the exhaust system are occurring in three directions. The simulation is in a good agreement with the measurement both in the acceleration amplitude and the phase. That indicates that the simulation is in a good agreement with the vibration mode of actual exhaust system. The simulation is also in a good agreement regarding the resonance in the proximity of 4000 rpm and 8000 rpm. The error of prediction of resonance frequency in this method is within $\pm 10\%$. The prediction error of peak acceleration is within $\pm 20\%$.

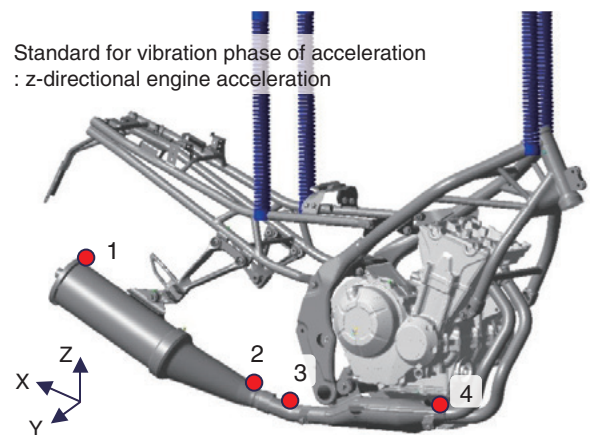


Fig. 11 Installation positions of tri-directional accelerometers

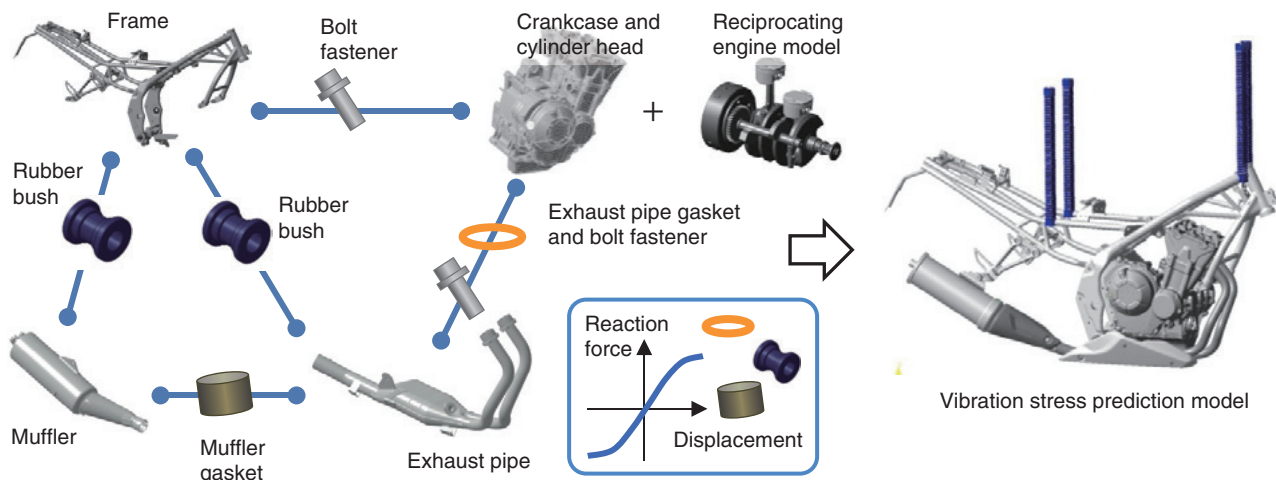


Fig. 10 Flexible multibody model to simulate dynamic responses and vibration stresses of exhaust system of motorcycle

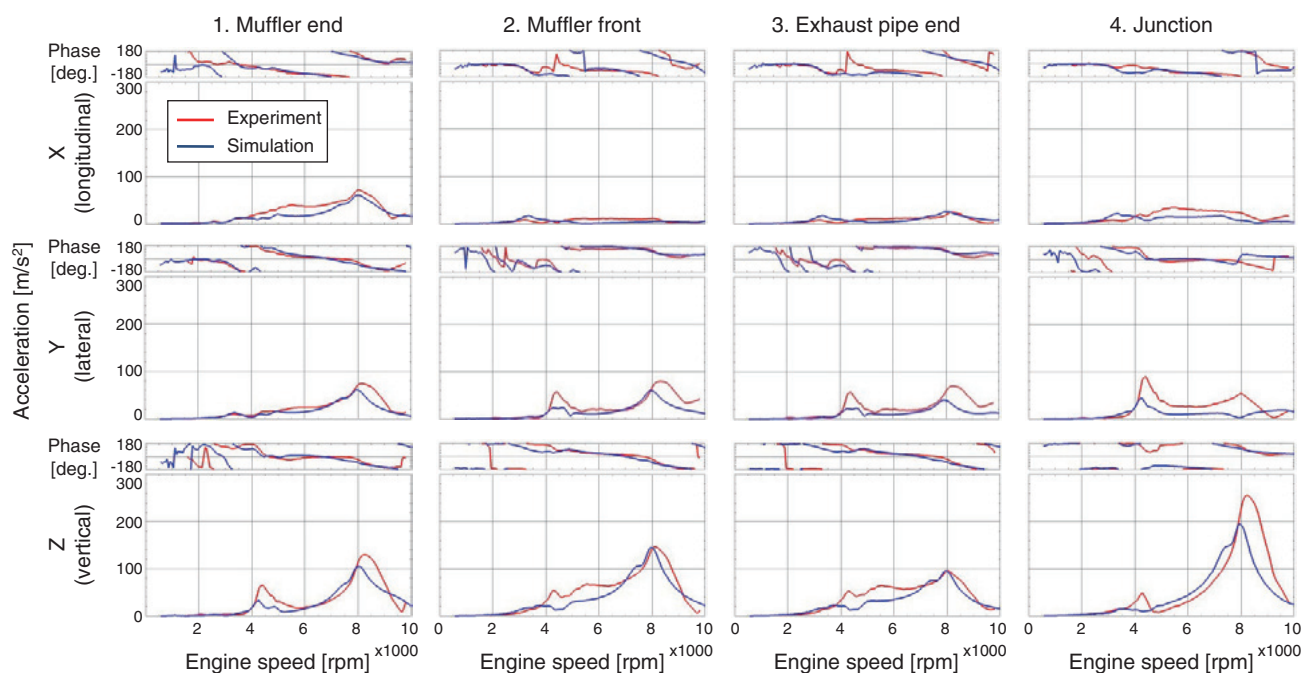


Fig. 12 Correlation of acceleration responses between experimental and calculation results measured at various locations in exhaust system

3.8. Correlation of Vibrating Stress

The correlation of vibrating stress was analyzed. The stress was measured at the bended radius section of the muffler mount bracket. A strain gauge was used for the stress measurement. The strain gauge location is indicated in Fig. 13. For evaluation of the fatigue strength of the exhaust system, an overall stress should be used. Accordingly, the correlation was validated using overall strain amplitude.

The strain data acquired from the experiment and the simulation are shown in Fig. 14. In the graph, the horizontal axis represents engine speed and the vertical axis shows the strain amplitude. The red line is measurement and the blue line is the simulation. In the experiment, the strain amplitude increases along with an increase of engine speed, and peaks at 9500 rpm. After that, along with an increase of engine speed, the strain amplitude decreases. The simulated strain amplitude is in a good agreement with the measurement in the resonance frequency and the quantity at each engine speed.

From the above findings, a good correlation between the simulation and measurement is seen in the behavior of entire exhaust system and the regional stress. The authors therefore conclude that the vibrating stress prediction method proposed in this project is appropriate.

4. Prediction of Thermal Stress

4.1. Prediction of Temperature Distribution in the Exhaust System

To predict thermal stress of an exhaust component, it is

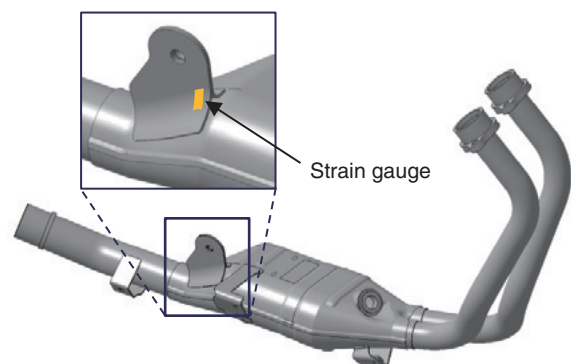


Fig. 13 Measurement point of stress amplitude using strain gauge

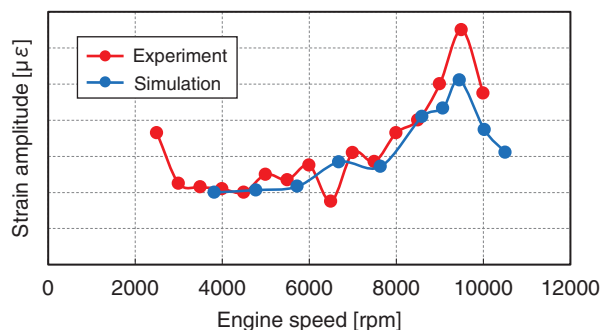


Fig. 14 Correlation between experimental and simulation results of strain amplitudes measured at exhaust pipe stay

necessary to estimate temperature distribution in the exhaust system. There are the following two methods for that. One is by the 3D CFD and the other is by the 1D engine cycle simulation⁽⁹⁾. Among those, the direct estimation of temperatures in the exhaust system by the 3D CFD requires extensive calculations, takes a very long time, and is not practical to apply in the early stage of design. Accordingly, the 1D engine cycle simulation was chosen in this project.

The temperature of an external surface of exhaust system depends on the balance of the heat input from the exhaust gas that passes inside, the heat conduction inside of the exhaust system component, and the heat release from the external surface to the ambience. In the 1D engine cycle simulation, the Colburn equation⁽¹⁰⁾ is used for the calculation of heat transfer from the exhaust gas to the internal surface of exhaust pipe. As the heat transfer from the exhaust gas to the internal surface of exhaust pipe is less affected by external factors, a highly accurate simulation is possible by that equation. In the meantime, the heat transfer from the external surface to the ambience is affected by the flow of air around the motorcycle. Accordingly, when developing a motorcycle having a very different shape from the conventional model, the existing data of heat transfer coefficient on the external surface was inapplicable and it was making an accurate simulation of temperature distribution unattainable by the 1D method.

In this project, the flow rate of air stream on the external surface of exhaust system is calculated by the 3D CFD, and converted to the heat transfer coefficient by the empirical formula⁽¹¹⁾. The calculation conditions of the 3D CFD used for the simulation of air flow rate distribution on the external surface of the exhaust system of the test motorcycle is shown in Table 2, and the calculated data in Fig. 15.

The overview of the 1D engine cycle simulation model⁽⁹⁾ is shown in Fig. 16. The distribution of heat transfer coefficient calculated by the 3D CFD is “mapped” on the external surface of the exhaust components in the model. The temperature distribution on the surface of exhaust component is simulated taking into account the heat transmission from the exhaust gas to the internal surface, the heat conduction within the component, and the heat transfer from the external surface to the atmosphere in the gas cycle simulation.

4.2. Correlation between Exhaust Gas Temperature and Surface Temperature of Exhaust System Component

The temperature distribution estimation method was validated. The exhaust gas temperature and the outer surface temperature of exhaust system components were measured on the chassis dynamometer and compared to the calculated result. The shift position was set at the 6th speed and the engine was fully loaded. The wind velocity in the chassis dynamometer room was controlled to be equal to the vehicle speed. The temperatures of exhaust system components and the exhaust gas were measured with thermocouples. The

Table 2 Conditions applied for 3D-CFD analysis

Solution type	Steady state
Working fluid	Air
Compressibility	Incompressible
Turbulent model	Realizable k- ϵ
Cell type	Hybrid (hex, tetra, pyramid)
Cell size	2-8 mm
Total number of cells	25,000,000
Vehicle speed	160 km/h

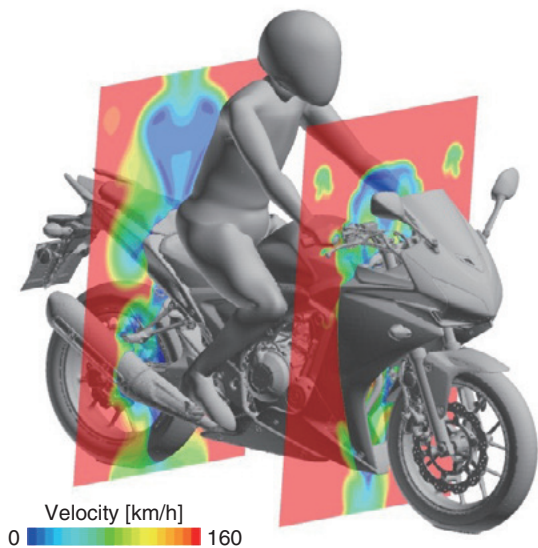


Fig. 15 Calculation results of wind velocity around the vehicle

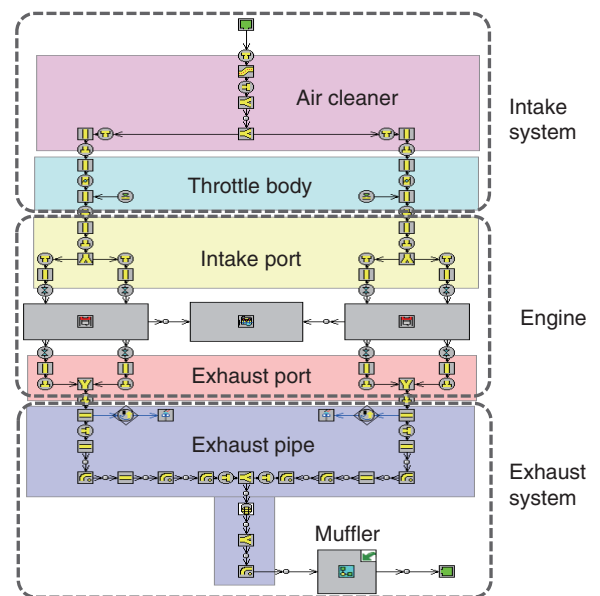


Fig. 16 Overview of one-dimensional simulation model for gas flow analysis

pictures of the motorcycle when measuring temperature and the locations of thermocouples are shown in Fig. 17.

The exhaust gas temperature and the external surface temperature when the engine speed is 9000 rpm are shown in Fig. 18. In the graphs, the positions of the measurement are shown on the horizontal axis and the vertical axis refers to the temperature. The red lines show experimental results and the blue lines show simulation results.

Though a small variance is seen between the measurement and the simulation results, the authors consider that the proposed temperature estimation method is acceptable for prediction of fatigue strength of exhaust system components.

4.3. Thermal Stress Estimation

In this project, the thermal stress occurring from the temperature distribution and the thermal stress occurring from the difference of linear expansion coefficient of materials were estimated by the heat conduction analysis and the stress analysis using the FEM model. The temperature distribution estimated by the 1D simulation was used as the boundary condition in the FEM analysis.

The estimated thermal stress is shown in Fig. 19. In the picture, high stresses are shown in the pipe-to-manifold welding and the catalyst-to-casing spot welding. As such areas tend to be damaged during durability tests, sufficient considerations should be given in the design stage.

The stress occurring from the constraint for thermal expansion of the exhaust component is calculated in the vibrating stress simulation model. By this method, the

thermal stress is calculated as mean stress component in the vibrating stress simulation.

4.4. Correlation of Thermal Stress

The part in the exhaust system that was most vulnerable to breaking in the durability test was the welding bead toe part. An accurately simulation of stress distribution around

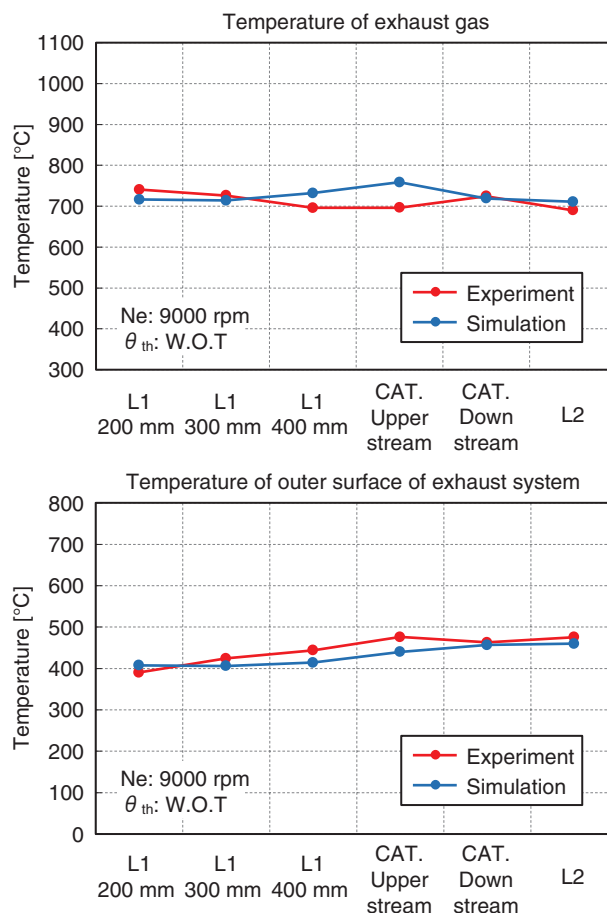


Fig. 18 Correlation of temperature distributions between experiment and simulation on exhaust gas and outer surface of the exhaust system

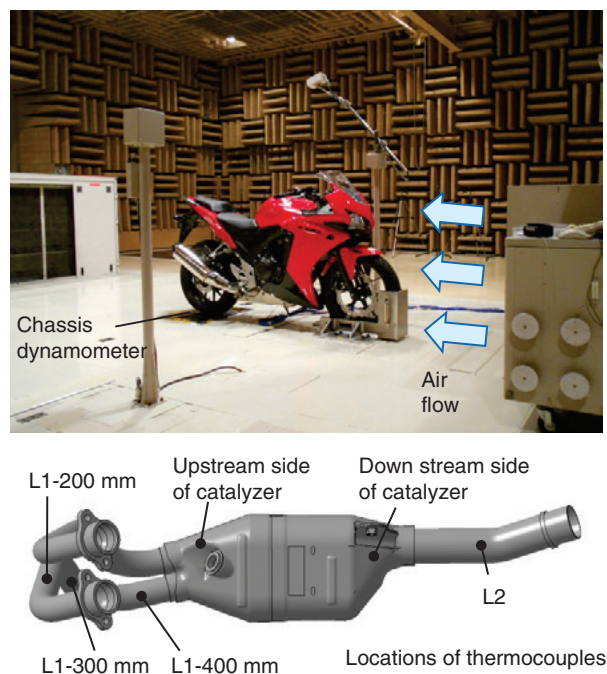


Fig. 17 Measurement of thermal distributions of exhaust gas and outer surface of the exhaust system

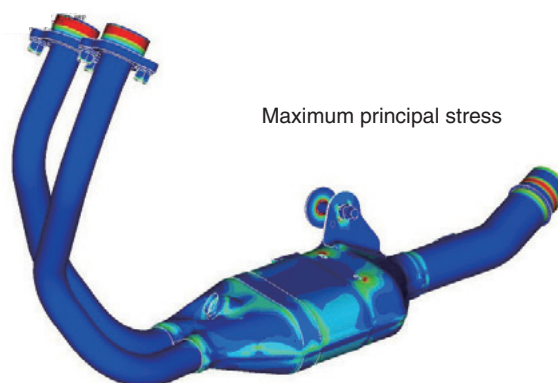


Fig. 19 Results of thermal stress analysis

that part is important when evaluating stress in the exhaust system. With respect to the thermal stress in the proximity of welding of stainless steel materials having different linear expansion, which is the characteristics unique in motorcycles, the correlation between the experiment and the simulation was analyzed.

The correlation was analyzed using a test piece. The test equipment and the test piece are shown in Fig. 20. The two stainless pipes having a different linear expansion coefficient are connected by MIG welding. The test piece was heated in the oven and the strain distribution in the proximity of welding beads was measured. The strain distribution was measured by the strain gauges laid lengthwise on the surface of the pipe from the welding bead toe part. The oven was set at a temperature 153 degree C above the room temperature.

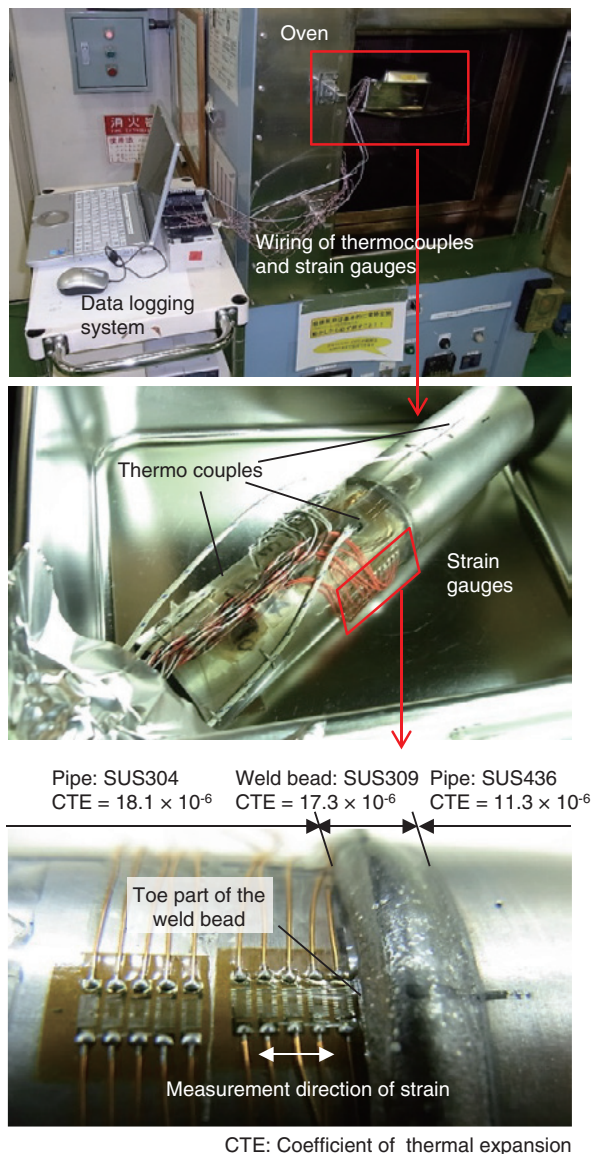


Fig. 20 Measurement of strains generated by heat deformation adjacent to the weld bead

The FEM model of the test piece and the analysis result for the thermal stress are shown in Fig. 21. The model is composed of shell meshes. The size and the pattern of the mesh were selected considering balance between the calculation speed and the analysis accuracy. The measured and simulated strain data are shown in Fig. 22. In the experiment, the strain is highest near the welding bead toe part, and gradually decreases as the length from the toe part increases. A good correlation is seen between the measurement and the simulation.

From the above findings, the authors have concluded that the method we propose in this project for estimation of the temperature distribution and the thermal stresses is appropriate.

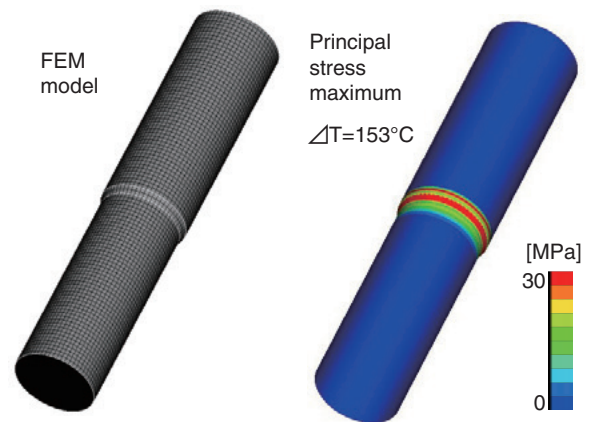


Fig. 21 Simulation result of FEM model of a test piece to investigate thermal stress distribution adjacent to weld bead

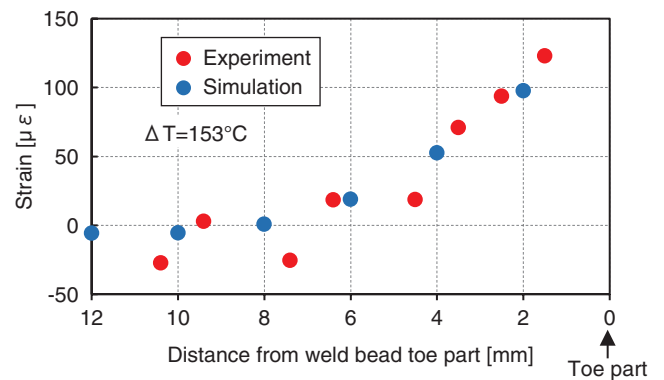


Fig. 22 Correlation of strain generated adjacent to weld bead by heat deformation

5. Calculation of Fatigue Safety Factor

5.1. Calculation Method

The procedure for calculation of the fatigue safety factor is shown in Fig. 23. From the analyses conducted so far, the time-history vibrating stress and the static thermal stress

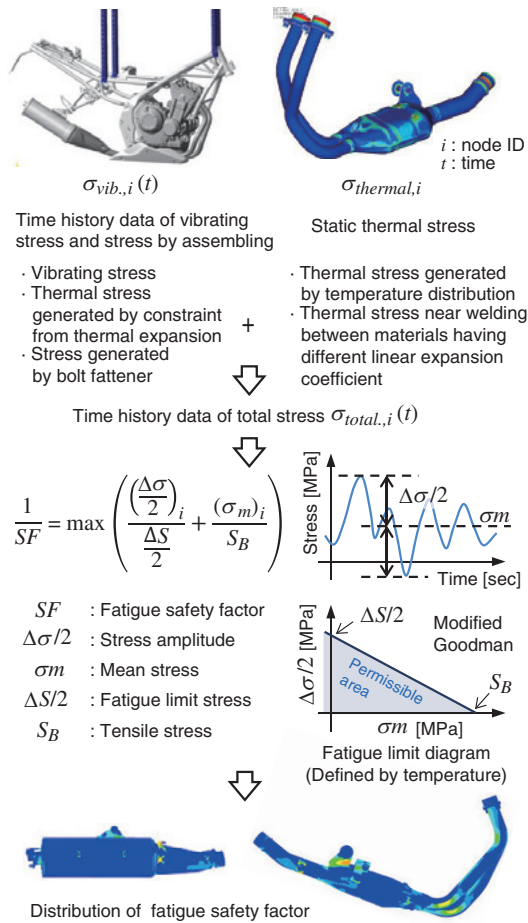


Fig. 23 Process of calculating fatigue safety factor

have been acquired. Firstly the time-history total stress is determined by superimposing the two stresses.

Then, using the total stress, mean stress and stress amplitude are calculated. Lastly the fatigue safety factor is calculated by plotting the mean stress and the stress amplitude on the fatigue limit diagram. In the calculation of the fatigue safety factor, the temperature dependency of the fatigue limit of materials and the creep limit are taken into account.

5.2. Correlation in Fatigue Safety Factor

The correlation in the fatigue safety factor was analyzed. The strain in the exhaust pipe mount bracket of the 399 cm³ test motorcycle was measured while sweeping the engine speed from idling up to 10000 rpm. The location of the strain measurement was the same as that in the vibrating stress analysis. Then, the mean stress and the stress amplitude were calculated and the acquired data were plotted on the fatigue limit diagram. The fatigue limit diagram on which the stresses are plotted is shown in Fig. 24. In the diagram, the horizontal direction indicates mean stress, and the vertical direction indicates stress amplitude. Also, to check for general applicability of the simulation method, the fatigue safety factor was measured and simulated in three other prototype motorcycles having a different engine displacement in addition to the 399 cm³ motorcycle. The data are shown in Fig. 24. In the diagrams, the red dots are the measurement and the blue dots are the simulation.

The estimated fatigue safety factor at a number of positions in a number of models shows a good agreement with the measured one. As shown in Fig. 2, the fatigue safety factor was calculated through many steps. Although

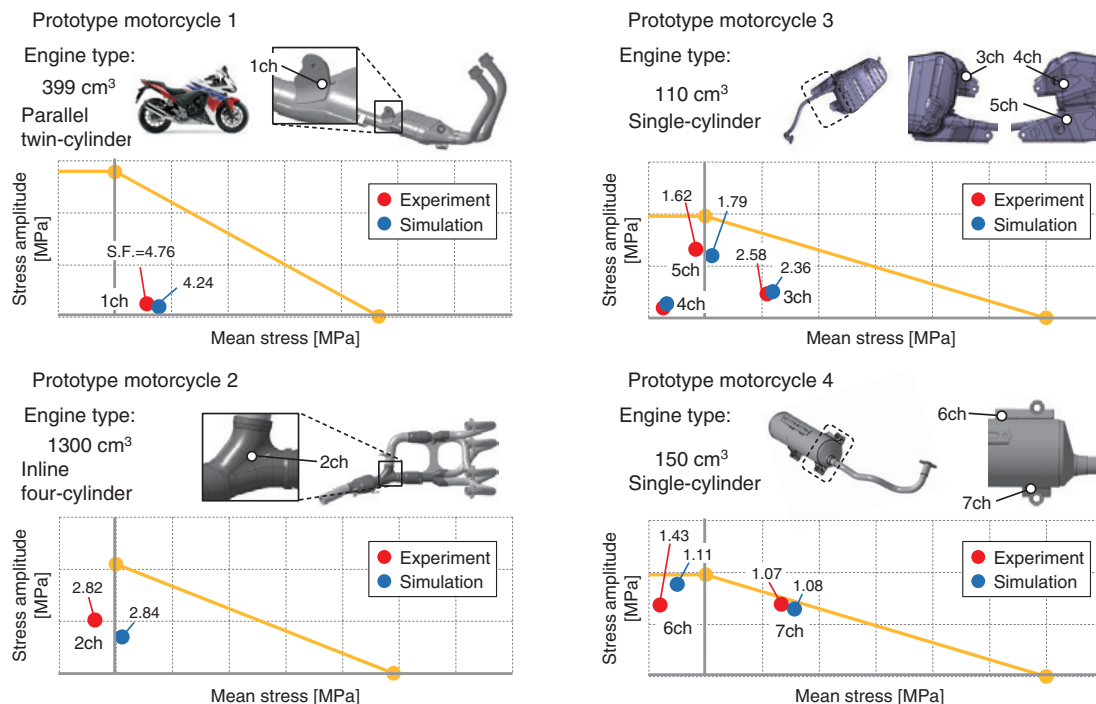


Fig. 24 Correlation between experimental and simulation results on fatigue safety factors

the calculated safety factor therefore contains cumulative errors, the error of estimated fatigue safety factor in this project is less than $\pm 30\%$.

From the abovementioned findings, the authors have concluded that the method for prediction of the fatigue safety factor including the estimation of vibrating stress, temperature distribution and thermal stress is appropriate and adequately applicable to motorcycles in general.

6. Example of Application to Product Development

This chapter introduces an example of application of the developed simulation method to a product development. The subject vehicle is frame-mount-engine type motorcycle equipped with a parallel-twin-cylinder engine.

In its early design stage, the fatigue safety factors were estimated for the components of the on-screen prototype of the exhaust system. Through the results of the investigation using the simulation, it was found out that some of the fatigue safety factors represented nonconforming values at the mount bracket of the exhaust pipe and at the mounting stay for the exhaust pipe covering. The contour representation of the distribution of fatigue safety factors for the exhaust pipe is shown in Fig. 25. Suppose that the prototype vehicle were produced based on this initial design and the durability tests were conducted, it is presumed that the breakages would occur at the sections mentioned above. Accordingly, the design changes were applied to fix these potential flaws. Iterative approach of repeating design changes followed by evaluations of fatigue safety factors for revised designs by developed simulation tool was applied. This iteration was performed until the fatigue safety factors for concerned portions exceed the required values.

Two examples of applied countermeasures are shown in the following. In Fig. 26, the shapes of mounting bracket for the original design and for the design after the changes are applied, together with the contour representations of the fatigue safety factors, are shown. In the initially designed configuration plan, the fatigue safety factor did not meet the

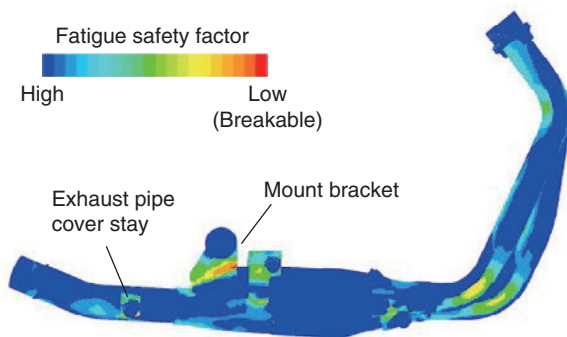


Fig. 25 Contour map of distribution of durability safety factor on the surface of the exhaust pipe

requirement at the curved area. It was because combined effects of bending stress brought by vibrations of the exhaust pipe and the stress arose from the thermal deformations. To cope with the potential design defect occurring in this area, the radius of the curvature was enlarged to mitigate the concentration of the stress. Thus, the fatigue safety factor of this curved area had become satisfactory to meet the requirement. Introducing the next example, the shapes of mounting stay of the exhaust pipe covering for the original design and for the design after the changes, together with the contour representations of the fatigue safety factors, are shown in Fig. 27. In the initially designed configuration plan, the fatigue safety factor did not meet the requirement at the curved area. It was because combined effects of vibrational stress generated in the system, composed of the exhaust pipe covering and its stay, and the stress arising from the difference of thermal expansion between the exhaust pipe and its covering. In addition, the lengths of two legs of the stay were different. Relatively speaking, a stay with shorter length has a structurally higher rigidity and bears higher load and is disadvantageous in terms of durability strength. Moreover, a smaller curvature tends to induce a concentration of stresses. To cope with the potential design defect in this area, the stays are redesigned to have the same leg lengths and the curvatures of the stay legs were enlarged. In addition, the welding points between the stay and the exhaust pipe were changed and the width of the stay was broadened. Thus,

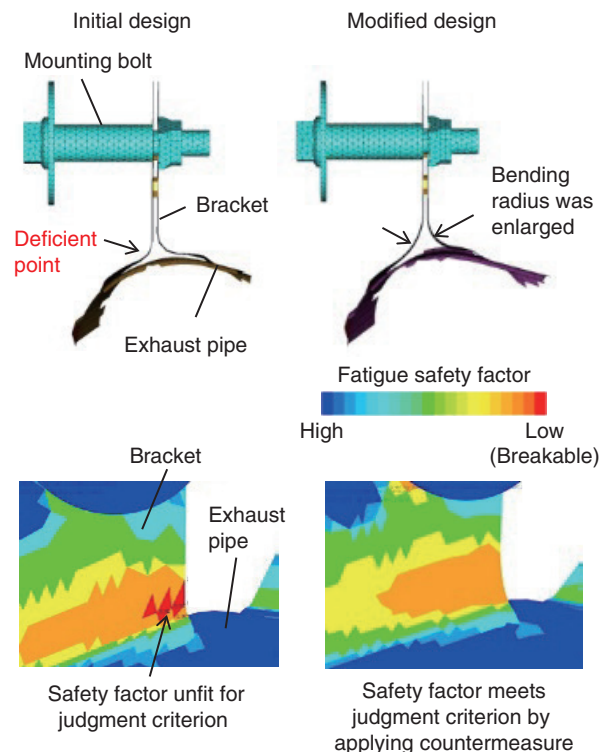


Fig. 26 Difference appeared in contours showing fatigue safety factor before and after application of countermeasures in designing for exhaust pipe mounting bracket

the fatigue safety factor of the concerned curved area had become to meet the requirement.

The comparison of the flow charts between the existing development flow and the redesigned flow applying the developed fatigue strength estimation method is shown in Fig. 28. By applying the fatigue strength estimation method to a design stage of a development, most of the evaluations were made possible to be finalized in the design stage of the development without carrying over those evaluations into the test and redesigning processes using actual prototype vehicles. As a consequence, the application of the developed method realized an increased capability of fatigue durability prediction in design stage and a reduction to minimize the fatigue-originated breakages experienced when testing prototype vehicles. That has enabled us to minimize the frequency of conducting durability tests necessary for developing an exhaust system.

Furthermore, in the conventional procedures, the information on stress available for reference used in the investigations for substituting shapes of the parts were limited to the data only for small localized areas. However, by applying the prediction method developed in this study, the designers are provided with the stress distribution data of whole area of the part as well as the ratio of vibrational stress to thermal stress and the information on

the mechanical behavior including natural vibration modes. The provided information can be utilized in the shape-change countermeasure investigations and the investigation efficiency is drastically enhanced. The other aspect to be noticed is that, by conventional approach, it had been required enormous efforts to make a precise prediction on the effects some shape change might bring about in surrounding areas of changing points. As a consequence, there used to be a case that, after applying a change in certain area of a part, different area on the same part broke in the durability test. On the contrary, using the developed prediction method, it is possible to comprehensively overlook the fatigue durability property for whole areas of a part under investigation and the case described above can be also evaded.

The examples introduced here were only a fraction of the examples actually experienced. There are many other successful application examples that have contributed to our developments. In recent years, other than a fatigue breakage prevention tool, the method is also utilized as an instrument for design investigation of weight reduction. The developed method is used to find out the area on a part that is unnecessarily bulky because of application of an excessively large magnitude of fatigue safety factor. As described above, the fatigue prediction technology developed in this study has been successfully implemented

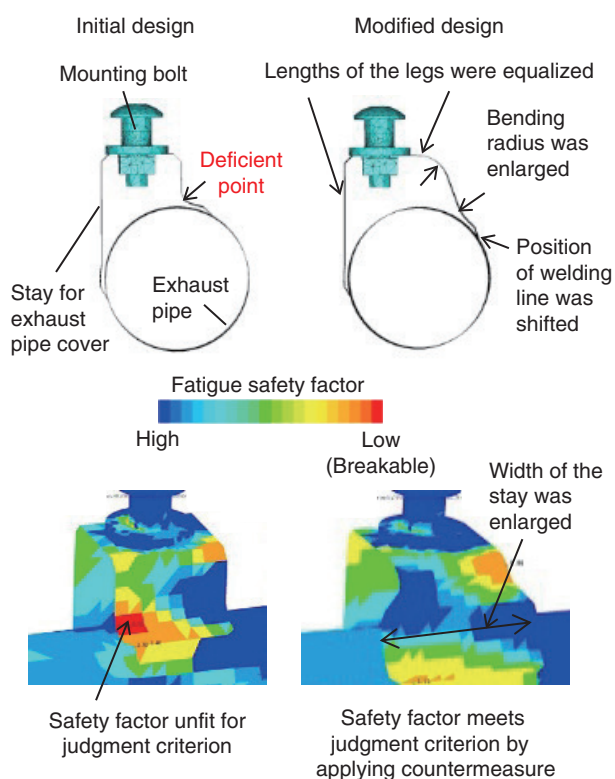


Fig. 27 Difference appeared in contours showing fatigue safety factor before and after application of countermeasures in designing for exhaust pipe cover stay

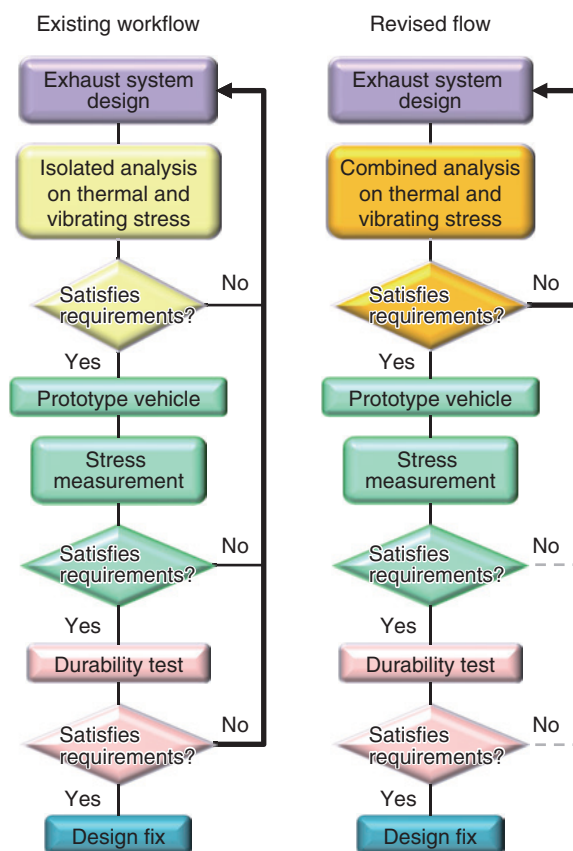


Fig. 28 Existing flow and revised flow of anti-fatigue durability evaluations

in the actual product development process and its significant contribution to the development efficiency has been proved.

7. Conclusion

The following has been achieved through this project.

1. Establishment of fatigue strength simulation method for exhaust system
In this study, the following three methodologies are coupled to make predictions on fatigue durability of an exhaust system in a motorcycle in its early stage of the development.
 - (1) Simulation of vibration stress in the exhaust system based on the flexible multi-body dynamics
 - (2) Estimation of surface temperature of exhaust system based on the 3D CFD and the 1D engine cycle simulation
 - (3) A method to calculate safety factor on the fatigue limit diagram by totaling the thermal stress and the vibrating stress
2. Verifications of validity and applicability of the developed prediction method
Verification of validity and applicability of the developed method was conducted using four test motorcycles. The predicted values of fatigue safety factors yielded by applying the developed method exhibited high correspondences with actual measured values. Based on the results, validity and applicability of the developed method was proved.
3. Empirical proof tests on effectiveness in an exhaust system development
The developed method was applied to an actual vehicle development in its early stage of the design process. The potential areas of fatigue breakages were identified and the countermeasures were implemented prior to the prototype vehicle production. By following this procedure, it was made possible to minimize the number of trials for durability tests of the exhaust system components. Moreover, the states of stresses and mechanical behaviors of the entire exhaust system components were made visually represented. Through that information, the designers were able to get the knowledge efficiently for the investigation on necessary changes of the part shapes. This eventually leads to provide high efficiency of decision making on an appropriate shape to achieve high fatigue durability.
Through the achievements mentioned above, it was proved that our established method is truly effective for overall efficiency enhancement of an exhaust system development.

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