

Research in Technology for Simulating Dynamic Behavior of Cam Drive Mechanism in Single-Cylinder Engines

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ABSTRACT

A technology has been established for theoretical evaluation of timing chain systems, including drive loss and slapping noise at idling engine speed, in single-cylinder engines. To date, almost no theoretical evaluation reports have been published about drive loss and slapping noise in cam drive systems including timing chains. The specifications for tensioner lifters and tensioner guides that satisfy slapping noise and friction loss requirements have therefore been determined only through tests with actual engines. The highly accurate mechanism simulation model developed in this research is populated with data obtained through bench tests with actual engines. This includes the static and dynamic characteristics of the cam chain and tensioner guide as well as the cam sprocket and cam chain contact stiffness and friction coefficient. The results have confirmed a high correlation at the absolute value level between the simulation values and the actual engine test values for the load generated when cam chain slapping noise occurs as well as drive loss in the cam chain system. This research enables examination at the initial design stage of cam chain systems intended to achieve a high-level balance of enhanced fuel efficiency and low noise in engine performance.

1. Introduction

Motorcycles equipped with single-cylinder engines make up the mainstream among small motorcycles, and there is demand for reduction of drive loss in cam drive systems in order to achieve greater fuel efficiency. Proper layout of the cam drive system can enhance the fuel efficiency of the engine. In addition, cam chain systems are used as the cam drive system in small motorcycles because of their compactness and the durability when driven under a high tensile load. There is demand for reduction of the noise generated when the cam chain and cam sprocket come into contact. Consequently, there is a need for development of a numerical analysis system to enable quantification of drive loss in the cam drive system as well as noise generated by contact with the cam chain. Numerical analysis has lately been employing structural analysis that makes use of three-dimensional models. In order to conduct structural analysis of cam drive systems, the valve assembly cam torque, the cam chain behavior, and the tensioner guide behavior must be determined simultaneously. This necessitated the creation of complex,

large-scale analytical systems, such that practical application became an issue. The modeling of the cam chain further involves issues with the large number of constituent elements and the quantification of contact with the cam sprocket. Meanwhile, advances in recursive methods and other such analytical algorithms in the domain of numerical computation have resulted in reductions in the time taken by analysis of multi-degree-of-freedom particle system models, and these methods are becoming practical tools for examining design parameters. Given this context, the present system was developed to perform comprehensive simulation of the behavior of the cam chain and cam drive system as well as the behavior of the valve assembly, and research was conducted on practical applicability of the developed system⁽¹⁾. This article presents an overview of the developed system, describes the method for modeling cam chain-related parts, and explains predictive evaluation performed by simulating the behavior that occurs when the cam sprocket and cam chain come into contact in the idling speed range as well as drive loss in the cam drive system.

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2. Overall Profile of System Development

The valve assembly mechanism to be developed was designed in SOHC configuration with a single cam shaft above the combustion chamber as frequently adopted in small motorcycles. Figure 1 shows an overview of the developed system. The cam torque changes at each engine speed due to the increase in the inertia force that results from acceleration of the valve system at high speeds. Consequently, the cam, valve, valve spring, and rocker arm were modeled so that the cam torque could be taken into account at all normal engine speeds. The tensioner guide, chain guide, and tensioner lifter, which influence cam chain behavior, were also modeled (hereafter referred to as the cam chain system model). The operating conditions of an actual engine were recreated by performing numerical integration in the time domain for each of these constituent elements using the Newton-Raphson method.

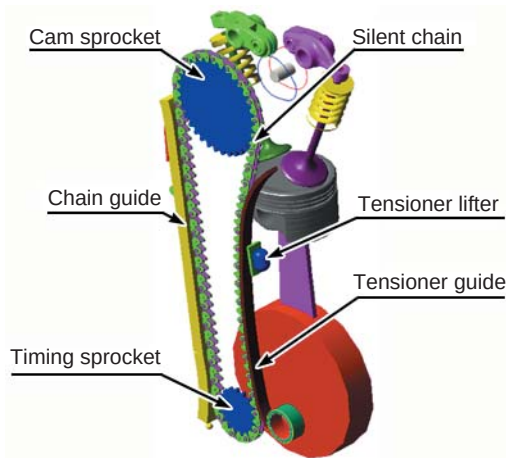


Fig. 1 Overview of developed system

with the cam sprocket and contact between the tensioner guide and chain, the actual shapes of the individual chain links were reflected in the model without reducing the links into simplified particle systems that have no shape. This system, as shown in Fig. 2, was made a multi-degree-of-freedom model in which each chain link is assigned a mass and moment of inertia and the connections between chain links are represented by non-linear springs. For the figure for stiffness between chain links, the cam chain was subjected to a tension test using an Amsler testing machine, and the correlation was confirmed from the load displacement. The accuracy of the resonant frequency of the cam chain, as representative of the dynamic characteristics, was also verified using the measurement tool shown in Fig. 3. Excitation was applied by an electromagnetic oscillator for each pre-tension and vibration acceleration, and the amplitude in the part marked A in Fig. 3 was measured. The results from actual measurement and simulation are shown in Fig. 4(a) and Fig. 4(b).

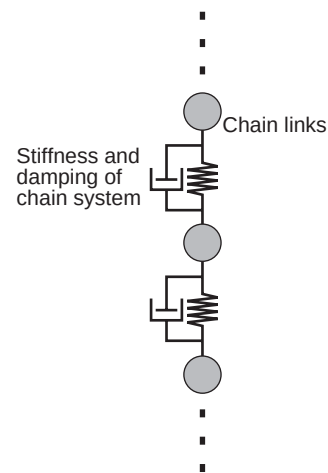


Fig. 2 Multi-degree-of-freedom model of chain links

3. Cam Chain System Modeling Method and Verification of Characteristic Model Values

3.1. Issues in Cam Chain System Models

The cam chain, which transfers the movement of the crankshaft to the cam shaft, is made up of a large number of link elements. The stiffness and attenuation of the chain as a whole possess non-linear characteristics because of such factors as friction and contact stiffness between chain links. In order to quantify the state of contact and friction between the cam chain and other parts, the characteristic values of the numerical model must also be obtained. Methods for modeling the chain system were therefore considered.

3.2. Cam Chain

In order to create an accurate model of engagement

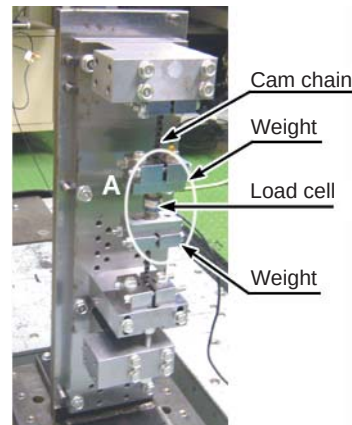


Fig. 3 Measuring tool for chain link dynamic characteristics

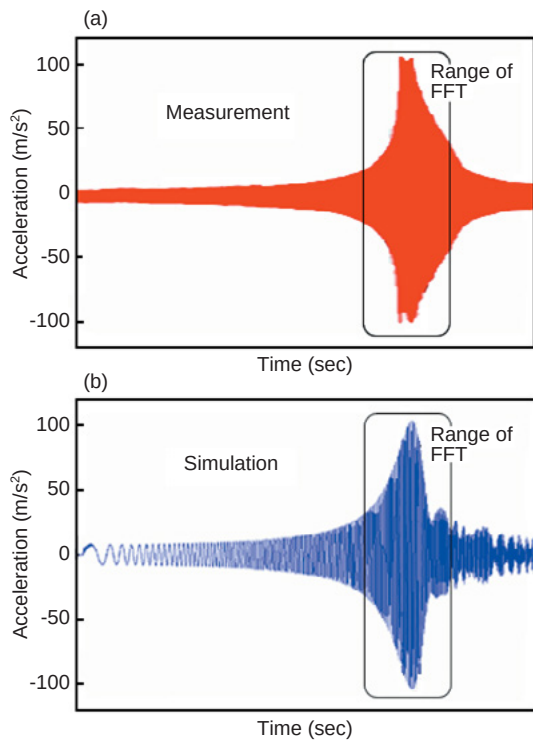


Fig. 4 Measurement and simulation results for the dynamic characteristics of chain links

Table 1 shows the FFT results from actual measurement and simulation. This confirms the close correlation of resonant frequency and amplitude when resonating.

3.3. Chain Guide

Figure 5 shows the model of the chain guide. The characteristics of the chain guide shape were expressed by dividing the chain guide into 20 beam elements. The amount of bending deflection of each part under unit load obtained by numerical calculation was matched to the actual measurement to identify the stiffness characteristic value for the beam elements.

3.4. Cam Sprocket

Figure 6 shows the model of the cam sprocket and cam chain. The engagement with the cam sprocket in the model was represented by incorporating consideration of contact stiffness, contact attenuation, and friction in the portion that comes in contact with the cam chain. The pendulum test shown in Fig. 7 was conducted in order to determine the characteristics of this engaged portion. This was done to find the change over time of the total energy of the system and to verify the correlation of the measurement and simulation. As shown in Fig. 8, the total energy is reduced over time, and it was confirmed that the calculation results provide a good match with this rate of reduction.

Table 1 FFT results of measurement and simulation

	Measurement	Simulation
Resonance frequency (Hz)	424.1	430.0
Amplitude (m/s ²)	31.7	31.9

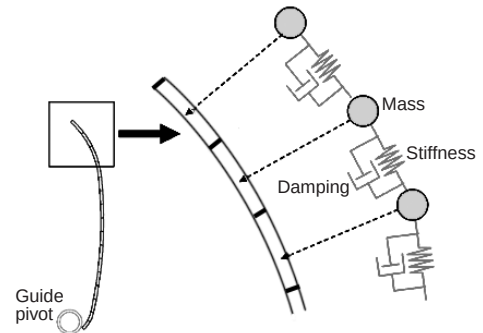


Fig. 5 Model of chain guide

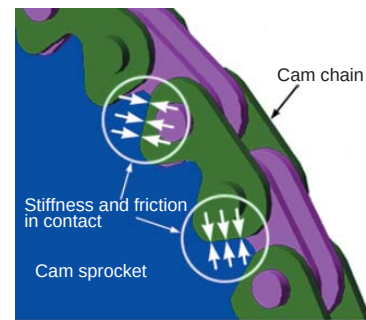


Fig. 6 Model of cam sprocket and cam chain

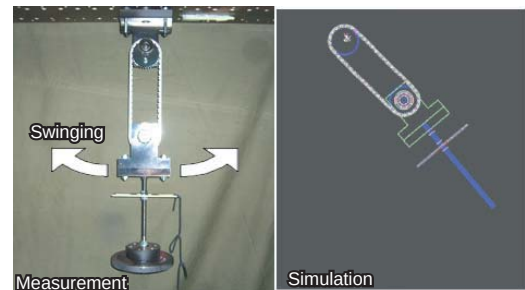


Fig. 7 Pendulum test for measurement of mesh area contact stiffness and friction

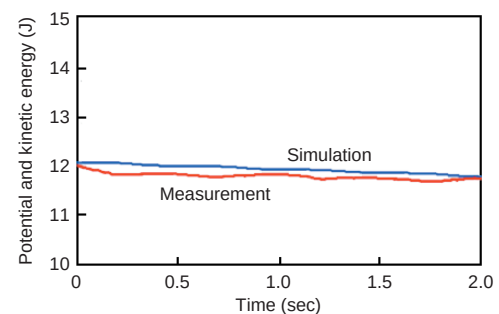


Fig. 8 Comparison of simulation result and measurement result of potential and kinetic energy

4. Verification of Cam Chain System Model Correlation with Actual Engine Operating State

The simulation figures for the cam drive torque and the load generated on the lifter were compared with the actual measurements to verify that the developed cam chain system model accurately represents the operating state of an actual engine. Figure 9 shows the actual engine used, which was a single-cylinder 150 cm³ engine. Measurements of the actual engine were made from 1400 rpm to 9000 rpm. Figure 10 shows a comparison of the

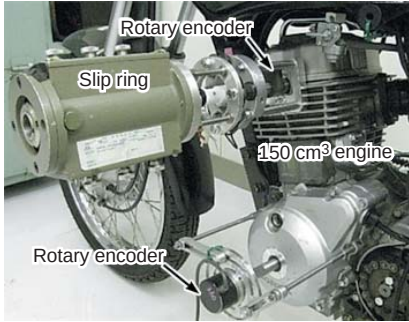


Fig. 9 Test engine and measurement system

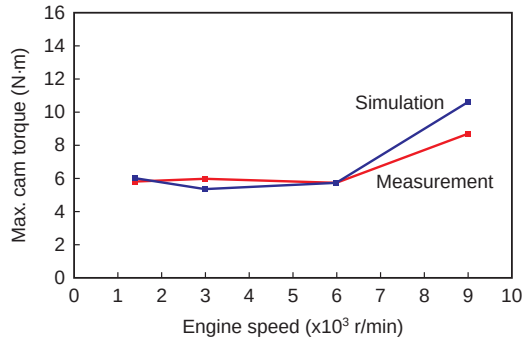


Fig. 10 Comparison of simulation result and measurement result of maximum values for timing sprocket drive torque

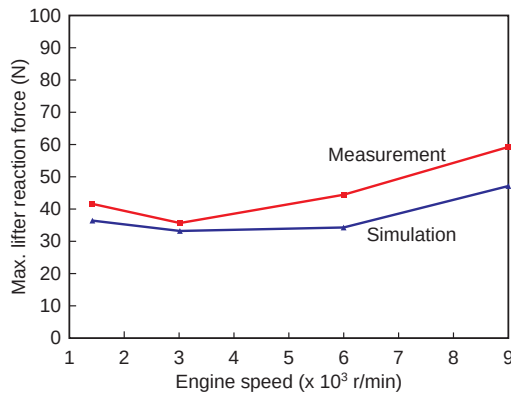


Fig. 11 Comparison of simulation result and measurement result for lifter reaction force

maximum values for cam drive torque over a single cycle. Figure 11 shows the results from comparison of load generated on the lifter. Some discrepancy can be seen at speeds of 6000 rpm and above, but the correlation is positive in the 1400-6000 rpm range. Given these results, the developed model can be said to accurately recreate the actual engine operating state.

5. Applied Research on the Developed System

5.1. Prediction of Cam Chain Drive Loss

This section describes the method for calculating cam chain drive loss. In the developed system, the crank sprocket drive torque and the cam drive torque are calculated. Methods for using these computed figures to calculate drive loss in the cam chain were examined. Equation (1) defines the drive loss torque FT for the average crank sprocket drive torque Tf and average cam drive torque Tc .

$$FT = Tf - Tc \quad (1)$$

$$Pslc = FT \cdot N \cdot \frac{2\pi}{60} \quad (2)$$

FT : Average cam chain drive torque (Nm)

Tf : Average crank timing sprocket drive torque (Nm)

Tc : Average cam drive torque (Nm)

$Pslc$: Horsepower drive loss (kW)

N : Engine speed (r/min)

This was taken as the basis for performing the comparison of cam chain drive loss in the engine as described in Chapter 2. Figure 12 shows the results.

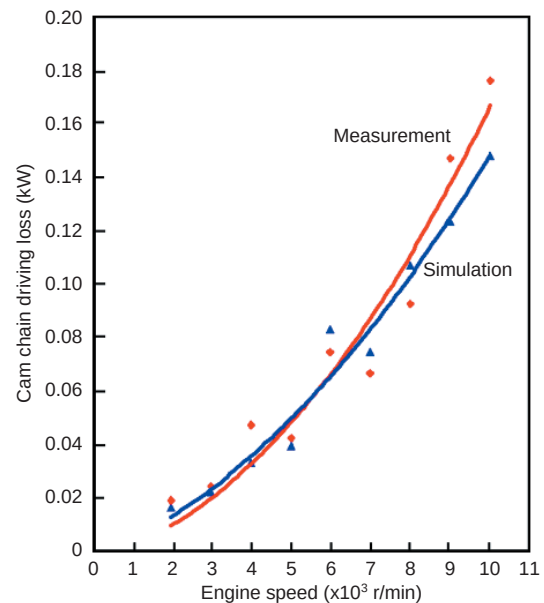


Fig. 12 Cam chain driving loss

Although fluctuations were apparent in the calculations for 6000-7000 rpm, the results show a close correlation.

5.2. Cam Sprocket and Cam Chain Contact Behavior and Slapping Noise

The noise that is made from the cam chain chamber during idling can cause discomfort and it damages the product appeal. The acceleration occurring in the vicinity of the part where the noise was generated was measured using an acceleration sensor to comprehend the timing of generation of this noise⁽²⁾. Figure 13 shows the measurement value. It was determined that the slapping noise occurred at exhaust top dead center due to the suddenly increased amplitude of acceleration. In order to further examine this phenomenon, measurements were made with a Morris damper, which attenuates the seating load, attached at the place where the cam chain is seated on the cam sprocket. The slapping noise vanished. It was discovered from the above that the slapping noise was generated by contact of the cam sprocket with the chain at exhaust top dead center. Next, in order to conduct theoretical evaluation of this slapping noise, an attempt was made to measure the force with which the cam chain and cam sprocket collide and thus generate the slapping noise. The measurement values were compared with the simulation values. The actual engine testing used the engine shown in Fig. 9. Figure 14 shows the tool used to measure the noise-generating excitation force. A three-component force gauge was fabricated to enable measurement of the X and Y components of the load on the plane surface of the cam sprocket and the cam torque, and measurements were made. Figure 15 shows a comparison of the actual engine measurement results and the calculation results with the engine running at 1400 rpm. The maximum load amplitude and the timing of noise generation both showed positive correlation, and this has enabled predictive evaluation by means of simulated slapping-noise-generating excitation force.

5.3. Evaluation of Cam Chain Layout

The main design parameters for the cam drive system include the chain guide shape, stiffness, and support point locations, and the angle of attachment and location of the tensioner lifter. These parameters have an influence on the layout of the engine as a whole. In order to achieve a

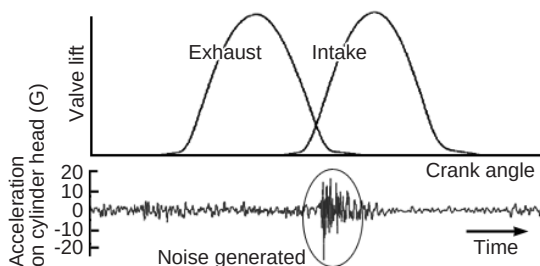


Fig. 13 Variation of acceleration on cylinder head

high-level balance of greater fuel efficiency and quietness, these design parameters have to be examined in the initial design stage. In the event that the simulations performed here were used for such a parameter study and the design parameters were changed accordingly, the change that would take place in the slapping noise was confirmed. Figure 16 shows the results of simulation evaluation of

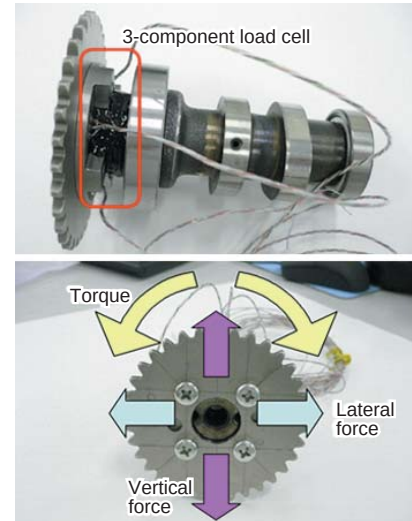


Fig. 14 3-component load cell for measuring excitation force

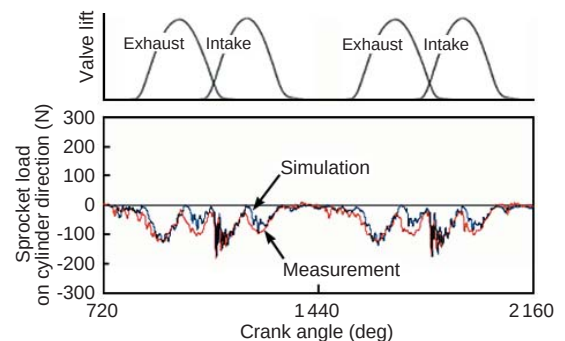


Fig. 15 Comparison of calculation result and actual engine measurement result for sprocket load on cylinder direction at 1400 r/min

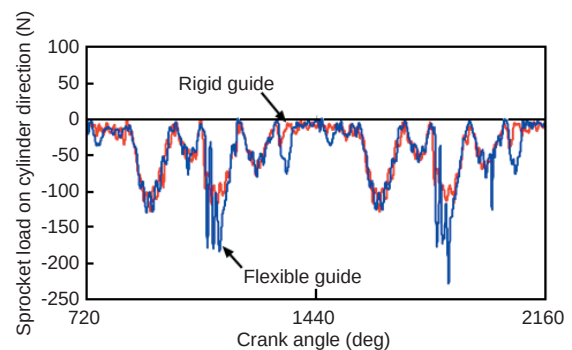


Fig. 16 Comparison of rigid guide and flexible guide result for sprocket load on cylinder direction at 1400 r/min

the excitation force that generates the cam chain slapping noise for differing degrees of stiffness in the chain guide at 1400 rpm. In the case of this engine, increasing the stiffness of the chain guide enabled a reduction in the noise-generating excitation force that was the primary factor in the cam chain slapping noise at 1400 rpm. It was found that this allowed greater quietness to be maintained.

6. Conclusions

- (1) Development of a system for coupled simulation of the cam drive system, reciprocating parts, and valve assembly enabled accurate simulation of the behavior of the cam drive system.
- (2) The phenomenon of the slapping noise that occurs when the cam sprocket and cam chain come into contact was explained, and a method for predictive evaluation of cam chain slapping noise in the idling range by means of simulation was found.
- (3) The research has enabled calculation of cam chain drive loss from the crank sprocket drive torque and the cam drive torque.

References

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