

Research on Dynamic Behavior Simulation Technology for Cam-Drive Mechanism in Single-cylinder Engines

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ABSTRACT

A theoretical evaluation technology for timing chain systems in single-cylinder engine has been established. Hitherto, there have been almost no theoretical evaluation reports published about drive loss and slapping noise in cam drive systems including timing chains. Thus, tensioner lifter and tensioner guide specifications to satisfy requirements related to slapping noise and friction loss have been determined only by tests with actual engines. In this research, a highly accurate mechanism-simulation model has been constructed that takes into account factors such as dynamic characteristics along with crank sprocket and timing chain contact stiffness and friction coefficient in addition to static characteristics of the timing chain and tensioner guide. Our results have confirmed a high correlation with actual engine tests at an absolute value level. This research has allowed a review at the early design stages of timing-chain systems that combine improved fuel efficiency with quietness and other engine performance factors at a high level.

INTRODUCTION

Single-cylinder engines are the main type of engine used in small motorcycles, and reduction of friction in the cam-drive system is required in order to improve fuel efficiency. Engine fuel efficiency can be improved by optimization of the cam-drive system layout. In small motorcycle engines, a cam-drive timing chain (hereinafter referred to as the cam chain) is used due to its compactness and durability in a high-tension drive, and reduction of the noise when the cam chain and cam sprocket mesh while driving. To reduce cam chain noise, design parameters should be set to achieve a tensioner lifter load that combines appropriate regulation of cam chain behavior without significantly increasing friction loss. It is thus necessary to develop a numerical value analysis system that can quantify the cam-drive system friction loss and the noise generated by the cam chain meshing. In numerical analyses, mechanism system simulations that utilize three-dimensional models have come into use ⁽¹⁾. To dynamically simulate the cam drive system using a mechanism system simulation, simulation of the torque of the camshaft operating valves, of the cam chain dynamic behavior, and of the tensioner guide behavior is needed at the same time. Thus, it is

necessary to build a complex, large-scale analysis system, and putting that into practical use proved difficult. Moreover, the large number of components and quantifying of contact status in a model of cam chain related parts seem to be impediments. In the area of numerical computation on the other hand, advances in analysis algorithms such as the recursive method allowed for a reduction in analysis time in multi-degree-of-freedom mass system models, allowing its practical use as a tool for the consideration of design parameters. In light of these factors, a system for these comprehensive simulation of cam chain and cam drive system behavior and valve operating system behavior have been developed and research on its application have been conducted. This paper will give an overview of the developed system, and it will cover cam chain related part-modeling methods as well as the quantification of cam-drive system friction loss and of the behavior where the cam sprocket and cam chain mesh.

OVERALL COMPOSITION OF SYSTEM DEVELOPMENT

The valve operating system mechanism, the subject of development, was made to be a SOHC type where a single camshaft is positioned over the combustion chamber. Figure 1 shows an overview of the system developed. The cam torque, which is the vibration source for the chain mesh noise, is susceptible to the influence of the valve system acceleration, particularly in the high engine-speed range, and it changes according to the engine speed. Therefore, the cam and valve, valve spring, and rocker arm were modeled so that all cam torques can be taken into account at normal engine speeds (hereinafter referred to as the cam chain system model). In addition, tensioner guide and tensioner lifter which is exerted on cam chain behavior were modelled. Numerical integration calculation by time range for each component was applied through the Newton-Raphson method to reproduce actual engine operation situations.

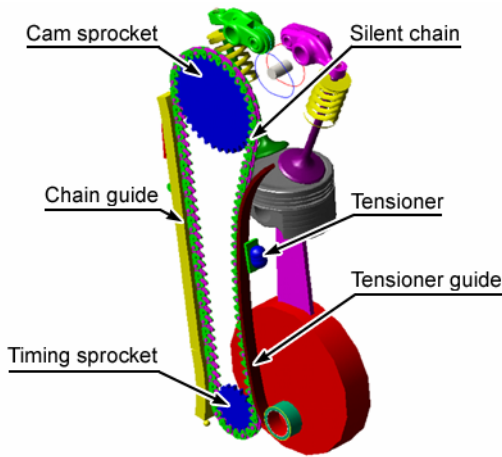


Fig. 1 Overview of developed system

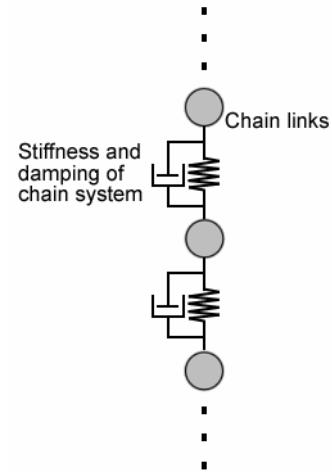


Fig. 2 Multi-degree-of-freedom model of chain link

CAM CHAIN SYSTEM MODELING METHOD AND MODEL CHARACTERISTIC VALUE VERIFICATION

ISSUES IN THE CAM-CHAIN SYSTEM MODEL - The cam chain that transmits crankshaft motion to the camshaft is made up of numerous link elements, and overall chain stiffness and damping have nonlinear characteristics due to factors such as the friction and contact stiffness between chain links. Furthermore, numerical model characteristic values need to be acquired to quantify the contact and friction status between the cam chain and other parts. Thus, methods to model the chain system were considered.

CAM CHAIN - Cam chain noise is presumed to be generated from the impact of the chain and sprocket. Under this presumption, to express the mechanism of the timing chain noise generation numerically in the system, it is necessary to accurately model the guide and chain contact as well as the meshing with the crank sprocket. Therefore, actual chain link shapes were reflected in the model without simplifying individual chain links as a shapeless mass system. This system is, as shown in Figure 2, a multi-degree-of-freedom model having masses and inertia moments for individual chain links where the link intervals are expressed as nonlinear springs. For the stiffness values between chain links, testing was conducted by pulling the cam chain on an Amsler testing machine, and the correlation was confirmed from the load and displacement. Furthermore, to verify the accuracy of the dynamic characteristics exemplified by the cam-chain resonant frequency, the measuring tool shown in Figure 3 was used. Excitation was performed by an electromagnetic exciter per tension and the excitation acceleration from 50 Hz to 1000 Hz, as well as the amplitude of part A shown in Figure 3 was measured. The measurement and simulation results are shown in Figure 4a and 4b. Table 1 shows a comparison of the chain links dynamic characteristic for FFT. Thus, it was confirmed that correlation is achieved between the resonant frequency and the amplitude value at resonance.

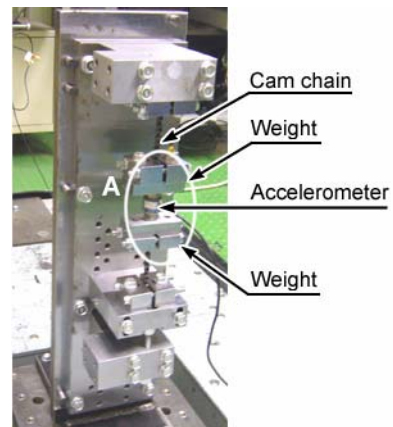


Fig. 3 Measuring tool of chain links dynamic characteristics

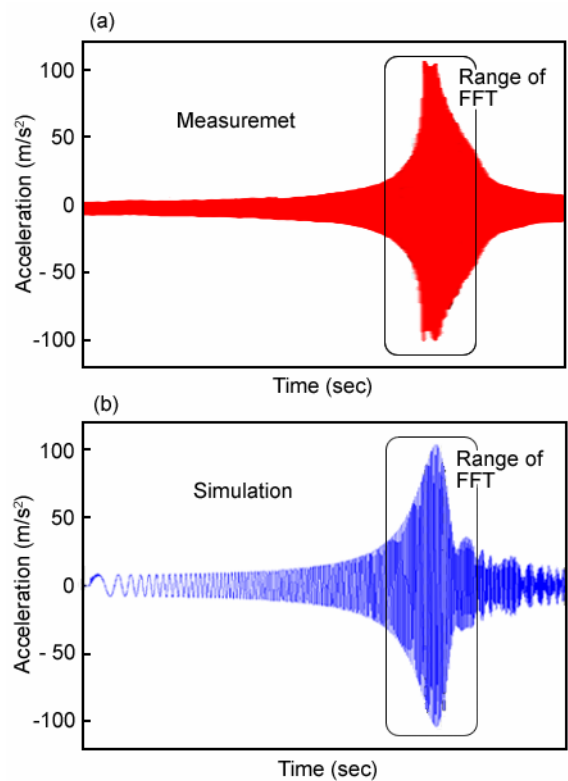


Fig. 4 Measurement and simulation results for the chain links dynamic characteristics

Table 1 Comparison of chain links dynamic characteristics for FFT

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

CHAIN GUIDE - The model for the chain guide is shown in Figure 5. The chain guide is expressed by beam elements divided into 20 parts. By matching the quantitatively calculated bend displacement under a unit load with actual measurements, the stiffness of the beam element is identified.

CAM SPROCKET - The model of the cam sprocket and cam chain is shown in Figure 6. To express the meshing with the cam sprocket, the model considers contact stiffness and friction. To identify that mesh area contact stiffness and friction, a pendulum test was carried out, as shown in Figure 7. The time variation of the total energy of the system was obtained, and the correlation between the measurement result and simulation result was verified. As shown in Figure 8, it was confirmed that the total energy is reduced by the time variation in actual tests; the simulation results show the reduction rate well. As for the reason where the measurement result is lower than simulation result, at measurement initial position of depth direction of the weight has been shifted, it is thought as for the sake of energy decreases with the friction of direction.

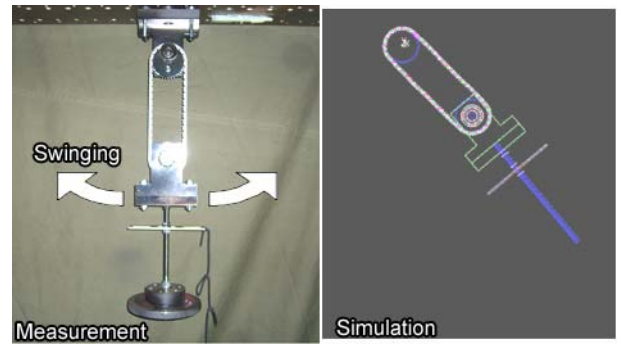


Fig. 7 Pendulum test for measurement of mesh area contact stiffness and friction

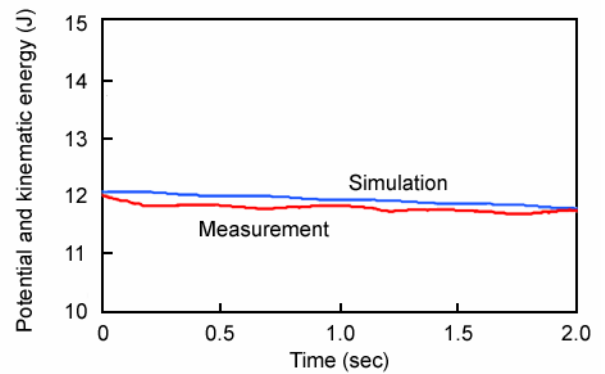


Fig. 8 comparison of simulation result and measurement result of potential and kinematic energy

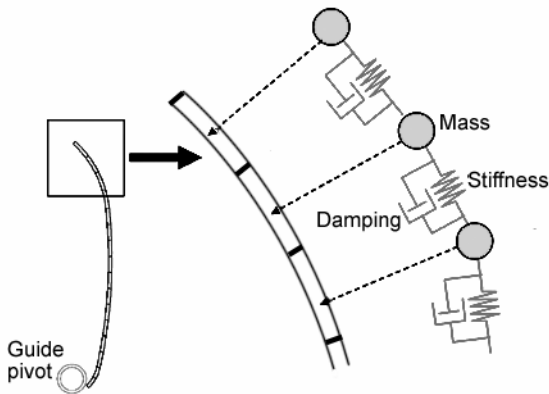


Fig. 5 Model of chain guide

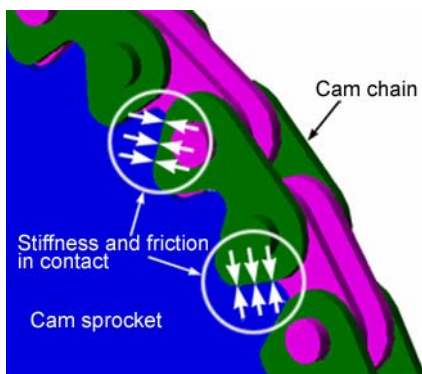


Fig. 6 Model of cam sprocket and cam chain

VERIFYING CORRELATION OF CAM CHAIN SYSTEM MODEL WITH ACTUAL ENGINE OPERATION STATUS

To verify that the developed cam chain system model accurately represents actual engine operation status, it was necessary to compare the numerical calculations and actual test values for crank-sprocket drive torque - the drive source for the timing chain and cams - and the load generated on the lifters. For the actual engine, a 150 cm³ single cylinder engine as shown in Figure 9 was selected. Measurements on the actual engine were made at 1400 to 9000 r/min. Figure 10 shows a comparison of the maximum values for the crank-sprocket drive torque in one-cycle, and Figure 11 shows the results of the comparison of the load generated on the lifters. In both cases, a good correlation is gained between 1400 and 6000 r/min. A slight variation is observed in the speed range greater than 6000 r/min, but good correlation can be observed in the 1400 to 6000 r/min range. From those results, it was verified that the developed model simulates the actual engine operating status well.

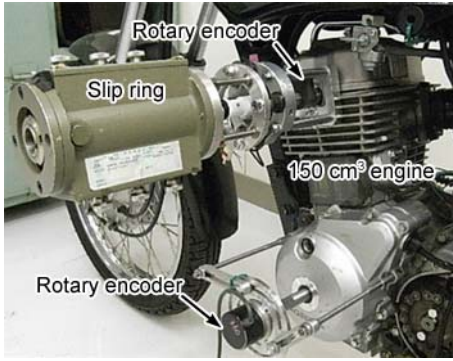


Fig. 9 Test engine and measurement system

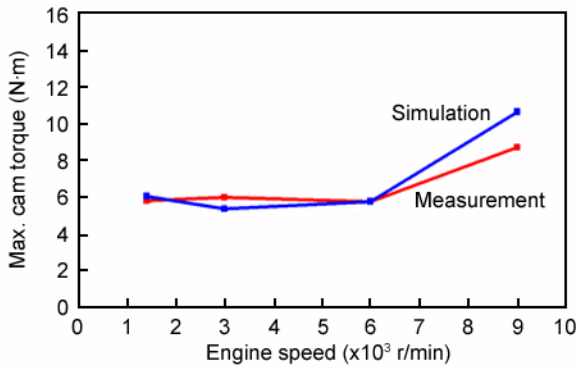


Fig. 10 comparison of simulation result and measurement result of maximum values for timing sprocket drive torque

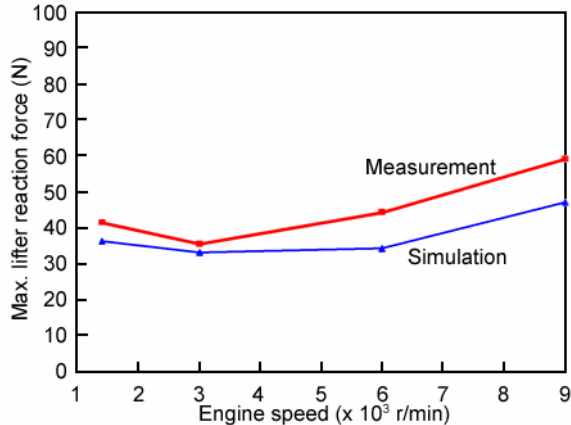


Fig. 11 Comparison of simulation result and measurement result of lifter reaction force

P_{slc} : drive loss in the cam drive system (kW)

Tr : crank sprocket drive avg. torque (Nm)

N : engine speed (r/min)

Based on this, a comparison of the drive loss in a cam-drive system for the engine shown in Figure 10 is shown in Figure 12. The drive loss is expressed well.

BEHAVIOR AT MESHING OF CAM SPROCKET AND CAM CHAIN - To identify the timing of the cam chain slapping noise, the acceleration produced near the sound source was measured with an accelerometer. Figure 13 shows the measurement result. It was discovered from the rapid increase in the amplitude of acceleration that the slapping noise is generated at the time of TDC valve overlap. To further investigate this phenomenon, a damper that attenuates the load of the chain seating on the cam sprocket was attached. By doing so, the slapping noise went away, and the increase and decrease in the amplitude of acceleration was reduced. From these results, we ascertained that the slapping noise is generated from the contact between the cam sprocket and the chain.

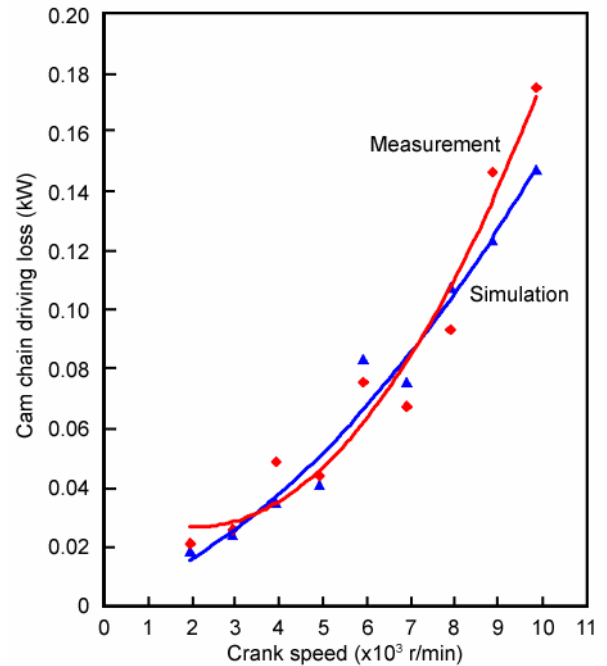


Fig. 12 Cam chain driving loss

APPLIED RESEARCH FOR THE DEVELOPED SYSTEM

PREDICTION STUDY FOR DRIVE LOSS IN THE CAM DRIVE SYSTEM - The crank-sprocket drive torque is calculated for the developed system. Using these calculations, the drive loss in the cam-drive system is given by equation (1).

$$P_{slc} = Tr \cdot N \cdot \frac{2\pi}{60} \cdot 10^{-3} \quad (1)$$

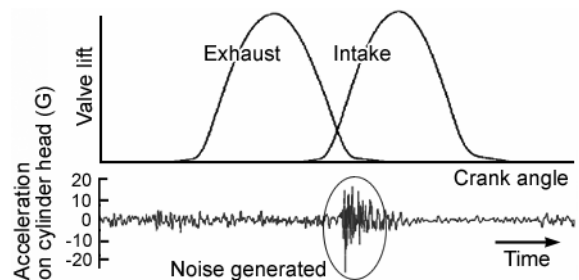


Fig. 13 Variation of acceleration on cylinder head

Next, we measured the force of the chain impacting the sprocket, the cause of the slapping noise, and compared it with the simulation result. The same engine, as noted in the above section, was used for the engine test. Figure 14 shows the tool used to measure the noise-generating excitation force. With that three-component load cell, the load in the crank sprocket flat face and the cam torque was measured. As there is a high correlation between the volume of the slapping noise and the load in the sprocket flat face, we learned that it was possible to determine if the slapping noise is loud or not by evaluating the load by simulation. Figure 15 shows a comparison of the simulation results and the actual engine measurement results at 1400 r/min. There is good correlation between both the amplitude of the maximum load and the generation timing, and we discovered the possibility of a quantitative evaluation of the noise-generating excitation force.

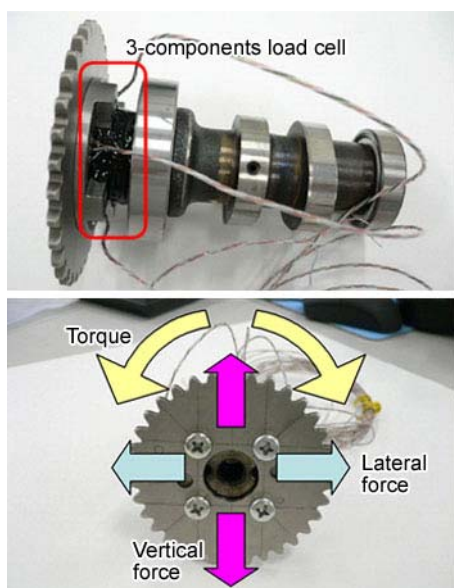


Fig. 14 3-components load cell for measuring excitation force

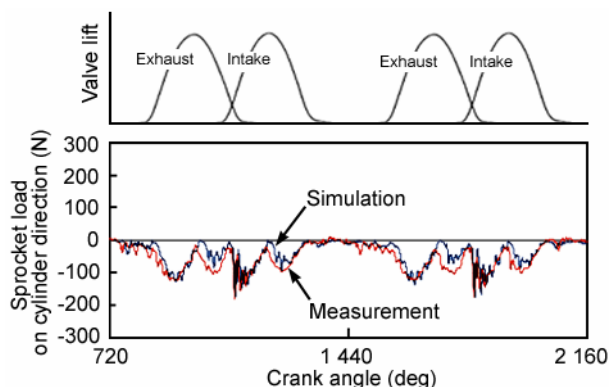


Fig. 15 Comparison of calculation result and actual engine measurement result of sprocket load on cylinder direction at 1400 r/min

SUMMARY

1. By developing a system that performs a coupled simulation up to the reciprocating parts centering on the cam-drive system and the valve-operating system, the behavior of the cam-drive system can be accurately calculated.
2. A high level of correlation was displayed between the simulation result of the sprocket load on the cylinder direction and that of the measurement result of the actual engine.
3. The slapping noise phenomenon at the meshing of the sprocket and chain was identified. A method that can quantitatively evaluate the noise was discovered.

REFERENCES

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