

Development of a Silent Drive Chain System for Motorcycles

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ABSTRACT

Chain noise, which is one of the influential factors to motorcycle pass-by noise regulation, can be classified into two categories: low frequency noise from the rear wheel originated from cordal action according to the second order component of chain meshing and high frequency noise generated by the impact when a chain roller contacts the sprocket bottom. A shape improvement using a urethane resin damper mounted on the drive sprocket and a steel roller drive chain with a urethane resin roller were effective for noise reduction, respectively. The new chain system that combined these new ideas has been proven to be capable of reducing the chain noise to half that of a conventional system.

1. Introduction

Generally, a chain, shaft or belt is adopted in the drive systems for motorcycles. As shown in Fig. 1, a roller chain (hereafter referred to as “chain”) is widely used for driving the rear wheel from the engine on large sport-type motorcycles. The chain drive is the only method that enables the kind of maneuverability required by a sport motorcycle while offering cost and weight advantages on a high dimension level. Due to advances made to reduce the primary source of motorcycle noise, i.e., air suction and exhaust, to cope with ever more stringent environmental noise regulations that will come into practice within a few years, the concern of chain noise is becoming a larger issue. To reduce motorcycle chain noise and at the same time retain the reliability of the chain drive system has been a difficult goal to achieve. An analysis on the mechanism of chain noise was conducted to show the different causes of the noise conditions. Based on the results of this study, a new chain system was developed in which the chain noise energy was reduced to half that of conventional system designs.

1.1. Chain Noise in Large Sport Models

The main sources of noise in a large chain-driven sport model motorcycle include the exhaust system, intake system,

engine, and the drive system. Among these, as shown in Fig. 2, most of the noise from the drive system is attributable to the drive chain. In large sport model motorcycles, the drive chain noise (hereafter referred to as “chain noise”) contributes to as much as 20% of all the noise from the vehicle. Chain noise is usually caused when the chain roller impacts the bottom of the sprocket between the sprocket teeth thereby generating an impact noise. Figure 3 shows attaching a cushioning material (hereafter referred to as “damper”) made of hard rubber or the urethane resin on

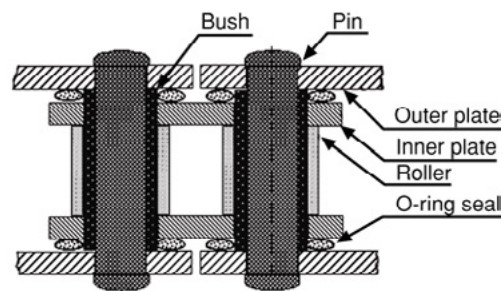


Fig. 1 Structure of conventional drive chain for motorcycles

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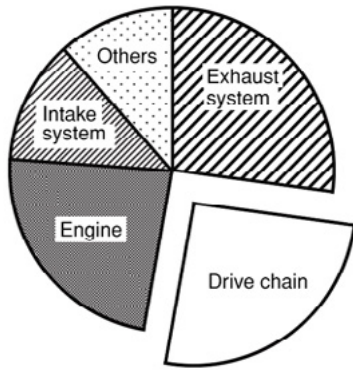


Fig. 2 Ratio of drive chain noise to others

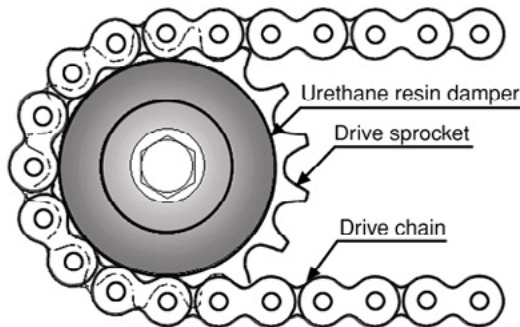


Fig. 3 Conventional drive sprocket and chain for motorcycles

the side of the iron sprocket. This serves to reduce the impact rate and impact noise between the chain roller and the bottom of the sprocket teeth. Also, a cover has been fitted over the drive sprocket assembly to prevent the direct noise radiation.

2. Analysis of Roller Chain Force

2.1. Chain Separated Test Equipment

It is difficult to accurately separate chain noise from all other noises being generated from an actual motorcycle. However, evaluation of the chain noise on the actual vehicle doesn't allow an analysis with high reproducibility due to the effects from other noise sources such as engine or exhaust system. Figure 4 shows the separated sprocket and chain assembly test equipment. This assembly has been devised to test the chain noise in conditions approximating actual vehicle driving conditions. The motor drives the drive shaft and the dynamometer absorbs the driving force. To block the noise generated from these auxiliary machines such as the motor, the drive assembly has been incorporated into a separate soundproof chamber.

2.2. Results of Impact Noise

Figure 5 shows the equipment used to measure the excitation force exerted on the sprocket by the chain. The acceleration pickup was attached to the drive sprocket and the linear acceleration generated by the drive sprocket driven under actual vehicle driving conditions of 1,186 r/min and the driving force 137 N·m was measured. Measurements

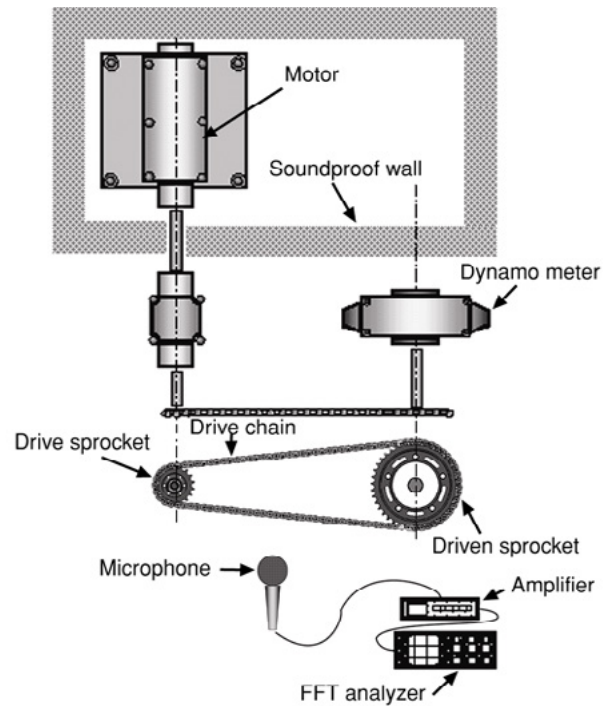


Fig. 4 Chain-separated test equipment

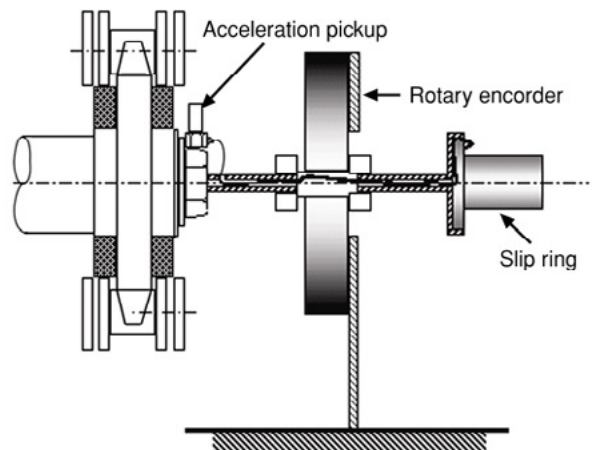


Fig. 5 Measurement equipment of drive sprocket acceleration

were also conducted without the application of a urethane resin damper and with a damper of Hs84 (Shore hardness) and Hs95 degrees of shore hardness respectively. As Fig. 6 shows, impact noise is generated whenever the roller meshes with the drive sprocket. Furthermore, the noise level decreased progressively as tests were conducted without a damper, and with a Hs84 and Hs95 damper respectively. The linear acceleration with a Hs84 and Hs95 damper was confirmed decreasing up to 1/10 compared to that without a damper. Measurement of noise within 1.5 m away from the side of the test equipment was conducted simultaneously, and a maximum noise reduction of 7 dB was confirmed. Thus, it has been confirmed that the cushioning effects of the resin damper have a remarkable influence on the chain noise level.

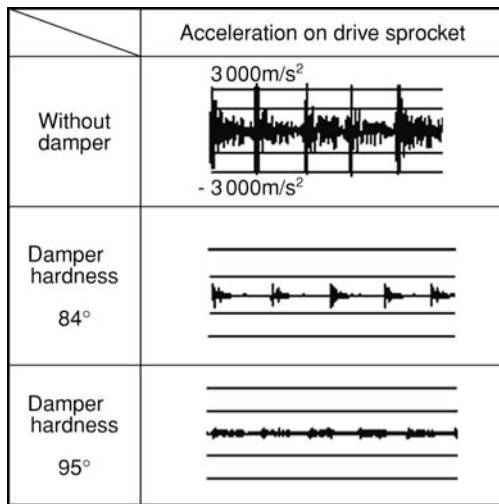


Fig. 6 Acceleration of time domain and frequency domain

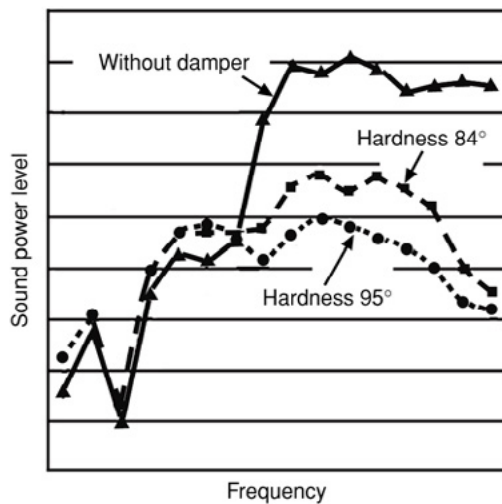


Fig. 7 Frequency analysis of noise from chain-separated test device using three types of urethane resin damper

3. Effectiveness of Impact Noise Reduction in the Actual Vehicles

The result of the chain separated test equipment, that the hardness of the urethane resin damper has significant influence on the degree of acceleration and noise generated, was verified on an actual vehicle. Figure 8 shows that noise generated on an actual vehicle with an applied damper hardness of Hs84 significantly reduces noise occurrence compared with testing conducted without the application of any resin damper. On the other hand, measurements of noise generated with the application of a damper with a Hs95 hardness unexpectedly showed an increase in noise which is actually different from the chain separated test device. Figure 9 shows the frequency analysis of noise generated from the chain-separated test devices. According to the frequency analysis results, it has been shown that the Hs95 damper increased the noise level to a high of 630 Hz compared with that generated by the Hs84 damper. This

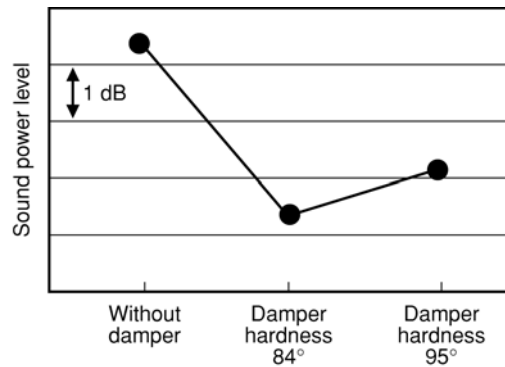


Fig. 8 Noise level of complete motorcycle using three types of drive sprocket

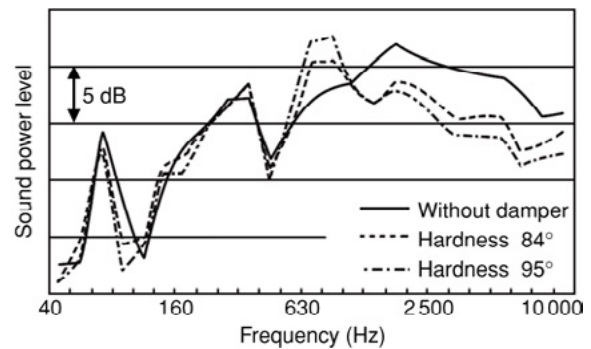


Fig. 9 Frequency analysis of noise from chain-separated test device with rear wheel using three types of urethane resin damper

clearly demonstrates that an increase in noise level exerts influence on the overall noise level and that there is a difference in noise levels generated in component testing (Fig. 7) and noise levels generated on the actual vehicle (Fig. 9).

4. Source of Noise from the Actual Vehicle

Noise measurements were taken from the actual vehicle to determine the source of the 630 Hz sound that did not occur with the test unit. The possible causes were assumed to be coming from the engine, swing arm, rear wheel, etc. Lead masking was applied to these respective locations in testing for noise sources on the actual vehicle. Figure 10 shows the effectiveness of the lead masking application to the rear wheel. These measurements clearly show that the urethane resin damper attached to the drive sprocket exerts influence on noise radiation generated from the rear wheel and that this has an effect on the overall noise from the actual vehicle.

5. Measurement of Rear Wheel Transfer Function

Currently, aluminum die-cast is widely used in the rear wheel component of modern sport type motorcycles. To verify this commonly held view, the rear wheel transfer function on the actual vehicle was measured. Using an impact hammer, force was applied from the driven sprocket

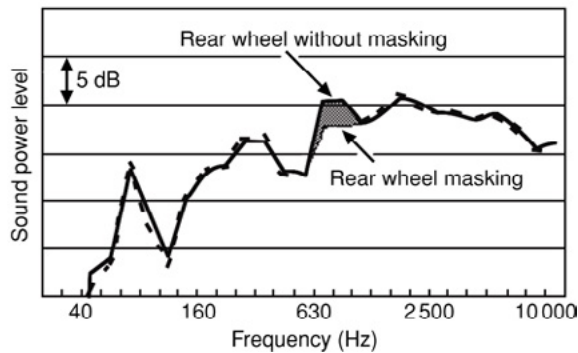


Fig. 10 Effectiveness of lead masking in rear wheel from the actual vehicle

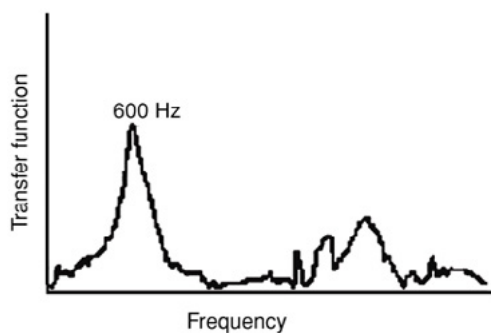


Fig. 11 Transfer function of rear wheel

tooth flank and the rear wheel transfer function was then measured. Figure 11 shows a resonance frequency of 600 Hz generated by the transfer function of the aluminum alloy die-cast rear wheel on the actual vehicle. This shows how easily frequency resonance is generated from the rear wheel. The location at which the resonance occurs is situated on the reduced rim area where lead masking has been applied on the actual vehicle. This proves that a rear wheel generating approximately 600 Hz of natural frequency creates a resonance from the similar level of resulting excitation.

6. Unit Tests Conducted with the Rear Wheel Attached

To clarify the cause and effect relationship between the specifications for urethane resin damper on the drive sprocket and the rear wheel radiation noise, the chain-separated testing equipment shown in Fig. 4 was used on the rear wheel. It was attached and fitted to an actual vehicle as shown in Fig. 12. The equipment was used to measure noise occurrences with differing urethane damper configurations: first without the use of a damper and then with Hs84 and Hs95 dampers, respectively. At the same time, to clarify the contribution of the drive and driven system, each system was masked in a wooden box covered with lead and acoustic material and measurements were conducted respectively. Figure 13 shows the results of this test. The following points were learned from the tests conducted on the rear wheel mounted chain drive system.

The noise generated from the drive system showed the

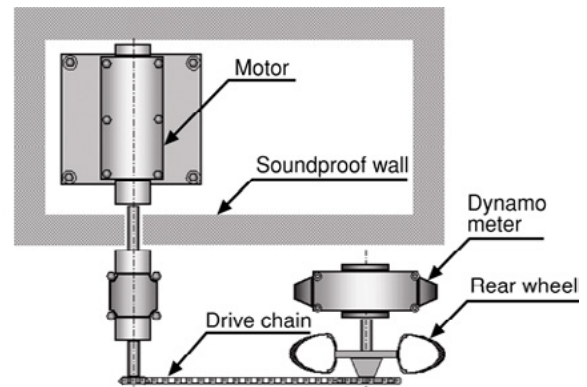


Fig. 12 Chain-separated testing device with rear wheel

following results: noise from testing conducted without a damper was greater than that in which an Hs84 damper was applied, and this in turn showed greater noise than testing in which an Hs95 damper was applied. This result confirms that the change of impact noise greater than 1.6 kHz has an effect. While the noise generated from the driven system showed the following results: noise from testing conducted in which an Hs95 damper was applied was greater than that in which an Hs84 was, and this in turn showed greater noise than testing without a damper, which is the opposite to the result with a drive system. The driven system noise exerted a frequency of 630 Hz. Putting these results together in accounting for the total level of the noise produced revealed that the noise tended to diminish first without a damper and then, with a Hs95 damper and finally with a Hs84 damper. The chain noise on the actual vehicle occurred in the high frequency components causing impact noise between the drive system roller and sprocket teeth bottom, and also in the comparatively low frequency levels of noise emanating from the wheel surface in the rear wheel mounted drive system. The trade off difference in the relationship of these two types of noise showed that they both determined the level of chain noise that occurred on the actual vehicle. This has resolved the question why there was an unexpected change in frequency level of 630 Hz and 800 Hz by modification of the resin damper.

7. Difference of Winding Radius

In testing conducted on the wheel components and the actual vehicle it was shown that while there was a reduction in the level of impact noise generated by the urethane resin damper attached to the drive sprocket, there was an increase in the wheel radiation noise frequency. The testing also confirmed the mechanisms in which this noise occurred. In principle, the roller chain has a variation in the winding radius. As the roller winds around the sprocket, the winding radius on the roller position shifts from position R to position r as shown in Fig. 14. The change in winding radius causes vertical shifting, called cordal action, on the chain line. The following formula expresses the difference in winding radius.

$$r = R \cos (\pi / N) \quad (1)$$

N : the number of sprocket teeth

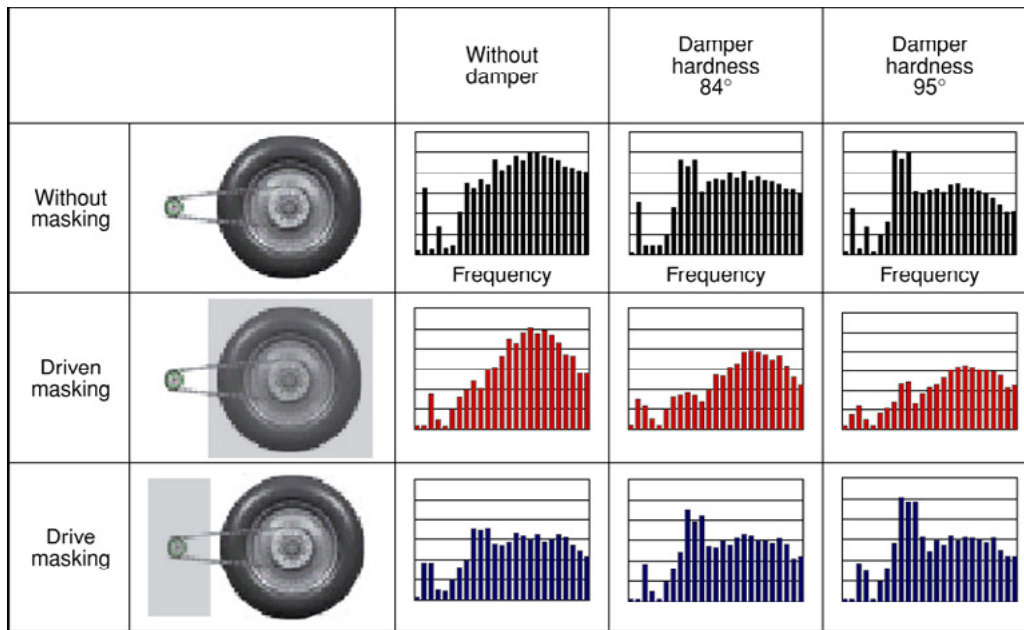


Fig. 13 Comparison of sound frequency from chain-separated testing device using three types of urethane resin damper

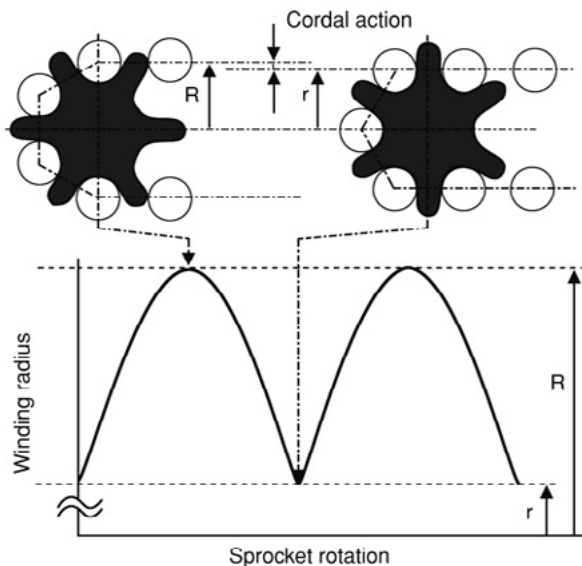


Fig. 14 Relation between winding radius and rotation of sprocket

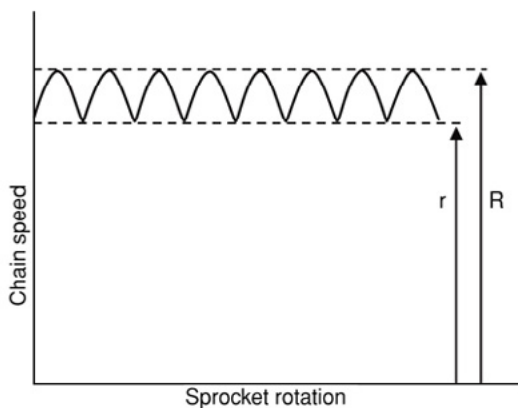


Fig. 15 Fluctuation in chain speed

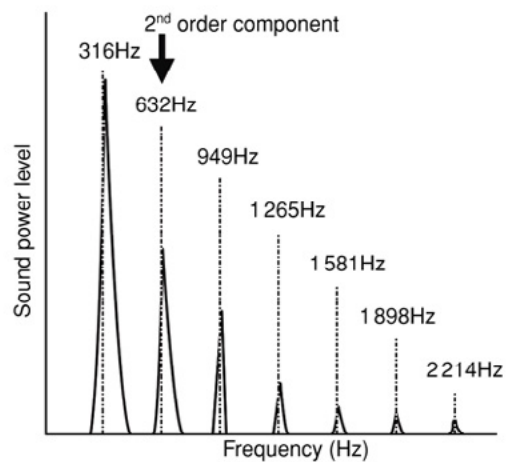


Fig. 16 FFT output of fluctuation in chain speed

The cordal action causes the chain speed to fluctuate even if the drive sprocket's angular velocity remains constant. Figure 15 shows the fluctuation in chain speed for a drive sprocket with 16 teeth that rotates at 1,186 r/min in an actual vehicle condition. Figure 16 shows the FFT output results of the fluctuating chain speed. The fluctuation of the drive sprocket winding radius causes the cordal action which then leads to a fluctuation in chain speed. Consequentially, this will cause a fluctuation in angular velocity flowing from the orderly component of meshing of the driven sprocket. The angular velocity fluctuation exerts an excitation force on the driven system and contributes to chain noise.

8. Why Does the Sprocket with the Resin Damper Increase the Changes in the Winding Radius?

The reasons are to be verified why the resin damper, used for reducing impact noise, was shown to cause greater deterioration in the orderly component of meshing than when no damper was used.

Figure 17 and Fig. 18 show the respective chain winding radius conditions on the resin damper fitted drive sprocket. At the initial winding position of the roller, indicated by the mark (●) in Fig. 17, the plate is positioned in the resin damper tooth indent. At this point, the roller does not sit completely over the bottom of the sprocket between the teeth. As Fig. 18 shows, the winding is continued so that the chain is wound completely over the sprocket. The winding radius is shown by r . The roller point, indicated by mark (●), is completely meshed over the bottom of the sprocket between the teeth. The winding radius R is increased only for the associated tooth indent portion of the resin damper. The difference in winding radius, expressed by $R-r$, is greater for a chain winding radius associated with a resin damper than that without the application of a resin damper. That is, it has become clear that with the combination of the round urethane resin damper and the gourd-shaped chain plate, the fluctuation of the winding radius becomes larger than when there is no damper. The fluctuation of angular velocity of the driven system increases and the velocity order component also increases. The result shows an increase in excitation force on the wheel and an increase in chain noise, which causes deterioration in the radiation noise level.

8.1. Countermeasures for Two Noise Types

Since there is a relationship between the trade off of the drive and driven system in relation to chain noise, it was believed that there must be a way of reducing noise for the total chain system including the drive and driven systems. It has now been shown that countermeasures are required for two different types of noise: for the impact noise on the drive system and for the wheel radiation noise on the driven system. The noise radiated from the driven system will be dealt with first.

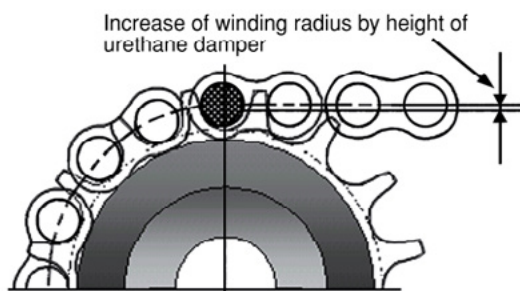


Fig. 17 Condition of meshing start

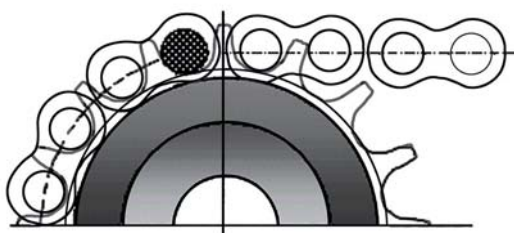


Fig. 18 Condition of completely meshing

8.2. Urethane Resin Damper for Reducing Winding Radius Fluctuation

Winding radius fluctuations approaching conditions close to those in which a resin damper was not used and meshing that enabled a reduction in impact noise were verified. Since fluctuations in winding radius increase the orderly component of meshing, attention was directed to reducing variations in winding radius. Improvements in the meshing between the chain and sprocket were attempted with the resin damper. As can be seen from Fig. 14, as the peak on the graph indicating the winding radius is decreased, the meshing of the roller and sprocket teeth becomes increasingly shallow leading to a greater potential for the chain to become disengaged while the vehicle is being driven. Further attention was then directed to lifting the low point between the peak winding radius points of chain penetration. To raise the low point of the winding radius to align with the chain plate's side view pattern shape, the sprocket protrusion was aligned with the resin damper wherever low points of contact occurred in the winding radius. Changing the winding radius decreased the chain's propensity to sag at those low points on the winding radius. To adjust the sprocket protrusions to avoid disruption to the original power transmission function, the height of protrusion was adjusted to approximate the indent points on the resin damper. Figure 19 shows the resultant resin damper with protrusions that was designed according to the test results.

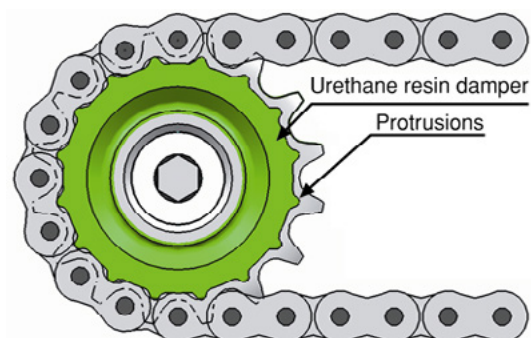


Fig. 19 New form urethane resin damper with protrusion attached

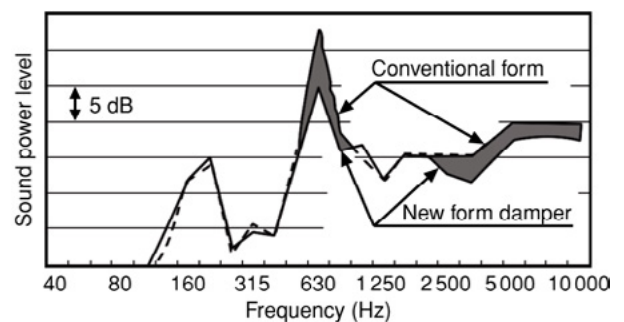


Fig. 20 Effectiveness of new urethane resin damper by chain-separated testing device

8.3. Verification of the Effectiveness of the Protrusion in the Resin Damper

Figure 20 shows the measured performance results of the newly designed urethane resin damper with protrusions including the reduction in impact noise and power transmission frequency. In the wheel connected unit testing and actual vehicle testing, it was shown that there were no significant increases in the previously measured 630 Hz sound level. It was also shown that the reduction in impact noise levels greater than 1.6 kHz was the same as that achieved with the conventional resin damper. Furthermore, by combining the newly devised resin damper with the chain plate, the resin helped to disperse the exaggerated force exerted during meshing, while preserving the qualities associated with the original damper and successfully improving the durability of the silent chain configuration. Also, reducing the irregular movement pattern of the drive sprocket greatly reduced the rockiness experienced by the rider and contributed to the overall improvement in vibration during operation.

9. Reduction of Impact Noise

9.1. Silent Chain

Reducing persistent chain noise requires an effective means for reducing impact noise. However, by attempting to further reduce impact noise with a resin damper attached to the drive sprocket, there was a concern that this would lower drive transmission reliability and bring on deterioration through the previously described trade off in winding radius. Therefore focus was shifted from the sprocket to the drive chain in developing a means for effectively reducing impact noise. However, it was not possible to develop a function capable of servicing the dual requirements for drive transmission while softening impact. This was resolved by separating the drive transmission function and the noise elimination on the chain roller to devise a roller chain with newly enhanced functionality.

9.2. Silent Chain Structure

Figure 21 shows the structural configuration of the newly devised silent chain. This newly developed chain adopts a urethane resin roller (hereafter referred to as resin roller) segment on the steel roller for supporting power transmission. Approximately 15% of the steel roller is constructed with a urethane resin roller segment, which is fitted along a cylindrical direction. The outer dimensions of the resin roller measure about 1.2 times that of the steel

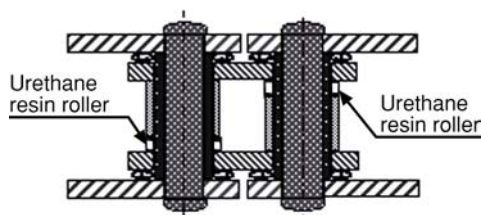


Fig. 21 Structure of developed silent chain

roller. This enables the resin roller to sit firmly on the bottom of the sprocket between the teeth and aligns the steel roller with the elastic deformation portion of the resin roller. This structural design successfully reduces chain noise by reducing the impact speed of the steel roller. The structural characteristics provide alternate positioning of the resin roller that is set on single sides while countering chain line shifting and wear imbalances on the steel roller. In determining a suitable width for the resin roller, both the silent characteristics and durability were taken into account in relationship to measurement restrictions defined by the steel roller. In determining the outer diameter dimensions for the resin roller, it was known that larger dimensions for the resin roller would provide greater reinforcement to the silent chain characteristics. By incorporating the driven sprocket resin damper in the newly devised resin roller chain, a greater reduction in impact noise was achieved. By the alternate positioning of the resin roller, even numbered toothed sprockets experienced the tooth flank wear. This was countered by recombining the drive chain along a half circle. The newly developed silent chain design has successfully been applied to 530 size chains that can be used on large scale motorcycles.

9.3. Effectiveness of the Silent Chain

Figure 22 shows the effective reduction in noise achieved by the newly developed silent chain. The measured results show a frequency reduction of more than 1.6 kHz. Also, no increase in the 630 Hz orderly component of meshing has been verified. The effectiveness of chain silence has also been tested and verified for up to 20,000 km of driving with assured durability. This has been made possible by addressing the requirements for the drive force transmission function and the silent chain function within a single roller assembly made up of steel and resin components. Additionally, applying this impact noise countermeasure to the main chain component has been an effective means in reducing chain noise generated from the driven sprocket.

This new chain system comprised of a new drive sprocket resin damper and silent chain has not only resolved the long studied roller impact noise but has also resolved the noise radiating from the drive system by isolating its origins to the orderly component of meshing mechanism. By successfully incorporating the described two results, this research has achieved a greater than 50% reduction in chain noise energy compared with that in conventional drive chain systems.

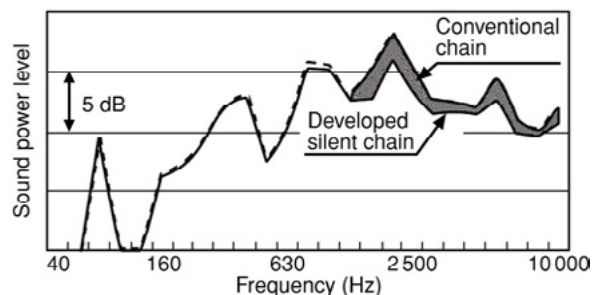


Fig. 22 Effectiveness of developed silent chain

10. Conclusion

In reducing the roller chain drive noise on rear wheel drive systems adopted by large scale sport type motorcycles, attention was focussed on the excitation force emanating from the chain noise, cordal action and the radiation noise generated by the drive system. The results gained from testing conducted on the unit equipment and on the actual vehicle are given below.

- (a) Two different types of noise were discovered: one is an impact noise greater than 1.6 kHz on the roller chain and the other noise is generated by the excitation force resulting from angular velocity fluctuations on the chain.
- (b) The noise from a rear wheel generated by the excitation force on the chain's angular velocity fluctuation was shown to cause the cordal action experienced by the roller chain.
- (c) In reducing the level of noise from the rear wheel, it was discovered that the attached drive sprocket resin damper actually worsened the cordal action.
- (d) By combining the newly developed silent chain and the resin damper in the new system, the chain noise energy level was reduced to less than half that in conventional system configurations.
- (e) By conducting testing on rear wheel assembly unit equipment, an analysis of the high chain noise was able to correlate these noises to the actual vehicle.

11. Acknowledgments

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