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Experimental Study on Standing Stability of the Motor-cycle*

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Because of difficulty in measurement and recording of the motion of running motor-cycle, the quality of its stability has so far been discussed merely through the feeling test.

In this paper, by using a new test equipment for in-door test, the stability, especially "hands off" stability, of motor-cycle is quantitatively examined as are the effects of several factors such as longitudinal and vertical position of center of gravity, amounts of trail, caster and moment of inertia about the steering axis. And also, the authors succeeded in confirming the results of in-door test by comparing with those of practical road running test. Finally the basic principle for designing motor-cycles from a view point of stability is established.

1. Introduction

It is very important to study the stability of the motor-cycle, in order to secure its safety in the run. With the recent popularization of motor-cycles, their safe run has been more keenly required among motor-cycle engineers. But the motor-cycle is fundamentally different from three- or four-wheelers in stability. As for the motor cycle, there are a large number of special problems, which have not so far been settled, though their theoretical researches have been attempted.

In order to make an experimental investigation on the stability of motor-cycles, it is necessary to measure and record the kinetic movement of running motor-cycles. It is, however, very difficult to record the above movement, when the cycle is running. Such a situation has made it difficult to study the stability of motor-cycles. In investigating the stability, the authors have run a motor-cycle on a test equipment in the laboratory room under the same condition as in an ordinary run to record the movement of the test motor-cycle on the measuring device installed in the laboratory room.

Thus the objective of the researches made by the authors was to examine experimentally the effect of various factors upon the stability of motor-cycles, quantitatively evaluate the factors so

far merely dependent upon the feeling of drivers, and subsequently establish the basic principle for designing motor-cycles from a viewpoint of stability. The researches made by the authors shall be outlined hereunder:

2. Test equipment and method

The test equipment can roughly be divided into three units: a belt apparatus, a test motor-cycle supporting device and a measuring instrument.

2.1 Belt apparatus

The main belt apparatus consists of two pulleys and a rubber-made belt thereon (10 mm thick and 800 mm wide).

When the test motor-cycle runs on this belt, the power is supplemented by a variable speed motor, if the output of the rear wheel of the motor-cycle is insufficient to drive the belt; on the other hand,

Fig. 1 Belt apparatus

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the power is absorbed by the hydraulic dynamometer, if it is too much. Accordingly, the test motor-cycle continuously runs under the same output condition as observed when it is running on the road.

2.2 Test motor-cycle supporting device

As shown in Fig. 2, the test motor-cycle is supported so that it may not be overturned. The test motor-cycle can move to right and left or swing its head on the belt freely. As for the rolling alone, the motor-cycle is influenced by the restoring moment caused by springs on both sides. The magnitude of the restoring moment caused by the springs is derived from the following formula:

$$R = \frac{M_R}{M} = \frac{2 \cdot L \cdot \sin \theta_R \cdot K(L-L')}{W \cdot G_z \cdot \sin \theta_R} \quad \dots\dots\dots (1)$$

Where

R : ratio of moments

M_R : restoring moment

M : falling moment

θ_R : angle of roll

K : spring constant

G_z : height of the center of gravity of the test motor-cycle (including the driver)

$L; L'$: setting height of the suspension wire rope

If K and L are selected arbitrarily, any desired restoring moment can be given.

In the next place, the test motor-cycle is supported by a wire so that it may not move forward or backward as shown in Fig. 3.

If the engine of the motor-cycle is run and the belt is driven, the wire rope is tensed so much that the front and rear position of the test motor-cycle

becomes constant. As the rope is far longer than the cycle body, the cycle can move to right and left and swing its head on the belt. If the engine of the test motor-cycle were run at the same output as in ordinary running, the tension acting upon the wire rope would be equivalent to the air resistance in the case of ordinary running.

2.3 Measuring instrument

The main measuring instrument is a "relative displacement meter," which records mechanically the displacement difference of two given points. As shown in Fig. 4, a steering angle, a rolling angle and a yawing angle are respectively evaluated from the difference of the displacement of a and b (symmetrical points on the right and left handles) in relation to c , the relative displacement of c and d , and that of e and f . A piano wire, 0.2 mm ϕ is used for transferring the displacement of each point to the relative displacement meter.

As the test motor-cycle, the Meguro EH-3 type motor-cycle (4-cycle, 125 cc.) was employed. It had been reconstructed to be equipped with the supporting and measuring devices (Figs. 3 and 4).

2.4 Test method

In a two-wheeler, steerings has a close relation to lateral stability. The two-wheeler, which falls when it comes to a standstill, keeps standing erect while it is running, because it is continuously steered to right and left as well as in a proper direction.

This is characteristic of two-wheelers. From a viewpoint of the driver, however, it is desirable that the two-wheeler can proceed forward, even his hands are off the steering handles, like the four-wheeler.

Especially in the two-wheeler, it is desirable from a point of view of stability that a motor-cycle is properly steered by itself to stand, even if the driver does not operate the steering handles to keep the motor-cycle in lateral stability.

In this experiment, therefore, the test motor-cycle is steadily run on the belt, with the steering handles left untouched, and then a disturbance is given to the handles from the outside to investigate the behavior of the motor-cycle.

3. Preliminary experiment

Fig. 5 is an instance of recording the variation

Fig. 2 Lateral supporting device

Fig. 3 Longitudinal supporting device

Fig. 4 Measuring points

of steering, yawing and rolling angles obtained when the steering handles of a running motor-cycle is disturbed. From such a record, the motion of a motor-cycle is clearly seen. Fig. 6, in which only the steering angle of the above three angular movements is picked up, shows its changing stage with the speed of a motor-cycle. Generally at low speed, increasing instability is observed as shown in Fig. 6 (a), when the disturbance is given. When the speed is increased, steady oscillation is observed at a definite speed as shown in Fig. 6 (b). When the speed is further increased, oscillation damps as shown in Fig. 6 (c). When the speed is still further increased, the damping becomes so large that the non-periodical damping

Speed 25 km/hr, $R=1$
Moment of inertia about steering axis $5.51 \text{ kg} \cdot \text{cm} \cdot \text{sec}^2$
Fig. 5 Record of the motion

Fig. 6 Typical modes of motion

is finally found as shown in Fig. 6 (d). Such being the case, Fig. 6 (b) is a transient point from instability to stability. The speed at this stage shall be termed the "hands off stability speed limit". If this hands off stability speed limit is found at lower speed under a definite test condition, the stable zone is wide. It can be, therefore, generally said that the motor-cycle is in a good stable condition. On the other hand, if the hands off stability speed limit is found at higher speed, it can be said that the motor-cycle is not in any stable condition. Accordingly, the authors have investigated the stability of the test motor-cycle by observing variations of the hands off stability speed limit with different test conditions.

Meanwhile, an optimum value of the restoring moment caused by springs, has been found in the experiment. Fig. 7 illustrates the result of influence of the moment ratio. Fig. 8 shows the period which corresponds to Fig. 7. The solid line found in Fig. 7 is a line connecting the points which are then considered to be the hands off stability speed limit when the driver rides the test motor-cycle. Meanwhile, the same test was given to the test motor-cycle without a driver. The dotted line in Fig. 7 shows the hands off stability speed limit of the motor-cycle without a driver. This line has disclosed that the stable zone is widened when a man rides the motor-cycle, and that less effect of the restoring moment is then found. Though it is natural that the larger the restoring moment becomes, the shorter the period becomes, it is interesting that the period is generally longer at lower speed when the motion of the motor-cycle is unstable. This phenomenon is favorable for

Fig. 7 Influence of ratio of moments

the driver to secure stability in practical running.

In consideration of the above results, we have assumed that $R=1$ in the later experiments.

If a man rides the motor-cycle, there is a danger of uncertain factors being added to the experiments even when he does not steer it intentionally. Considering this condition, at first the authors planned to have a doll ride which is equivalent in weight and size to a human rider. When this method was put into practice, the doll was overturned, damaging the equipment, immediately after the equipment started its run. As it was thus impossible to make the test, we changed our plan and decided to let a man ride on the test motor-cycle.

4. Results of the experiment

4.1 Effect of the position of the center of gravity

In order to examine the effect of the position of the center of gravity upon the stability, both sides of the motor-cycle were equipped with a pipe-made framework in the longitudinal and vertical direction, to the right and left side of which the weights, totally 61.4 kg were set. Then the tests were performed so that the position of the center of gravity might freely be changed in the longitudinal and vertical direction, when the above weights were moved in the longitudinal and vertical direction.

4.1.1 Effect of the longitudinal position of the center of gravity The experiment was made, when the position of the center of gravity was longitudinally changed so that the front wheel load ratio changed from 29.3% to 51.0%.

Fig. 8 Period against speed

Fig. 9 Effect of longitudinal position of C.G.

Fig. 10 Shimmy against C.G.

Fig. 9 shows a characteristic distribution of stability classified on the basis of the oscillation measured in the above experiment. The abscissa G_x is a horizontal distance from the rear wheel axle to the center of gravity. The gradient line down to the right in the figure shows the hands off stability speed limit. It has disclosed that the stable zone is wider, when the center of gravity is put forward. In this experiments, the suspension springs are replaced by the rigid members to prevent the pose of the motor-cycle from being changed by the travelling of the center of gravity. Meanwhile, a test was also made, when the motor-cycle was equipped with buffer springs. In this case, some change is found in the front wheel alignment, being caused by the movement of the center of gravity. But the general trend is the same as that found in Fig. 9.

With an increase in the front wheel load, shimmy is found in the front wheel, independently of the overall motion of motor-cycle. Fig. 10 shows a classification of shimmy obtained when the same marks as those in Fig. 7 are used. If $G_x=650$ mm, in this figure, shimmy varies with speed from damped, to steady to amplified vibration. But if $G_x=745$ mm, shimmy shows a serious amplification at any speed. As hands off running became impossible, the experiment was immediately stopped after measuring the shimmy in the case of 45 km/hr alone. The period of the shimmy is approx. 0.2 sec and seems to be affected only a little by the speed of the motor-cycle.

4.1.2 Effect of the height of the center of gravity When a man rode the test motor-cycle

in a normal condition, the height of the center of gravity $G_z=612$ mm. It was changed up to $G_z=904$ mm to examine its effect. The results are shown in Fig. 11, which discloses that little change is found in the hands off stability speed limit, even if the height of the center of gravity is increased beyond a practical limit, and that the period becomes longer with the increase in the height of the center of gravity.

4.2 Effect of the trail and caster

At this stage, the motor-cycle was reconstructed so that the swinging arm of the front wheel suspension unit might be horizontal, while a large number of setting holes for the front axle were provided at intervals of 25 mm so that the trail could be changed

Fig. 11 Effect of the height of C.G.

Fig. 12 Effect of trail

within a range of 2~127 mm independently of the caster. In this experiment, the change in the trail was combined with that in the longitudinal position of the center of gravity. Fig. 12 shows the results of the experiment. This figure discloses that the stability is better, when the trail is smaller, and when the center of gravity is more forward. In the experiment, however, the following facts were observed: Even though the hands off stability becomes better when the center of gravity proceeds forward, it is difficult to recover stability, and it takes rather a long time to control the rolling, when the driver grasps the handles to secure stability in steering from the unstable condition. In contrast with this, when the center of gravity is backward, it is easy to secure stability by steering lightly, even when the unstable zone is wide and the unstable motion is observed.

In conclusion, when the center of gravity is in a front position, the hands off stability is better, while the controllability seems to be worsened.

In the experiment on the trail effect, too, shimmy was often observed. Fig. 13 shows the characteristics of the shimmy observed when the trail was changed in the case of $G_x=690$ mm. In the section between two curves in the figure shimmy shows an unstable amplification form. As disclosed in Fig. 10, the shimmy of amplification form is found at lower speed, when the trail is large and the unstable zone is wide. When G_x is small, i.e., the center of gravity falls back, this unstable zone becomes narrower. The larger the trail is, the shorter the period of shimmy becomes.

In the next place, in order to examine the caster effect, which had generally been believed to have

Fig. 13 Characteristics of shimmy

the closest connection with stability, the motor-cycle was reconstructed so that its caster might be changed within the range of 20~40 degrees. For each value of various casters, the trail was changed for the experiments. Even when the caster was changed, however, the hands off stability speed limit was distributed over the range of experimental errors, while a definite trend could not be observed.

4.3 Effect of the moment of inertia about the steering axis

When the test is given, the test motor-cycle is equipped with the straight handle-bar, to the right and left of which weights approx. 5 kg each are set, so that the moment of inertia about the steering axis may be changed according to the distance of the weights. Fig. 14 shows the results of the test. As revealed in the figure, the larger the moment of inertia becomes, the higher the hands off stability speed limit becomes and wider the unstable zone becomes. When the moment of inertia is remarkably high, the oscillation of amplification form is immediately observed only when the motor-cycle is in hands off condition without any disturbance. Thus the hands off run is quite impossible. There is observed a trend that the period becomes slightly longer, when the moment of inertia becomes higher.

5. Practical road running test

When the indoor test by means of the belt unit was made, a large number of interesting facts were noted. But there remained some doubt about similarity in conditions between the indoor test and practical running. In order to confirm the results of the indoor test, therefore, a practical road running test was per-

Fig. 14 Effect of moment of inertia about steering axis

formed on the test motor-cycle. The test method was as follows: While the motor-cycle is steadily running, a disturbance is given by striking the handles to observe the later motion of the motor-cycle. Meanwhile, the deflection of the steering angle is recorded by a recorder fixed on the fuel tank. Like in the case of the indoor test, the driver makes every possible effort not to steer. In the test, the longitudinal position of the center of gravity is connected with the trail. Fig. 15 shows a comparison between the hands off stability speed limit obtained in the practical running test and that obtained in the indoor test. The figure discloses that almost the same tendency is found in the above two tests in relation to the trail as well as the position of the center of gravity. In the case of the practical road running test, however, curves seem to be not continuous, while the hands off stability speed limit seems to be somewhat lower. This seems to have come from the fact that in the case of the practical road running test, the driver unconsciously controls the motor-cycle to keep it stable, when it is in a boundary condition between stability and instability. From this point of view, too, the superiority of the indoor experiment is recognized.

In the case of the practical road running test, too, shimmy was often caused, according to the test condition. The condition for the shimmy agreed with that in the indoor test. Fig. 16 is one of the results obtained between the trail and the period of the shimmy. As seen from the figure, the indoor test

Fig. 15 Results of practical running and indoor experiment

has well agreed with the practical road running test in records.

6. Conclusion

From the above research results, the authors have made the following conclusions:

(1) When the motor-cycle is given a disturbance which tends to make the steering wheel turn to the right while it is running, the yawing angle appears in the right direction with a little time delay. In contrast with this, the rolling angle appears in the left direction. The appearance of the rolling angle in the left direction is part of the function to direct the front wheel to the left for the next stage, and consequently significant in studying the motion of the motor-cycle. If the phase of the first peak of the wave form of three angular motions caused by the disturbance is observed, the yawing angle lags behind the steering angle by approx. 45~90 degrees, while the peak of the rolling angle appears when the steering angle almost returns to the neutral position.

(2) At lower speed, three angular motions display a periodic amplified type oscillation. At higher speed a steady oscillation is found. If the speed is higher, the periodic damped type is observed. With a further increase in speed, the damping becomes more intense, resulting in the non-periodic damping. On the border of the hands off stability speed limit observed in the steady oscillation, the high-speed side becomes the stable zone, while the low-speed side becomes the unstable zone. In the case of a practical road running test, not the periodic but the non-periodic amplification is observed even in the unstable zone. Then the motor-cycle starts its turn.

(3) With an increase in speed, the oscillation period is shortened. Conversely, the period is long at unstable lower speed. This is a property favorable for artificial steering to maintain safety.

(4) The stability of the motor-cycle with a driver on it is better than that of the motor-cycle without a driver. In other words, the driver contri-

butes to the stabilization of the motor-cycle, because he does not follow the rolling or yawing of the motor-cycle body. When the period of the motion becomes shorter, he can hardly follow it. A remarkable difficulty in the test given with a doll bound to the test motor-cycle body has testified to the above fact.

(5) When the center of gravity is more forward, the hands off stability speed limit is lower, i.e., the stable zone is widened. Here the following points should be noted: From the above fact alone, it should not be recommended that the center of gravity be put forward in designing the motor-cycle. The reasons are: 1. The rear wheel needs a large load to produce a large driving force. 2. When the front wheel load is large, shimmy would easily be caused even at lower speed. 3. In the case of a large front wheel load, it is difficult to steer the motor-cycle back into stability, once it begins an unstable motion. In short, the controllability is worsened. 4. As for steady circular turn, it is natural that the sideslipping angle of the front wheel becomes large when the center of gravity is forward. Though the two-wheeler is said to make a steady circular turn, it actually makes a non-steady motion continuously while steering continues to swing to the right and left to secure stability. If the front wheel sideslipping angle is large on the average, it becomes larger momentarily, affected by the fluctuation of steering, and consequently the cornering force becomes so large as to lose a linear relation to the sideslipping angle. Thus it is conceivable that the controllability is worsened. This condition seems to be the ground for the popular conception that the motor-cycle can be steered in the turn more easily, if the riding position is brought to the rear.

(6) If the height of the center of gravity is at a higher position the period becomes longer, the stable zone remaining unchanged.

It has so far been generally accepted that the "stability is better, when the center of gravity is located at a lower position". The recent study has, however, disclosed that such a view is a mistake. In this study, the stability has been judged within the range of stable zone alone, the magnitude of the disturbance given to the motor-cycle not being studied. In this connection, the motor-cycle should be insensitive to the disturbance of a definite magnitude, because the moment of inertia about the axis through the contact points to the road surface becomes larger when the center of gravity is higher. Meanwhile, it should be easier to control the motion by the additional steerage, because the period becomes longer. It can, therefore, be said that the stability is rather better when the center of gravity is higher. At the same time when the

Fig. 16 Period of shimmy against trail

stability becomes better, however, the motion becomes so dull that the maneuverability becomes worse. And also a too high position of the center of gravity must be avoided for practical use. Anyway, from a viewpoint of not only the stability but also the controllability, many mistakes have so far been made in the conception as to the height of the center of gravity. Such mistakes should be corrected.

(7) When the trail becomes larger, the period is shortened, and the unstable zone is widened.

(8) When the front wheel load and the trail are large, shimmy is easily caused at lower speed, and over a wider range of the speed.

The results mentioned in the above (7) and (8) are also worthy of note. It has so far commonly been understood that the "stability is better, when the trail is larger". It has also been revealed that such a view is not correct. In this connection, the same results have been obtained not only in the indoor test but also in the actual road running test. According to the recent test, it would be generally more favorable for a high-speed motor-cycle to retreat the center of gravity and reduce the trail, in order to prevent shimmy from being caused over a wide speed range. It is, however, impossible to define the optimum value of the trail from a viewpoint of stability.

The motor-cycle on the actual road may run not only on a paved road but also on a rugged one. When it runs on a bad road, the contact point of the front wheel with the road surface may be brought re-

markably forward momentarily. On the other hand, if the caster variation is caused by the pitching of the motor-cycle body, the steerage would often become impossible when the trail is too small. Meanwhile, when the trail is small, the steering moment becomes small, and the rolling period of the whole motor-cycle body becomes so much longer that a long time is required for convergence even in a stable zone. From a viewpoint of the steerage feeling, the above points would be unfavorable in some cases.

In conclusion, the trail is restricted by many such conditions as the road condition, steerage feeling, etc. From a viewpoint of stability, a large trail would be unfavorable on the flat road at least.

(9) When the authors made the experiments, the caster value had little effect upon the hands off stability, not so large as the trail at least. It is said from experiences that the caster effect is considerably evident. This effect seems not to influence the stability, but the controllability.

(10) When the moment of inertia about the steering axis becomes large, the unstable zone is widened. When it is excessive, the motor-cycle cannot run. From a viewpoint of controllability, it is undesirable that the value of moment of inertia is large, because this interferes with quick control. In designing motor-cycles, efforts should be made to reduce the moment of inertia about the steering axis as much as possible.

Reference

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