技術論文

Fundamental Research and Observations Concerning Leaning Multi-Wheel Vehicles

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要旨

2007 年に東京モーターショーでコンセプトモデル「Tesseract」四輪モーターサイクル（Photo 1）を出展した当社は、2014 年には二輪と同じように傾斜してコーナリングする三輪以上の乗り物（以下、「LMW」という）として、ニューコミューターモデル「Tricity」（Photo 2）の市販を開始した。次いで 2015 年の東京モーターショーでは、「コーナリングマスター」をコンセプトに開発された「MWT-9」（Photo 3）を参考出品し、その 2 年後となる 2017 年には「NIKEN」として発表した。

一方で、当社における LMW 技術の研究開発には長い歴史があり、スクーター「Passol」が大ヒットした 1977 年にはすでに、このモデルをベースとしたフロント二輪のバイクを他社に先駆けて開発していた（Photo 4）。そこで本報では、ヤマハにおける LMW の歴史を紹介するとともに、2004 年から 2012 年にかけて研究開発された四輪モーターサイクルの試作車「Tesseract Ⅱ」（Photo 5）について報告する。

Abstract

Yamaha Motor Co., Ltd. (hereinafter “Yamaha”) exhibited the “Tesseract” 4-wheeled motorcycle (Photo 1) at the Tokyo Motor Show in 2007. Then in 2014, Yamaha began sales of its first Leaning Multi-Wheel (hereinafter “LMW”) vehicle, the “Tricity” (Photo 2), as a new kind of city commuter model. At the Tokyo Motor Show in 2015, Yamaha displayed the “MWT-9” (Photo 3) developed under a “Cornering Master” concept.

Photo 1

Photo 2

Photo 3

Yamaha has a long history of research and development into tilting multi-wheel technology. When the “Passol” 2-wheeled scooter became a big market hit in 1977, Yamaha took the model as a base and has been carrying out development of motorcycles with two front wheels in secret ever since (Photo 4). This report will introduce Yamaha's history with tilting vehicles and discuss the LMW prototype (Photo 5) developed as the result of tilting wheel vehicle R&D work conducted from 2004 to 2012.

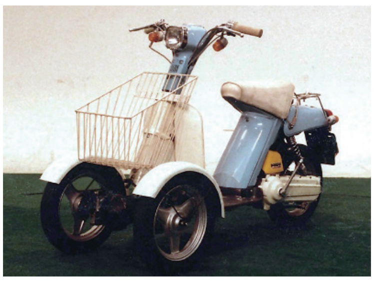

Photo 4

Photo 5

1 INTRODUCTION

The idea of a vehicle with three or more wheels that could lean through turns with camber thrust had already been proposed in Germany in the 1930s. Since then, there have been a variety of similar vehicle proposals over the years, primarily originating in Europe. The Piaggio MP3 marketed from 2006 can be cited as the world's first mass-produced tilting multi-wheeled vehicle. Tilting multi-wheeled vehicles have been subsequently commercialized by Peugeot, Quadro Vehicles, Yamaha Motor and other manufacturers. In recent years, these vehicles are steadily becoming more established as a new form of motorcycle in the world's markets.

On the other hand, the Tesseract (Photo 1) as well as the R&D prototype (Photo 5) were developed under the concept of “Four Wheels but a Motorcycle” as a deeper study into tilting multi-wheeled vehicle technology. Although the prototype has four wheels like an automobile, it features a specially engineered lean mechanism that achieves zero vehicle roll rigidity, making it a system that functions in essentially the same way as a conventional motorcycle. As such, it has the same basic vehicle dynamics as a conventional motorcycle and makes turns with cornering forces based primarily on camber thrust[1]. Therefore, the steering operation is exactly the same as a 2-wheeled motorcycle. However, due to the increase in the number of wheels, the suspension system and the presence of a lean mechanism, structurally, it differs greatly from a 2-wheeled motorcycle. As a result, the prototype adopts new modes of motion not present in either 2-wheeled motorcycles or 4-wheeled automobiles, which give it more complex vehicle dynamics.

In search of greater knowledge of this previously unknown field of vehicle geometry and dynamics, design work based on desktop studies and analysis were conducted to produce a prototype 4-wheeled motorcycle.

2 SPECIFICATIONS AND FEATURES

Table 1 shows the basic specifications of the prototype 4-wheeled motorcycle.

Table 1 Basic specifications of the 4-wheeled motorcycle prototype

Item	Specifications	Comments
Suspension (front)	Cantilevered leading dual-scythe arms	Double wishbone
Suspension (rear)	Cantilevered trailing arms	(Swingarm)
Lean mechanism	Mechanical balancer type	On both front and rear wheels
Frame	Twin tube	All-aluminum
Tilt control	Hydraulic roll feedback control	Only when stationary
Brakes	Hydraulic disc brakes for all wheels	–
Engine	4-stroke, 2-cylinder, DOHC, 900cc, 5 valves per cylinder	PS: N/A Torque: N/A
Drive mechanism	Rear-wheel shaft drive	Single-index beveled gear
Power distribution	LSD fitted	–
Transmission	Constant mesh 6-speed	With reverse gear
Vehicle weight	N/A	–

2-1. Detailed Specifications

2-1-1. Front suspension and the lean mechanism

There are several points crucial to creating a 4-wheeled motorcycle, which is still just a concept. The most important point is that the vehicle has zero vehicle roll rigidity. Achieving this makes the basic vehicle dynamics of a 4-wheeled motorcycle identical to those of a conventional motorcycle[1], meaning “it can have four wheels but still be a motorcycle.” Therefore, zero vehicle roll rigidity is a key factor for this concept. Furthermore, setting the track (in mm) will not only determine the vehicle's basic performance, but will also greatly affect the specifications of the lean and suspension mechanisms. This is because there is a correlation between the track corresponding to the required lean angle and the operating angle of the lean mechanism. The operating angle of the lean mechanism increases as the track becomes wider, regardless of the type of suspension and lean mechanisms used.

In making a 4-wheeled motorcycle, we placed top priority on retaining the benefits of a motorcycle, like the narrow vehicle width, while still adding multiple wheels. This created the basis for adding the benefits of multiple wheels while keeping the benefits of a conventional motorcycle. To accomplish this, a leading arm suspension was chosen for the front end, and a Yamaha-exclusive layout called the "leading dual-scythe arm" was designed to keep vehicle width compact. Figure 1 shows this layout.

The upright has a shape that suggests the scythe-like claw of a praying mantis, from which the name "scythe arm" was derived, and the basic configuration positions a double wishbone suspension in the leading direction in order to allow vertical motion. A lean mechanism is created by using a seesaw-type stabilizer to link the right and left sides of this double wishbone suspension via shock absorbers. Figure 2 shows the difference in the up and down movement between the left and right sides when leaning.

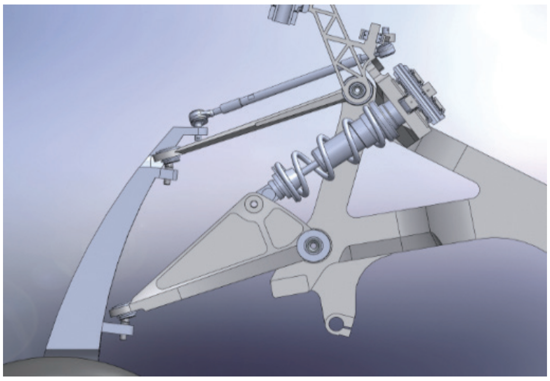

Fig.1

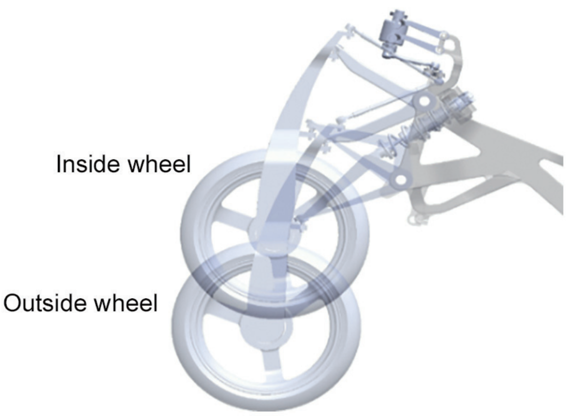

Fig.2

2-1-2. Relationship between the track and the leading arm operating angle

The suspension and the lean mechanism are very closely related, in which the suspension can be considered to be contained inside the lean mechanism. Equation (1) shows the relationship between the track and the lean mechanism (here, the operating angle of the arm of the double wishbone comprising the scythe arm).

$$\alpha = 2 \cdot asin\left\{\frac{L_{tr} \cdot tan\theta/2}{L_{arm}}\right\} \tag{1}$$

α: Arm operating angle L_{tr}: Track width
θ: Lean angle L_{arm}: Arm length

From this equation, we can see that when the lean angle and track width increase, so does the required operating angle of the arm. It can also be seen that altering the arm length has the opposite effect. For the lean angle, given that a tilting multi-wheeled vehicle gains cornering forces based primarily on camber thrust and considering it to be similar to a conventional motorcycle, it can be said that optimizing the track width and the arm length is of great importance.

2-1-3. Examination of the front geometry

The front suspension must be equipped with not only a lean mechanism, but also a steering mechanism. Obviously, during operation, the steering mechanism, lean mechanism and suspension travel must not interfere with each other. When leaning, the suspension arm oscillates significantly in a way similar to how a shock absorber operates. However, with a tilting multi-wheeled vehicle, it is necessary to generate camber thrust in the tires by leaning, so preventing large changes in the camber angle of the inside and outside wheels when leaning is absolutely essential. Furthermore, if a scrub radius is set, the scrub radius will differ greatly between the inside and outside wheels when leaning, adversely affecting steering torque characteristics.

In the suspension of a 4-wheeled vehicle, in order to optimize the ground contact surface of the tires while taking roll center into consideration, it is common to vary the length of the upper and lower arms, or vary the arm installation angle to be approximately equal to the camber angle. However, based on the aforementioned leaning characteristics, we set the difference in length between the upper and lower arms as zero (equal length); the difference in the arm installation angle in the lateral direction as zero (both arms are parallel), which means the camber angle is also approximately zero; the scrub radius as zero; and the king pin angle as zero. Also, the height of the LMW vehicle was set under the prerequisite that the installation angle of the upper and lower arms in the longitudinal direction under 1G conditions be parallel. In other words, setting the arm installation angle to zero minimized changes in the wheelbase of the right and left wheels and in the rake and trail when in a leaned state.

Furthermore, it is also important to keep in mind the Ackermann steering angle, which must be set according to the track width. However, because the track on the prototype is extremely narrow at 180 mm, we set the Ackermann steering angle to nearly zero and adopted a vehicle geometry based on a “completely zero alignment concept” for the suspension and the lean mechanisms.

In the basic geometry, in deriving the rake and trail in particular and accounting for the fact that there are two front wheels, we worked from the equation for steering torque characteristics[2] for the steering apparatus. As a result, a geometry different from that of a conventional motorcycle was computed, i.e., a rake of 15 degrees and a trail of 62mm. Equation(2) shows the normal trail α_n during cornering, and Equation (3) shows the steering torque.

$$a_n = \sqrt{(a_1^2 + a_2^2 + a_3^2)} \quad (2)$$

$a_1 = -(Y_{\rho f} \cos\varphi + t_r \sin\varphi)\cos(\varepsilon+\mu)$

$a_2 = [X_{\rho f} \cos(\varepsilon+\mu) - p\cos\varepsilon + R_r \sin\varepsilon - a_n]\cos\varphi - (\rho_r \cos\varphi + t_r)\sin(\varepsilon+\mu)$

$a_3 = Y_{\rho f} \sin(\varepsilon+\mu) + [X_{\rho f} \cos(\varepsilon+\mu) - p\cos\varepsilon + R_r \sin\varepsilon - a_n - \rho_r \sin(\varepsilon+\mu)]\sin\varphi$

ε : Rake angle μ : Pitch angle δ : Steering angle
ϕ : Roll angle d : Offset p: Wheelbase R_f: Front wheel outer radius R_r: Rear wheel outer radius t_f : Front tire cross-section radius t_r: Rear tire cross-section radius
ρ_f : Front wheel Torus radius ρ_r : Rear wheel Torus radius
$X_{\rho f}, Y_{\rho f}$: Coordinates of the front wheel ground-contact point

$$M_Z = M_{msg} + 2M_{fz} - 2M_s + 2M_c \quad (3)$$

M_{msg}: Moment due to steering system mass
M_{fz} : Moment due to front wheel vertical load
M_s : Moment due to front wheel lateral force
M_c : Moment due to front wheel camber torque

2-1-4. Rear suspension and the lean mechanism

It is possible for the suspension and lean mechanisms at the rear to have a simple structure as they do not require a steering mechanism like the front. The rear employs the trailing arm (swingarm) commonly used on motorcycles, and by linking the right and left sides via a seesaw like the front, zero vehicle roll rigidity is achieved and leaning became possible.

However, for the shock absorber, taking the overall vehicle weight into consideration made it possible to position a single unit on the vehicle body side of the seesaw. Figure 3 shows the layout. Additionally, as was done for the front, vehicle height was adjusted and set so that the arms become parallel under 1G conditions and the camber angle was set to zero, so that the basic rear alignment was zero like the front.

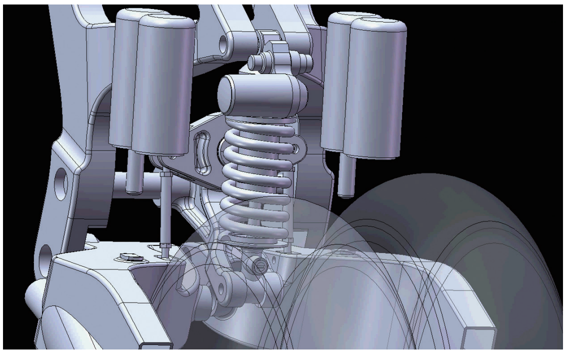

Fig.3

2-1-5. Drivetrain

The drive system and delivery of drive force for the left and right wheels are especially important. Shaft drive was adopted for the drive system and a limited-slip differential (LSD) was adopted for drive force delivery. Although shaft drive has disadvantages in terms of weight, it has clear advantages over chain drive in terms of delivering traction and its ease of maintenance. Since it is basically impossible to ensure straight-line stability for a vehicle with zero roll rigidity when a wheel on only one side is being driven, powering the wheels on both sides becomes a necessity. Even in the case of narrow track width, i.e., 180 mm, consideration must be made for the turning radius difference of the inner wheel when turning at full lock. Furthermore, when leaning, the angle of the swingarms for the inside wheel and the outside wheel differ greatly, creating a difference in the level of traction between the left and right sides of the vehicle (Fig. 4).

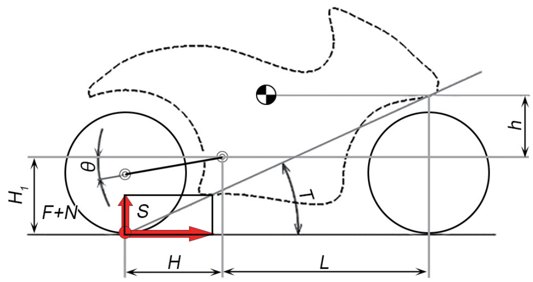

Fig.4

Taking these factors into account, the decision was made to adopt an LSD unit. When cornering, the drive force from the shaft drive produces different reactive forces for the inside and outside wheels, and as a result, a moment that tries to bring the vehicle upright is generated around the center of gravity. In this way, a roll moment is generated in the prototype vehicle as it has a front and rear track. Equation (4) shows this roll moment, and Figure 5 shows this roll moment and the difference in ground-contact load between the inside and outside wheels.

$$M = (F_{out} + N_{out} + mg)\cdot\{(T/2) - t\} - (F_{in} + N_{in} + mg)\cdot\{(T/2) + t\} \quad (4)$$

m: Vehicle weight distributed by one rear tire
T: Track
t: Shift in the ground-contact point during banking
N: Ground-contact load due to load shift
F: Ground-contacting load due to anti-squat moment

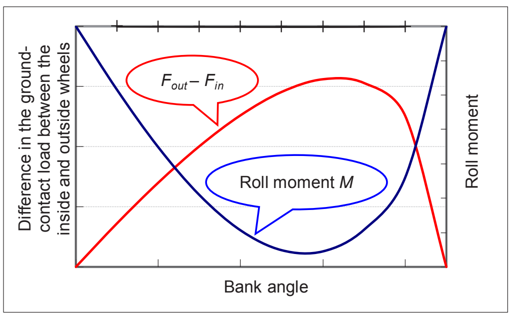

Fig.5

3 RIDING EVALUATION

3-1. Basic riding

Setting the roll rigidity in particular to zero helped achieve smooth lean characteristics, and we were able to ride and corner using the same inputs as a conventional motorcycle with no unnatural feeling (Photo 6 and 7).

Photo 6

Photo 7

3-2. Riding over uneven road surfaces

Likewise, since zero vehicle roll rigidity provides the vehicle with balancing dynamics, it is not easily affected by road surface undulations and a road test proved that it can ride smoothly over uneven road surfaces at an angle (Photo 8).

Photo 8

3-3. Tilt control

Because the LMW vehicle has two wheels on the left and right sides, a pair of hydraulic cylinders are provided on the upper portion of the swingarm for each wheel (Fig. 6 and 7).

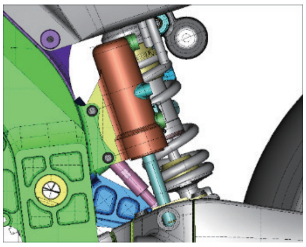

Fig.6

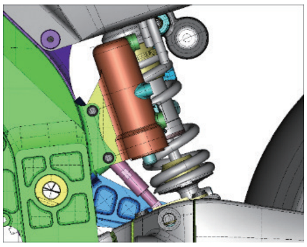

Fig.7

When riding at a fixed speed, the hydraulic cylinder rods are stored to enable smooth riding and counteract any influence on the vehicle's lean. On the other hand, it was confirmed that when vehicle speed is nearly zero, the movements of the swingarms can be controlled by pushing the hydraulic cylinder rods against them, enabling the LMW vehicle to remain upright on its own based on roll rate feedback control (Photo 9).

Photo 9

4 CONCLUSIONS

With this prototype vehicle and its especially narrow track, adopting zero vehicle roll rigidity and the "completely zero alignment concept" made it possible to materialize the concept of "Four Wheels but a Motorcycle."

As a result, we were able to verify the potential of an LMW vehicle, such as tilt control and the ability to ride smoothly over uneven road surfaces at an angle, through actual road tests.

On the other hand, though not discussed in this paper, while the basic vehicle dynamics of this prototype are the same as those of a conventional motorcycle, the systems we employed cannot be considered "the same" as a conventional motorcycle as our prototype uses more tires, a different type of suspension and a lean mechanism. From this, we can begin to understand that tilting multi-wheeled vehicles have a unique vibration mode and values, and we believe there to be a great deal of room for further research in this area.

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