Optimisation of the chain drive system on sports motorcycles

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Abstract

This paper investigates the optimisation of the chain drive system on sports motorcycles. Recently there has been the development of a chain transmission efficiency model that is suitable for motorcycles. The new model is used to predict the efficiency of a 600cc sports motorcycle at different speeds. The transmission efficiency is estimated to be between 96 and 99% for speeds less than 75 mile/h. Between 75 and 150 mile/h the transmission efficiency can be as low as 85% due to inertial tension. The transmission efficiency model presented in this paper enables optimisation of sprocket and chain sizes. In general, large sprockets are better at low speeds and smaller sprockets are better at high speeds. The optimum chain size is the chain with the smallest pitch that can meet the torque and power requirement. The sprocket centre distance also has a big effect on efficiency and it is important to use an effective installation procedure. In particular, it is important to set a chain up when the rear wheel axle, front crank and swing arm bearing are all in-line.

Keywords: transmission efficiency, power loss, roller chain

Introduction

Background

This paper investigates the optimisation of the chain drive system on sports motorcycles. Chain drives are used on the vast majority of sports motorcycles because they are much more efficient than belt drives and prop shafts. The chain drive system is a critical subsystem on sports motorcycles. For any sports motorcycle it must be decided:

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- what size of sprockets to select (for a given gear ratio)
- what size and type of chain to select
- what installation procedure to select.

One of the key problems until now has been that there have been no equations for calculating the efficiency of a motorcycle chain. This makes it difficult to determine the optimum size of sprockets and chain. At present, designers use experience and rules-of-thumb for optimising the chain drive system.

This paper presents a recently developed model of a chain transmission system that is suitable for motorcycles (Lodge, 2002) and shows how it can be used to optimise the components of the transmission system. A case study is carried out on a 600cc sports motorcycle to show how efficiency varies with speed. In addition, it is shown how to optimise the size of the sprockets and chain as well as the installation procedure.

Sports motorcycles

The sports motorcycle industry is very large and diverse. On a global scale there are hundreds of thousands of people who are involved in some kind of motorcycle sport. Fig. 1 gives a classification of the main types of motorcycling sports. Motorcycling can be divided into two main classes: competitive racing and leisure. Within both of these categories there are two main types of motorcycling which are road and off-road. As shown in Fig. 1, there are many types of motorcycle racing, especially off-road. These motorcycle sports attract competitors with a very wide range of ages from youth to very senior. For most types of competitive motorcycle sports there are both amateur and professional riders.

The fastest speeds occur in road racing on circuits such as Silverstone and Brands Hatch, where the top riders reach speeds in excess of 200 miles per hour (mile/h). (Note: 200 mile/h = 322 km/h). The Moto Grand Prix contains motorcycles which are at the leading edge of technology. However, the Superbike series involves bikes that are similar to models which are available to the public.

A picture of a typical road bike and a typical off-road bike are shown in Fig. 2. Professional riders must select the chain drive system carefully in order to get maximum performance from their motorbikes. However, amateurs are also very keen to get maximum performance from their motorbikes even when they are riding just for leisure.

Past research

The mechanics of roller chains are very complicated because there are many variables that affect transmission efficiency and load sharing within a chain. In 1998 a simple equation was developed for transmission efficiency that was suitable for slow-speed drives such as those found on bicycles. Studies with this equation showed that the best performance for bicycle road racing is often achieved with large sprockets (Burgess, 1998a; Hamer, 1998; Burgess, 1998b).

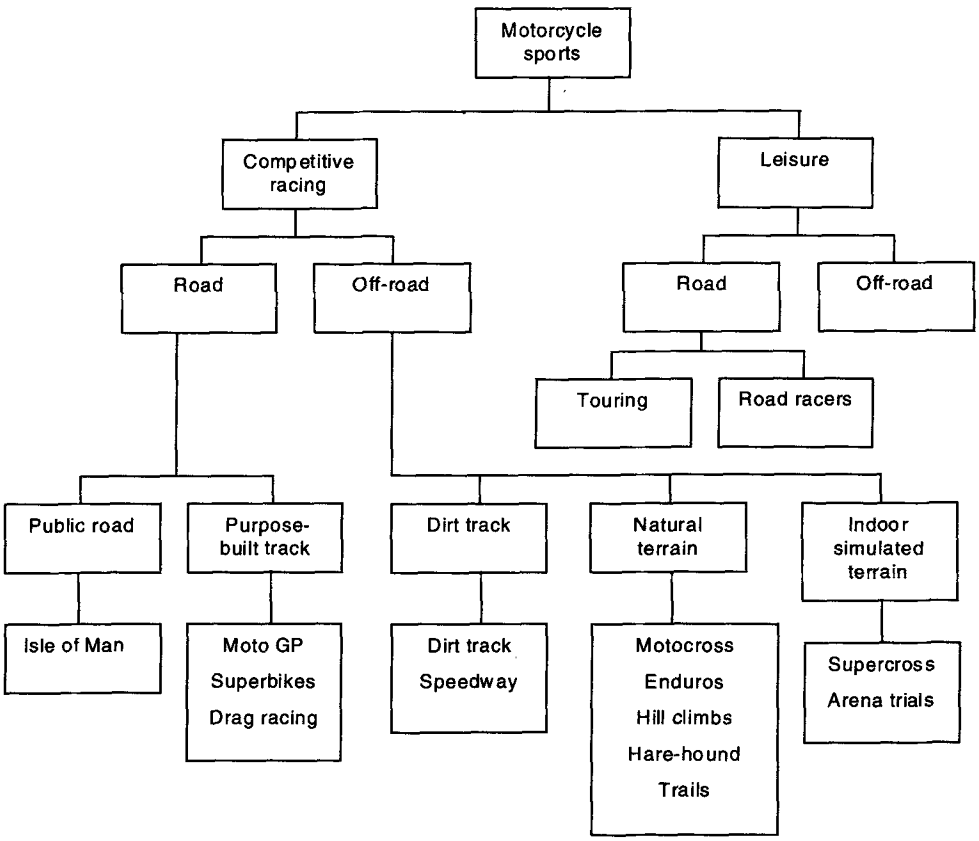

Figure 1 Classification of the main motorcycle sports

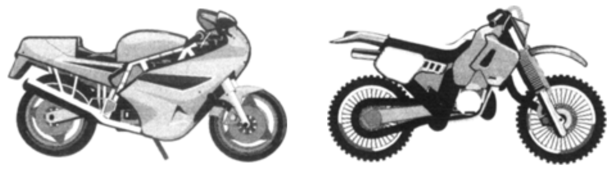

Figure 2 Typical sports motorcycles

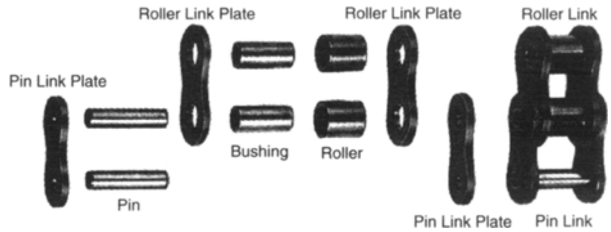

Figure 3 Construction of a motorcycle roller chain

The equation used for the bicycle studies described above has two limitations. First, it does not include a centripetal term and therefore the equation is not valid for high-speed drives. Secondly, it makes an approximation for the load in the chain and so it has limited accuracy. Since motorcycle drives are high speed, the equation used previously for bicycles is not suitable for analysis of motorcycle drives.

In the last year there has been much progress in understanding and predicting the efficiency of chain drives with the publication of an accurate chain efficiency model which is valid for high-speed drives (Lodge, 2002; Lodge & Burgess, 2002). For the first time, it is possible to carry out a detailed optimisation study on motorcycle chains.

Types of motorcycle chain and sprocket

Types of motorcycle chain

Fig. 3 shows the construction of a typical motorcycle chain. The roller chain consists of a series of links. There are two types of links: roller links (or inner links) and pin links (or outer links). The roller link consists of two bushes that are fixed to two plates with a loose roller assembled over each bush. The pin link consists of two pins that are fixed to two plates. Most chains are made from high-carbon steel which is case hardened for wear resistance. Some motorcycle chains have o-rings around the pins between the side plates to help keep lubricant in the pin area.

Motorcycle chains come in a variety of sizes. One of the most important dimensions of a chain is the pitch which is defined as the distance between pin centres. The pitch of motorcycle chains varies form 3/8 inch to 3/4 inch. However, the most common size for sports motorcycles is 5/8 inch. (Note: one inch = 25.4 mm).

Table 1 summarises the key dimensions of chains used on sports motorcycles. The first number in the chain code represents the number of 'eighths' in the chain pitch. If the first number of a chain code is 5 then the chain has a 5/8 inch pitch. If the first number of the code is 4 then the chain has a pitch of 4/8 = 1/2 inch and so on. The second number in the code indicates the number of 'eighths' in the width dimension of the bush. A 520 chain has a bush width of 2/8 = 1/4 inch whereas a 530 chain has a bush width of 3/8 inch. The third digit in the code indicates whether there is a special size. In the case of a 428 chain, the 8 indicates that there is an extra 1/16 of an inch on the width.

Types of motorcycle sprocket

The main materials used for sprockets are low-carbon steel, high-carbon steel, stainless steel, aluminium alloy and titanium. Aluminium alloy and titanium have higher specific strengths than the steel materials and therefore can give a weight saving. However, the best match in stiffness is obtained with steel, so there is no obvious best material for sprockets.

An important factor with sprockets is how they are manufactured. When sprockets are stamped into shape they generally do not have very high tolerances on the tooth profiles. Therefore stamped sprockets do not provide the smoothest and lowest friction drives. The smoothest drives are produced when sprockets are machined or laser cut.

Table 1 Typical motorcycle chain sizes

Chain code	Chain pitch (inches)	Roller width (inches)	Roller diameter (inches)	Pin diameter (inches)	Typical bike size (cc)
428	1/2	5/16	0.335	0.174	100
520	5/8	1/4	0.4	0.2	500
530	5/8	3/8	0.4	0.2	1000
630	3/4	3/8	0.469	0.234	1300

There have been some innovations in sprocket design. Some sprockets have an undercut on their teeth so that it is easy for dirt to escape. This feature can be very beneficial in off-road riding if there are large quantities of mud on the chain. The sprocket can also have features such as lips and grooves which produce a cleaning effect.

Sprockets can be made with any number of sprocket teeth. There are obviously limitations on the minimum and maximum number of teeth that are possible on any given motorcycle. However, there is usually scope for choosing smaller or larger sprockets for a given gear ratio. This will be demonstrated in a later section which analyses the effect of sprocket size on a 600cc motorcycle.

Performance criteria in motorcycle chain drive selection

The chain drive system is a critical sub-system on a motorcycle. It is important that the chain drive system is carefully selected and installed. Apart from cost, the main performance criteria to consider when selecting parts of the chain drive system are:

(i) Transmission efficiency

Transmission efficiency is important because it directly affects the torque that can be delivered to the rear wheel. Even though roller chains are very efficient, a significant amount of torque can be lost if the chain drive has not been optimised. For example, if a chain has a transmission efficiency of 90%, then 10% of the torque applied to the rear wheel is completely lost in the chain.

(ii) Mass

Mass is an important factor because this affects the power-to-weight ratio of the motorcycle. The mass of the chain drive is particularly important because it is part of the unsprung mass.

(iii) Velocity profile

One feature of sprocket drives that can cause problems is that the radius of the chain around the sprocket is not constant. The radius of the chain is determined by the position of the roller as it sits between two sprocket teeth. As the sprocket turns, the roller moves from top dead centre (TDC) to a position away from top dead centre, as shown in Fig. 4. This change in position causes the radius of the chain around the sprocket to change from r_s to $r_s \cos(\theta/2)$ where r_s is the pitch radius of the sprocket and θ is the angular pitch of the sprocket teeth. The effect of the continually changing radius is to cause a fluctuating velocity in the drive system for a given drive torque. This fluctuating velocity is called polygonal action (Boullion & Tordion, 1965). Polygonal action becomes more severe as sprockets become smaller. The problem of polygonal action is that the rider can feel jerkiness in the drive system, especially when the motorcycle is accelerating hard. The problem of polygonal action means that designers must be cautious about selecting small sprockets.

(iv) Durability

Chain wear is not necessarily a big issue for professional racers who can afford to change their chains often. However, in an endurance race, chain wear can

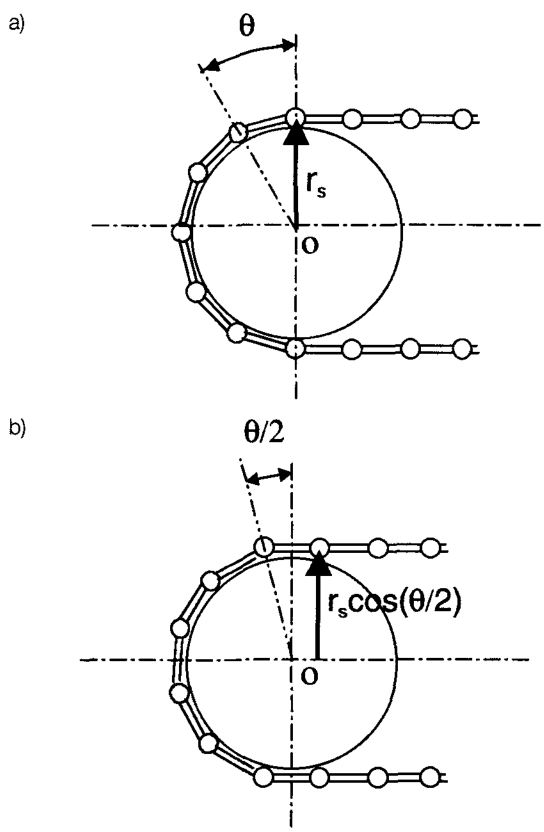

Figure 4 Change of chain radius due to polygonal action. a) Chain at TDC, b) Chain away from TDC.

be an issue. In addition, most amateur riders do not like to have to change the chain too often. Features such as o-rings can dramatically increase the life of a chain. Therefore, when wear is an issue, this can have an impact on chain selection.

Current selection methods

Because of the lack of data and equations for calculating chain efficiency, many decisions are based on experience and rules-of-thumb. There are some key questions that have not been answered until now. One question is whether small or large sprockets are best for a given gear ratio. For bicycles, large sprockets can often be best so designers would like to know whether this is also the case for motorcycles. Another question that motorcycle designers would like to know is how chain size and the installation procedure affects transmission efficiency.

Analysis of a 600cc sports motorcycle chain

Chain efficiency model

A model of the transmission efficiency of a chain drive running at constant torque and rotational speed has been recently developed (Lodge, 2002; Lodge & Burgess, 2002). The model calculates the transmission efficiency based on the frictional losses in the chain. The chain efficiency, η, is given by

$$\eta = \frac{\eta}{P_o + N_o \omega_o \Sigma W} \tag{1}$$

where P_o is the power output, N_o is the number of teeth on the output (rear) sprocket and ω_o is the speed of the output sprocket (rev s^{-1}). W is the work done, in joules, at the four points of articulation. Considering friction losses only between the pin and the bush, the work done, W, at each point of articulation is given by

$$W = \frac{F_c + F_{cf}}{\sqrt{1 + \mu_p^2}} \mu_p r_b \alpha_m \tag{2}$$

where F_c is the force in the chain due to the drive torque, F_{cf} is the force due to centripetal acceleration, μ_p is the coefficient of friction between pin and bush, r_b is the inner radius of the bush and α_m is the maximum articulation angle of the sprocket as shown in Fig. 5.

The force due to centripetal acceleration, F_{cf} is given by

$$F_{cf} = m r_d^2 \omega_d^2 \tag{3}$$

where m is the mass per unit length (kg m^{-1}), r_d is the pitch circle radius of the driving (front) sprocket (m) and ω_d is the rotational speed of the driving sprocket (rad s^{-1}).

The force in the chain due to the drive torque, F_c, is given by

$$F_c = \frac{T}{r_d}$$

where T is the input drive torque.

The main variables in the model of efficiency are:

- pitch circle radius of the sprockets
- internal diameter of the chain bush, r_b
- input drive torque, T
- rotational speed of the sprockets
- coefficient of friction, μ_p.

Laboratory experiments on chain transmission systems have shown that the model is accurate for drives carrying a significant torque (Lodge, 2002). A significant torque is defined as a torque where the slack span tension is small (say less than 5%) compared to the tight span tension. Experiments were carried out on chains and sprockets that were typical of motorcycle transmissions. The model ignores the losses due to impact with the sprocket and vibration in the chain span. However, vibration should be minimal for a correctly designed transmission. Also, experimental verification of the model (Lodge, 2002) showed no significant errors in the model due to neglect of the impact losses when there was significant tension in the chain span. Since the case study considered in this paper involves significant chain span tension, it is reasonable to neglect these

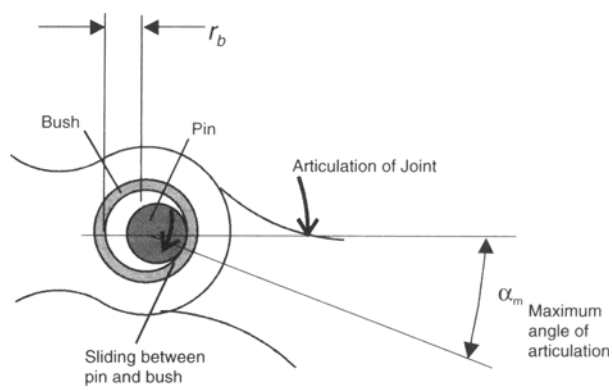

Figure 5 Pin/bush sliding due to chain articulation

losses. In this paper the coefficient of friction is assumed to be 0.11, which was found by simple experimental measurements on oil-lubricated steels similar to those used in motorcycle chains.

Efficiency predictions

A 530-type motorcycle chain has been assumed which has a pitch of 5/8 inch. The maximum power has been approximated to a constant 62.5 kW (85 hp) over the engine speed range. The largest inaccuracy in this assumption is at low speed (less than 15 mile/h), where either the clutch is slipping or the engine is not in the power band. However, the efficiency of the chain transmission is not sensitive to the transmitted power at low speed as long as the tight span chain tension is significantly higher than the slack span chain tension. Since this is the case, this assumption should not affect the accuracy of the transmission efficiency, although the power loss from the chain transmission will be slightly overestimated at low speeds.

The chain dimensions used were the nominal dimensions for the specified 530-size motorcycle chain. The transmission is modelled with the standard 15-tooth driver (crank) sprocket and 47-tooth driven (wheel) sprocket with the slack span at the bottom of the drive and no tensioning device.

The transmission efficiency was calculated for full power and half power running at road speeds between 0 and 150 mile/h. The results are shown in Figs. 6 and 7 respectively. It can be seen that in both cases the efficiency of the chain decreases rapidly with increasing speed. At low speeds (less than 50 mile/h) the transmission efficiency remains similar regardless of the transmission power.

It is commonly thought that well-lubricated chains are over 98% efficient. The results show that this is approximately correct for speeds up to 75 mile/h. However, at high speeds efficiency can drop dramatically to 91% at full power and 84% at half power. In racing situations, where torque is required to accelerate and overtake rivals, such drops in efficiency can have a significant impact on the performance of the motorcycle. These results show that it is critically important to choose a chain drive system that has a high transmission efficiency.

Power loss equation

The power loss is given by the equation:

$$P_L = T_o \omega_o (1 - \eta)$$

where T_o is the output drive torque, ω_o is the output speed and η is the efficiency of the chain.

Power loss predictions

The transmission power loss was calculated for full power and half power running at road speeds between 0 and 150 mile/h. The results are shown in Figs. 8 and 9 respectively. It can be seen that in both cases the power loss from the chain increases with increasing speed. The power loss at high speed (above 75 mile/h) is very significant, regardless of the level of transmission power. This is caused by inertial tension, which

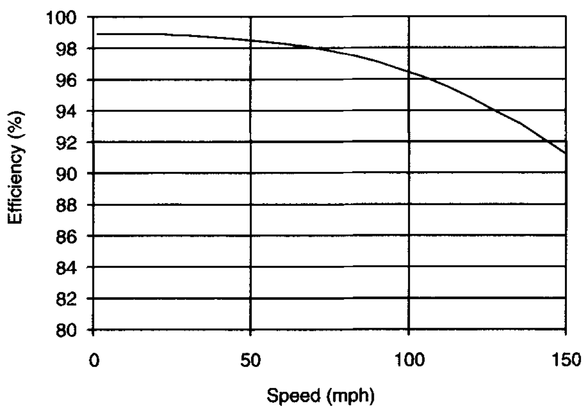

Figure 6 Predicted transmission efficiency for a 600cc motorcycle chain at full power

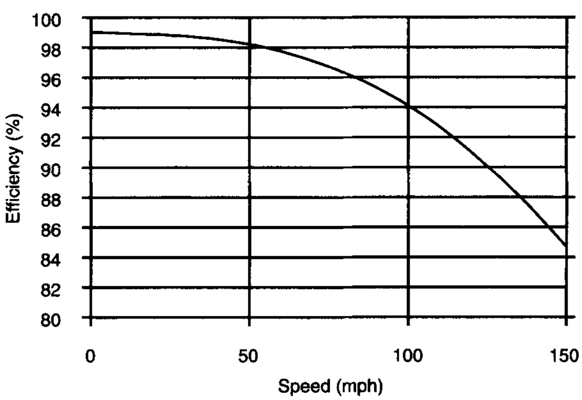

Figure 7 Predicted transmission efficiency for a 600cc motorcycle chain at half power

causes frictional losses that are independent of the transmitted power. Inertial tension is caused by centripetal acceleration of the chain and is defined in Eqn. (3). This fixed power loss at high speeds means that the transmission efficiency for lower power transmission is significantly affected. At low speeds (less than 50 mile/h) the power loss is scaled with the transmitted power.

The results emphasise the previous observations that there can be a significant amount of torque reduction at the rear wheel.

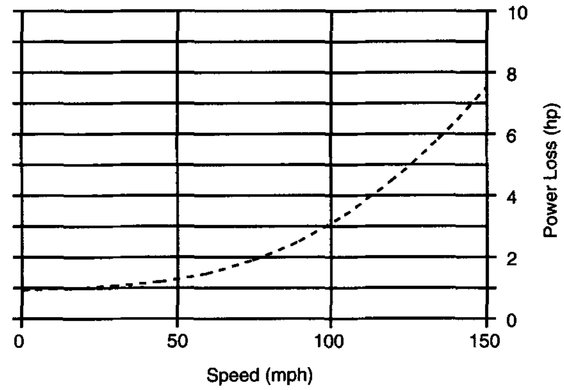

Figure 8 Predicted power loss from a 600cc motorcycle chain at full power

Optimisation of sprocket sizes

Since a chain transmission efficiency can drop to low levels at high speeds, it is critically important to determine what chain drive system gives the best transmission efficiency. A key question is whether it is best to have large sprockets or small sprockets (for a given gear ratio). Eqns. (1), (2) and (3) show that sprocket size does affect the efficiency of the chain drive system.

The model was also used to investigate the effect of scale of the transmission system in terms of sprocket size. The model was run using different available sprocket sizes, whilst maintaining a similar gear ratio. The sprocket combinations used were 13/41 tooth (1:3.15), 14/44 tooth (1:3.14), 15/47 tooth (1:3.13) and 16/50 tooth (1:3.13). All four of these combinations have a similar gear ratio as shown.

The power loss for each of these drives is shown in Fig. 10. It can be seen that the use of larger sprockets results in less power loss at speeds less than 70 mile/h. However, at speeds above 70 mile/h the increased inertial tension from the larger sprockets results in more power consumption by the chain. These results show that the optimum sizes of the sprockets can be highly dependent on the speed range of the motorcycle.

A motorcycle used only on the road for leisure, where speeds are less than 70 mile/h, may benefit from larger sprockets because the increase in the mass and inertia of the transmission would be more than compensated by better efficiency, smoother drive and potentially a longer chain and sprocket life.

Conversely, racing motorcycles that race at speeds above 70 mile/h would benefit from minimisation of the sprocket size because of the lower mass, lower inertia and better high-speed efficiency. Possible disadvantages of small sprockets for racing motorcycles are slightly more power variation and drive 'jerkiness' due to polygonal action.

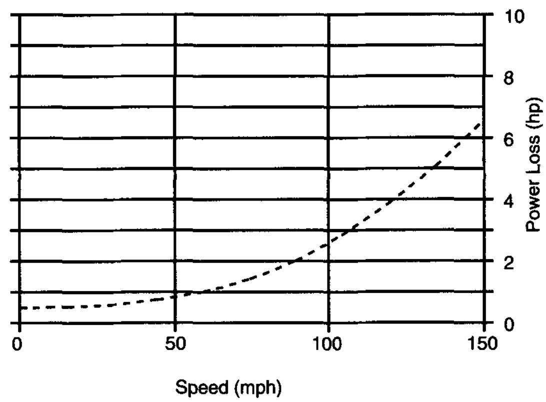

Figure 9 Predicted power loss from a 600cc motorcycle chain at half power

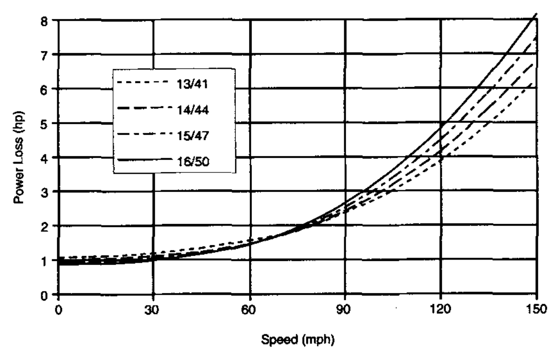

Figure 10 Predicted transmission efficiency of a 600cc motorcycle chain using different sprocket sizes

Optimisation of the chain

There are several different manufacturers who supply motorcycle chains. Each manufacturer states the load carrying capacity of each of their chains. The designer/constructer of the sports motorcycle must select a chain that can cope with the power and torque of the motorcycle. Often the motorbike designer has a choice of different chain sizes and types to choose from.

From Eqns. (1) and (2) it can be seen that the transmission efficiency is directly related to the internal diameter of the bush. Therefore, the most efficient transmission is produced by selecting the chain with the smallest bush internal diameter. It should be noted that the internal diameter of the bush is virtually the same as the pin diameter because the pin is a clearance fit in the bush. Therefore the transmission efficiency is also maximised by selecting the chain with the smallest pin diameter.

From Table 1 it can be seen that there is about a 15% increase in pin diameter when the pitch increases from 1/2 inch to 5/8 inch and there is a further 15% increase in pin diameter when the pitch increases from 5/8 to 3/4 inch. This means that a 5/8 inch pitch chain will have about 15% greater power loss compared to 1/2 inch pitch chain when all other things are equal. Therefore, the most efficient chain is the chain with the smallest pitch that can meet the torque and power requirement.

The efficiency of the chain is also affected by the lubrication system. Some chains come with o-rings which help make the chain last longer by trapping lubricant in the pin and bush area. There is no data for the efficiency of chains with o-rings. However, it is certain that o-rings will add friction to the chain. For critical race applications, it is advisable not to use o-rings.

The chain lubricant is also a critical factor in the transmission system. The lubricant should be thin enough to get into the tight spaces around the pin. However, it should not be so thin that it runs off the chain too quickly. One of the most critical factors for the lubricant is its operating temperature. Most chain lubricants start to thin and become weak above 70°C. When racing hard in hot conditions, care must be taken to re-lubricate the chain before it gets too hot. In addition, the lubricant should be carefully selected.

Optimisation of chain installation

The efficiency of chain drives is greatly affected by the centre distance. Studies have shown that the efficiency of a roller chain decreases rapidly if the chain is too tight. For example, experiments have shown that the power loss in a roller chain can be doubled when the centre distance is 0.5% above the ideal centre distance (Lodge & Burgess, 2000). Therefore it is critically important to have a reliable procedure for setting up the correct centre distance on the chain.

The centre distance of the chain is set up by adjusting the rear wheel position so that a certain degree of mid-span slack is achieved. A typical recommended amount of mid-span sag is 2–3% of the centre distance between the sprockets. One of the problems with motorcycle chains is that the chain has a variable centre distance because of the suspension system.

Fig. 11 shows the rear drive when the suspension is unloaded and loaded. The rear wheel has suspension by virtue of a swing arm which pivots near to the front sprocket. The action of the swing arm means that the chain does not have a constant centre distance, c. When the suspension is unloaded the chain has a short centre distance. When the suspension is loaded there comes a point when the front and rear sprockets and the centre of the swing arm are all in line. At this point the chain centre distance is at a maximum.

If the chain is set up when the suspension is unloaded there is the danger that the chain will be too tight when the suspension is loaded. Therefore it is very important that the chain and sprocket system is set up when the centre distance is at a maximum. There are two techniques for compressing the suspension system during chain set-up. One method is to use an adjustable harness that locks the suspension. A second method is simply to get people to sit on the motorcycle.

Chain efficiency is also affected by the alignment of the sprockets. If the rear wheel is not in-line, there will be uneven forces in the chain links and excessive friction between side plates of the chain. The front and rear sprockets also need to be in-line.

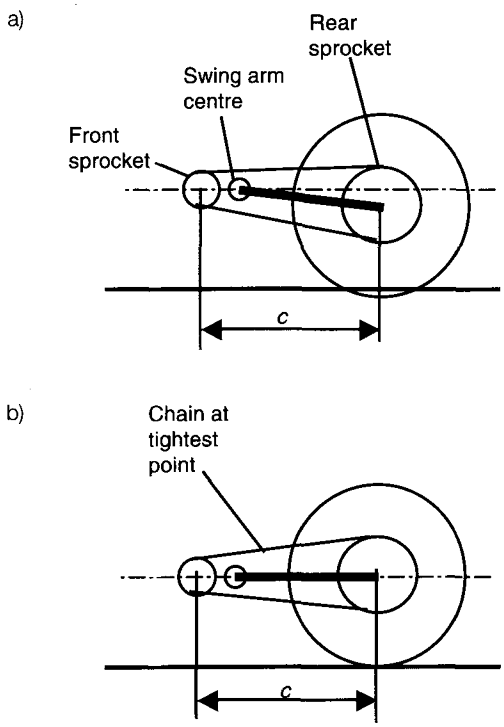

Figure 11 Effect of the suspension system on chain centre distance. a) Unloaded suspension, b) Loaded suspension.

Conclusions

The transmission efficiency of the chain drive has a very significant effect on the performance of sports motorcycles. The transmission efficiency of a 600cc sports motorcycle chain has been estimated to be between 96 and 99% when travelling at speeds less than 75 mile/h. Between 75 and 150 mile/h the transmission efficiency can be as low as 85% due to inertial tension and more than 7 hp (5.2 kW) can be lost from the chain.

The transmission efficiency model presented in this paper enables optimisation of sprocket and chain sizes. In general, large sprockets are better at low speeds and smaller sprockets are better at high speeds. The optimum chain size is the chain with the smallest pitch that can meet the torque and power requirement. The sprocket centre distance also has a big effect on efficiency and it is important to follow an effective installation procedure. In particular, it is important to set a chain up when the rear wheel axle, front crank and swing arm bearing are all in-line.

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