The Split Friction Model - Introducing Mixed Lubrication to Curling

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The Split Friction Model - Introducing Mixed Lubrication to Curling

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In general, the curling stone is subject to mixed lubrication, resulting in the characteristic Stribeck-curve. As velocity increases, the friction force falls quadratically just to rise linearly yet almost flat after the minimum. In the case of a rotating curling stone this results in a torque. Due to isotropy, the lateral force arises as a delta of asymmetric friction forces opposite to the centripetal forces.

This in turn allows a split friction model that splits up the quadratic curve into two rather constant values for the friction force on the advancing and the retreating side below a critical velocity difference of these sides: the flee force on the advancing side must not exceed the normal force of the retreating side. Only then a curl can happen. This explains why a stone curls towards the end of the throw.

Following basic static considerations, the stone may theoretically rest on up to three points during a throw. Each single static case is investigated. These results are discussed with additional heuristic calculations that involve Scratch-Theory. Lastly, the influence of gyroscopic precession yields a graph that reflects established experimental observations: A desired flat curve within deviations ranging from 0.80 to 1.02 meter for up to 20 rotations just to rise linearly up to 2 meters for 80 rotations.

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OBJECTIVE

The objective is to provide an explanation why the curling stone in the sport of curling deviates independent of rotation. In a typical throw of 28 meters the rotation remains roundabout one meter regardless if it was thrown with 1 or 10 rotations. For the last seven years, I came up with many different ideas that I discarded after a while and therefore also did not publish. Finally, I came up with an idea that I feel comfortable with enough to publish it in a specialized journal. I did not gather any experimental data myself. Instead, this work is a theoretical solution based on experimental data gathered in previous studies. The data provided in the excel-worksheet contain ample calculations quantifying my considerations regarding normal force, flee force, statics, deviation, scratch-force and effect of gyroscopic precession.

The data described in this Data note can be freely and openly accessed on <https://figshare.com/authors/Martin.Ziegler/10334915>. Please see table 1 and reference list for details and links to the data.

TABLE 1

1. data file SplitFrictionModel excel-worksheet
2. data file StribeckCurling.png

3. data file StribeckTorque.png
4. data file StribeckCurlingSplit.png
5. data file StribeckLateralForce2.png
6. data file ModelSketch123blocks.png
7. data file ModelSketch123angles.png
8. data file SplitScratchCombinedGyro2.png

DECLARATIONS

- Funding: No funding
- Conflicts: None
- Availability of data and material: available

DEDICATION

I dedicate this article to the soils of Lower Bavaria and to my wonderful hometown Deggendorf.

I. INTRODUCTION

A. The Curling Problem

Let us begin by informally getting a clear idea what the curling problem is about, picturing the following scenario. There are 5 identical regular stones on fresh ice. We also have the best curling team in the world and they

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can make the stone stop right after 28 meters. The ice is the same high-quality as in the Winter olympics and just got freshly pebbled, as curlers would say. For this drill, the thrower is all on his own. The sweepers are not allowed to help him after he released the stone.

He throws a stone with 1 rotation, it deviates roundabout 1 meter.

He throws a stone with 2 rotations, it deviates roundabout 1 meter.

He throws a stone with 3 rotations, it deviates roundabout 1 meter.

He throws a stone with 4 rotations, it deviates roundabout 1 meter.

He throws a stone with 5 rotations, it deviates roundabout 1 meter.

This behavior has baffled a lot of physicists. You can not help but to wonder about the reason for this motion. The stone is exposed to the air, so the Magnus-Effect might be responsible for the deviation. No, because that would depend on the rate of rotation.

The stone has got a rough running band, so it might have something to do with the stone scratching the ice. But would not that also depend on the rate of rotation?

The quest for the answer can fascinate you for years and makes the curling problem one of the most exciting and interesting unsolved physics problems. Furthermore, it is also one of the last – if not the very last – macroscopic problems in all physics.

B. Basic characteristics

- A curling stone typically travels for a distance of 28 meters.
- The deviation in the trajectory- is seemingly independent of the rotational speed of the stone: In standard throws, the stone always deviates roughly one meter. The typical rate of rotation (1-5 rotations) does not seem to have any influence on the deviation.
- The more the stone loses velocity in the end of the curling throw, the more it deviates.
- A standard curling stone with a polished running band shows no significant deviation.

C. Previous approaches

So far, there have been three advanced friction based models. [2] stated that the main reason for the deviation of the trajectory of the curling stone is the transport of melted friction water from the advancing side to the front side of the curling stone. This reduces the friction coefficient on the front side and makes that part of the stone move faster. That in turn makes the trajectory of the entire stone deviate.

However, [3] do not agree with this approach. Instead, they stress the importance of asymmetric scratches created by the running band. The running band on the front creates scratches that exert forces on the running band on the trailing band. These forces then make the trajectory of the entire curling stone deviate. [5] claimed he experimentally contradicted the findings by [3]. [6] insisted on their validity. [7], [8] then abandoned the friction-water approach to introduce a new model called Pivot-Slide that uses a velocity-dependent friction coefficient. Unfortunately, they try to explain this velocity-dependency with the elasticity of ice pebbles, an approach so far unheard of in physics.

From then on, the debate seems to turn slowly into a scientific standstill even though many papers get published. Two follow-up papers of new authors [9] and [11] then neglected this approach and supported the idea of a scratch-based mechanism. However, two papers by the authors of the Pivot-Slide party [10] and [12] claimed to experimentally disprove these new findings. The latter got published with an immediate counter-reply by [11]. [14] experimentally confirmed the importance of surface roughness supporting Scratch-Theory. Meanwhile, [16] published a paper that supported the Pivot-Slide model. Most recently, the original authors of the Pivot-Slide party published a comment [15] in which they pointed out mistakes in that supportive paper. This comment was again published together with an immediate response [17] to that comment.

Since other authors, among the first [3], have already conjectured that there may ultimately be a combination of many factors that explains the deviation of the curling rock, let us ask the question: Could the answer simply lie somewhere in between these two general approaches?

II. THE BASIC MECHANISM

A. Mixed Lubrication

First, let us introduce the concept of mixed lubrication to the curling discussion. This concept was introduced more than 100 years ago by [1] but so far got overlooked. The key feature is that friction becomes velocity dependent in the presence of a lubricant (see figure 1). At low velocities, there is boundary lubrication between the surface and the moving body. As the velocity rises, mixed lubrication emerges as an intermediate friction type that quadratically diminishes the friction coefficient. In the minimum of the curve, the friction changes to hydrodynamic friction with the friction coefficient rising almost flat with velocity again.

[3] measured the friction coefficient accurately with a specially designed machine and reported a rising friction coefficient as velocity approaches zero. It seems therefore reasonable to design a Stribeck-Curve that best reflects the values they measured.

For high rates of rotation, the velocity of the retreat-

FIG. 1. Suggested Stribeck-Curve applied to a non-rotating curling stone. Boundary lubrication at very low speeds, μ hardly varies. After threshold velocity at 0.05m/s mixed lubrication makes μ fall quadratically. This stops at around 1.42m/s , as hydrodynamic lubrication turns in μ to a slow rise. Same properties get mirrored for negative velocities, omitted in sketch for better visibility.

FIG. 2. Differing friction forces create torque on the stone.

ing side of a curling stone can get negative. For these cases the Stribeck-Curve and its properties were simply mirrored in the origin (see figure 1).

B. Lubrication-induced Torque

As the retreating side travels at a lower speed, it enters the minimum of the μ/v -curve earlier than the advancing side. This makes the corresponding friction force on the retreating side grow faster than on the advancing side. As a consequence, a torque is generated that additionally accelerates the advancing side. The difference in velocities among the two sides of the curling stone grows (see figure 2).

FIG. 3. Suggested Stribeck-Curve applied to a rotating curling stone. At sufficiently low speeds, here at 1.42m/s , the friction curve splits up. This results in two flat μ curves for each side of the curling stone.

C. Split Friction

This growing divergence of the velocities allows a model that splits the μ/v -curve into two branches in the minimum of the μ/v -curve. The μ of the advancing side jumps to the level of the boundary lubrication for a non-rotating stone. The μ of the retreating side remains approximately at the level of the minimum. These two μ then stay the same as the velocities of the two sides of the stone decrease to zero (see figure 3).

D. The Role of the Flee Force

Moreover, the friction force of the retreating side counteracting the flee force of the advancing side must be sufficiently large: $F_{\text{friction, retreating side}} \geq F_{\text{Flee, advancing side}}$. Only then the curve splits up. If it is smaller, then the stone continues traveling straight. Using this relation, we can determine the critical velocity difference $\delta v_{\text{critical}}$ below which a noticeable curl will occur.

E. Origin of Lateral Force

Typically friction coefficients are isotropic meaning they are equally big in any direction. For the general case of a non-rotating stone, the friction coefficients anywhere

FIG. 4. Differing friction forces opposite to centripetal forces. Delta F in middle results from subtracting the friction force on the advancing side from that on the retreating side.

on the running band are equally big and appear opposite to the line of motion or acceleration. But in reality they are isotropic, as is typical for friction coefficients.

Due to the velocity dependence in mixed lubrication, the friction coefficients on a rotating curling stone are different right to begin with. These two properties, velocity dependence and isotropy, appear similar but are not the same. So, the friction coefficients on a curling stone apparently can be unequally big but still isotropic.

This becomes noticeable within $\delta v_{critical}$ (see figure 4). The friction force on the retreating side is big enough to counteract the flee force on the advancing side. Consequently, the segments of the stone get accelerated relative to the ice by the centripetal force. In other words, the segment of the curling stone on the retreating side remains in line with the linear motion whereas the segment on the advancing side gets accelerated laterally.

Illustrating it another way, the centripetal forces on each side accelerate the segments of the running band inwards, the friction force therefore points outwards. Below $\delta v_{critical}$, the lateral force on the stone then originates as a difference of these two opposing forces.

Admittedly, that consideration is a tough one to understand. But overall, it's surprisingly basic. And the model calculations in section III back up that interpretation.

F. The Role of Pebbles

I want to explicitly point out that the elasticity of the pebbles in this model is ignored. The pebbles simply provide valleys for the lubricant to roll down into, thereby thinning the lubricant on top of a pebble and increasing μ .

G. Segmental Lateral Force

Another surprise to curling experts may be that the lateral force can be smaller than the usually assumed $18kg * g * \mu = 1.8N$. First of all, μ is not constant at 0.01, as already experimentally measured in [3]. But more importantly: For the center of mass of the entire stone to move laterally, the lateral force only needs to act on segments of the advancing side of the stone. Even though the segments on the retreating side remain in line with

the linear motion at the same time, the center of mass of the entire stone then still deviates.

H. Dependence of rotational and linear velocities

As pointed out by [18], [20] and [19], the decrease of linear and rotational velocities of hockey pucks are dependent of each other. That means they tend to decrease in such a way that they stop at the same time. Since curling stones are quite similar to hockey pucks, it seems reasonable to assume a strong dependence of linear and rotational velocities. That means both tend to drop with the equal ratio.

I. Gyroscopic Precession and Statics

The final piece of the puzzle is to understand how gyroscopic precession influences the statics during the throw. As [3] have pointed out, the stone rests on only a few points throughout the throw. It never rests on the entire running band. Statically, a non-rotating stone is stable standing on three points. The more a stone rotates, the more gyroscopic precession stabilizes the rotating stone and thus favors the stone standing on two points or even one point rather than three points. More clearly, more rotations of the stone statically mean less points the stone rests on.

J. Static Ratio Nomenclature

To complete the theoretical part of this paper, it is therefore convenient to introduce the ratio of points the stone rests on (one point: two points: three points) for a given rotation. A static ratio of (0:1:1) means that the stone rests no time on one point, half the time on two points and half the time on three points. In this work, this ratio should be thought of as an estimated static expectation value for a given rotation. In real life, a throw of course would also have a static variance for a given rotation.

III. MODEL CALCULATION

You can find the excel-file with the calculations in my figshare repository.

A. Technical sketch

For the model calculation, it seems reasonable to first investigate three basic cases: the stone rests on one(1:0:0), two(0:1:0) or three points(0:0:1). Standing on two and three points, the stone is split up into two and three equal parts with their own mass and center of

FIG. 5. Technical sketch of the curling stone in the model.

FIG. 6. Technical sketch of the constant assumed angles of the curling stone in the model.

mass (see figure 6). These centers of mass are assumed on the running band in a 90 degree respectively 45 degree angle to the line of motion.

Standing on one point, the stone is also split up into two parts, with one half rotating above ground. In addition, the stone is assumed to remain on the retreating side throughout the curl in the end of the shot. The torque generated by the differing forces may stabilize the stone on that side. In reality, the stone may toggle back and forth between sides standing on the retreating side substantially longer than on the advancing side. The only remedy would be to estimate an arbitrary toggle ratio that additionally would need to depend on the rate of rotation. For simplicity, this is omitted.

For the cases of standing on one and two points, the stone is split into two halves with a mass of $18\text{kg}/2 = 9\text{kg}$ whose center of mass are at a distance equal to the diameter of the running band 0.12m .

The case of standing on three points may even be more intricate. Analogously, the stone is divided into three thirds with a mass of $18\text{kg}/3 = 6\text{kg}$. Overall though, the stone is still divided into an advancing and a retreating side, with masses of 12kg respectively 6kg . In this model, the mass of the stone on each side changes from 6kg to 18kg every 0.1s . To further facilitate calculating, the distance of the center of mass on the advancing and retreating side is approximated by $0.12\text{m} \cdot (2/3) = 0.08\text{m}$.

Another simplification is that the direction of the friction force on each of these blocks remains constant. It is assumed to be in line or 0 degrees with the linear motion

for standing on one and two points and to be in a 45 degree angle with the line of motion on the side with two blocks for standing on three points. Standing on three points, this angle would not just be different throughout the shot but would also depend on the rotation rate of the shot to begin with. This simplification seems necessary to make the already very complicated and advanced calculations clearer and halfway comprehensible for the reader.

B. Trigonometric Correction

Of course, we can not assume the points on the running band to always be in a perfect 90 respectively 45 degree angle to the linear path of motion. The stone could as well stand on points exactly in line (0 degrees) with the linear path, thereby contributing nothing to lateral deviation. To account for that it seems reasonable to correct the deviation values by multiplying them with the trigonometric factor $\sin(45\text{deg}) = \cos(45\text{deg}) = 0.5 \cdot \sqrt{2} \approx 0.707$.

C. The Critical Velocity Difference

We then first determine $\delta v_{\text{critical}}$ for each of these three cases, at which $F_{\text{friction, retreating side}} \stackrel{!}{=} F_{\text{Flee, advancing side}}$ holds: 1 point ($0, 27 \text{ m/s}$), 2 points ($0, 19 \text{ m/s}$), 3 points ($0, 19 \text{ m/s}$). That means if the velocity difference between the advancing and the retreating side is below these values the stone will curl.

D. Small Number of Rotations

Next, the model calculation for the cases that stand on two respectively three points shows a rather stable deviation in the range of one to seven rotations. Trigonometric correction already applied, the deviation only grows moderately from on to seven rotations, always staying within 0.81 m to 0.98 m (2 points) respectively 0.91 m to 1.09 m (3 points). Standing on 1 point, the deviation moderately grows up to 12 rotations, albeit it is smaller in general: 0.33 m to 0.45 m .

For illustration assuming a combination that stands e.g. equally long on one, two and three points ($1:1:1$), we get a range of 0.68 m to 0.82 m for the first seven rotations.

E. Large Number of Rotations and Scratch Theory

First off, the model calculation showed that throws at high rotation rates are very sensitive to minimal changes in the initial velocity.

FIG. 7. Combination of Split Friction and trigonometrically approximated scratch force after trigonometric correction and taking into account the stabilizing effect of gyroscopic precession. The stone stands on one point longer. The higher the rotation rate, the fewer points the stone stands on.

In addition, throws with more than seven (2 and 3 points) respectively 12 (1 point) rotations show a steeply declining deviation. In other words, from then on, the more a stone rotates, the less it deviates. That happens because $\delta v_{critical}$ is reached later and later in the throw.

However, experiments with up to 80 rotations conducted by [2], have shown a not always linear increase in deviation up to two meters for 80 rotations.

This article is not primarily about Scratch-Theory. Still for higher rotations, it appears reasonable to include the concept Scratch-Theory first presented by [3] into the split friction model. To start out, it may seem pragmatic to assume a linearly rising scratch force from 1 to 80 rotations as a first approach. On this basis, the next step is to include trigonometric considerations to determine the angle of the vectors of the translational and rotational momenta of the stone at 80 rotations which corresponds to a $2m$ deviation. This then serves as a multiplier for the angle at fewer rotations yielding the scratch graph in figure 7. In both approaches the curl of the stone caused by scratch theory will happen throughout the throw and not at the end of the throw, as it is independent of $\delta v_{critical}$.

F. Gyroscopic Precession

Due to gyroscopic precession, the stone is likely to stand on fewer points as the rotation rate increases. This flattens the curve in the area where the split friction component plummets. Assuming a trigonometric model of scratch theory, the ratio of points the stone rests on (one point: two point: three points) changes throughout the throw.

Calculating the change of ratio accurately is very tricky. So let us take a pragmatic approach and esti-

mate the most and least effect it can have. First, let us examine the case that optimally reflects the observed reality.

In figure 7, the stone rests equally long on two and three points that is ratio (0:1:1) for one and two rotations. This ratio gradually shifts towards standing on one point as rotations increase, e.g. at 10 rotations the ratio is (3:2:1). From 20 rotations on upwards the stone rests on one point three quarters of the time only (3:1:0). For 1 to 7 rotations, the deviation rises from $0.90m$ to $1.02m$ for 7 rotations. It then drops to $0.81m$ at 10 rotations just to rise to $0.86m$ for 12 rotations. Again it drops $0.80m$ at 15 rotations. For the rest of the shot, it then grows up to $2.01m$ for 80 rotations.

To show the least optimal effect the stabilizing effect of gyroscopic precession can have, we can simply leave it out. Assuming a constant ratio of e.g. (1:1:1) throughout the shot, the shot deviation would start at $0.72m$ for 1 rotation to rise to $1.08m$ for 7 rotations to drop to $0.78m$ at 14 rotations. From then on, the deviation grows up to $2.01m$ for 80 rotations.

For yet additional transparency, while we are at it, we can leave out the tricky case of the stone standing on one point entirely mentioned in III A. Assuming a constant ratio of e.g. (0:1:1) throughout the shot, the shot deviation would start at $0.90m$ for 1 rotation to rise to $1.29m$ for 7 rotations to drop to $0.76m$ at 13 rotations. From then on, the deviation grows up to $2.01m$ for 80 rotations.

IV. CONCLUSIVE DISCUSSION

A. Introduction of Mixed Lubrication

A major accomplishment of this paper is to introduce mixed lubrication to the world of curling physics. That way the idea of a velocity-dependent friction coefficient is based on a solid foundation. The concept of mixed lubrication has been generally accepted in tribology for over 100 years.

B. Match with Observed Curling Reality

The Split Friction Model can explain a rather stable deviation of $1m$ below 20 rotations. Curling players intuitively keep their throw within the relatively stable deviation around $1m$ for 3-7 rotations. The data suggests a local maximum at 7 rotations that curlers may intuitively aim for. A stable shot with maximum deviation can be most effectively put into target by the sweepers straightening the curve.

A throw at a high rotation rate above 20 might curve more throughout the throw and thus seem the best solution in some game situations. However, due to the sensitivity to the initial velocity at a high rotation rate

that the model calculation suggested, it is best to avoid such a throw at all times.

C. Previous Approaches

The reason for the deviation at higher rotation rates might thus be interesting only to physicists and can be explained with with Scratch-Theory. The weak initial curl also happens due to Scratch-Theory.

Speaking of, is the solution to the curling problem a combination of the previous approaches as conjectured in the introduction? Sort of.

The pivot-Slide model is only remotely conceptually correct. The lateral force does not arise from some - so far unheard of - elasticity of ice pebbles. Instead the lateral force originates by consequently applying a long

established concept named mixed lubrication.

D. Split Friction Put into Perspective

The split friction model as presented in this paper is a good heuristic to explain curling physics. But it is far from an ultimate undeniable solution. That is mainly due to the trickiness of quantifying properties like how gyroscopic precession stabilizes the stone standing on less than the statically stable three points for increasing rotation rates. Curling will always remain a game after all.

Still, I want to invite other scientists to expand and refine this model. Ultimately, every physicist may have their own personally best model to explain curling physics. But the split friction model being a combination of proven and existing concepts namely mixed lubrication and scratch-theory provides a solid starting platform to find that solution.

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Figures

Figure 1

Suggested Stribeck-Curve applied to a non-rotating curling stone. Boundary lubrication at very low speeds, μ hardly varies. After threshold velocity at 0.05 m/s mixed lubrication makes μ fall quadratically. This stops at around 1.42 m/s, as hydrodynamic lubrication turns in μ to a slow rise. Same properties get mirrored for negative velocities, omitted in sketch for better visibility.

Figure 2

Differing friction forces create torque on the stone.

Figure 3

Suggested Stribeck-Curve applied to a rotating curling stone. At sufficiently low speeds, here at 1.42m/s, the friction curve splits up. This results in two μ curves for each side of the curling stone.

Figure 4

Differing friction forces opposite to centripetal forces. Delta F in middle results from subtracting the friction force on the advancing side from that on the retreating side.

Figure 5

Technical sketch of the curling stone in the model.

Figure 6

Technical sketch of the constant assumed angles of the curling stone in the model.

Figure 7

Combination of Split Friction and trigonometrically approximated scratch force after trigonometric correction and taking into account the stabilizing effect of gyroscopic precession. The stone stands on one point longer The higher the rotation rate, the fewer points the stone stands on.