A Drilling Force Model for Use in Multibody System Simulation Environments

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Abstract. In this work, a drilling-force model for the use in multibody system simulations is presented. The model is based on drilling-force calculations, collision detection, a compliant contact model, and a method for applying the forces to a multibody environment. The model can be used in two ways. First, it can be used to calculate drilling forces based on a given velocity and angular velocity of the drill. Second, it can be integrated into a model to interact as a body in a multibody scenario and be subjected to an external force and angular velocity.

Introduction

Drilling processes are widely used and occur in many different areas, such as manufacturing or construction. Several models exist to calculate the forces during a drilling process. However, they usually cannot be used for body interaction in a multibody context (e.g. if the drilling forces are to be applied to the robot in order to optimize the robot-assisted drilling process).

Therefore, in this work, a drilling-force model is presented that can be used in multibody simulations. The goal is to use it in system simulation environments. This allows the creation of multi-domain models. For example, the drilling model can be combined with the dynamics model of a robot and other models such as the control system or the motors of the robot. This can then be used to analyze the influence of the drilling process on the robot dynamics or energy consumption. The object-oriented and multi-domain modeling language *Modelica* [7] is used as system simulation environment.

Models are built based on the multibody components [9] from the *Modelica Standard Library* (MSL) [8].

The developed drilling-force model is based on drilling-force calculations, collision detection, a compliant contact model, and a method for applying the forces to the multibody environment.

In the next section, the state of the art is introduced. In Section 2, the developed drilling-force model is presented. Examples are given in Section 3. Finally, the results are discussed and future developments for the model are considered in Section 4.

1 State-of-the-Art

In this section, the basics are introduced. These include the forces in the drilling process and collision detection and response for multibody simulation environments.

1.1 Forces in the drilling process

Drilling is a machining process. Because the geometry of the cutting edges is known, it is classified as a *machining process with a geometrically defined cutting edge* (similar to turning and milling) [5]. There are several models for calculating the forces in the drilling process. Examples are the works of Dietrich (2016) [2] and Fritz and Schulze (2015) [5].

The most suitable parameters for a drilling process are often determined using table values [3]. In this work the model of Dietrich (2016) is applied [2]. It is used to calculate the cutting force F_c and the feed force F_f from a given rotational frequency n and feed per rotation f.

First, the feed per rotation per cutting edge f_z as well as the stress thickness h, the stress width b, and the stress cross-section A are calculated.
Inputs the are number of cutting edges z_E, the tip angle of the drill σ, and the drill diameter d (see Figure 1) [2].

$$f_z = \frac{f}{z_E} \quad (1)$$
$$h = f_z \cdot \sin(\frac{\sigma}{2}) \quad (2)$$
$$b = \frac{d}{2 \cdot \sin(\frac{\sigma}{2})} \quad (3)$$
$$A = h \cdot b \quad (4)$$

The specific cutting force k_c depends on the stress thickness h and the material dependent parameters z and $k_{c1.1}$ [2]. The latter is the specific cutting force of a given material for $h = 1$ mm. There are also correction factors which are not considered in this work.

$$k_c = \frac{0.001^z}{(f_z \cdot \sin(\frac{\sigma}{2}))^z} \cdot k_{c1.1} \quad (5)$$

The cutting force per cutting edge F_{cz}, the cutting force (for the entire drill) F_c, and the feed force F_f are then calculated as follows [2].

$$F_{cz} = \frac{d \cdot f_z}{2} \cdot k_c \quad (6)$$
$$F_c = z_E \cdot \frac{d \cdot f_z}{2} \cdot k_c \quad (7)$$
$$F_f = z_E \cdot F_{cz} \cdot \sin(\sigma) \quad (8)$$

1.2 Collision detection

The basis for calculating drilling forces in a multibody environment is the interaction between the bodies. This requires collision detection. Common algorithms for collision detection are the Gilbert-Johnson-Keerthi distance algorithm (GJK) [6] and the Minkowski Portal Refinement algorithm (MPR) [12]. Both algorithms provide the penetration depth of two colliding bodies.

There have been several approaches to enabling collision detection for the system simulation environment *Modelica*. Most of them extend *Modelica* with an external library for collision detection. An overview can be found in Reiser and Reiner (2023) [11].

1.3 Multibody contacts

Based on the collision detection, the next step is to prevent the bodies from intersecting. This is also known as collision response. There are two main approaches to handling multibody contacts: compliant (penalty-based) and non-smooth (constraint-based).

In this work, only compliant contacts are considered. Contact forces are calculated based on the penetration depth. [4]

A common model is the Kelvin-Voigt contact force model. It uses a spring-damper element to calculate the normal force F_N based on the penetration depth s [4]:

$$F_N = k \cdot s + d \cdot \dot{s} \quad (9)$$

where k is the spring stiffness and d the damping factor. In addition, a friction force dependent on F_N acts in the tangential direction (not considered in this work).

Multiple works have dealt with compliant contacts between bodies in *Modelica* multibody environments. One example is Buse et al. (2023) [1]. Further works are listed in Reiser and Reiner (2023) [11].

2 A Drilling-force Model for Multibody Environments

The developed model for drilling forces in multibody simulation environments is presented in this section.

2.1 Overview

A key component of the model is collision detection. It is used to determine the drill diameter and the penetration depth of the drill. The model has two parts.

In the **kinematic model**, the rotational frequency and the feed per rotation are provided and the model calculates the drilling forces. These are not used for body interaction. However, they can be used in a simulation to check if certain forces are exceeded.

In contrast, the drilling forces in the **dynamics model** are applied to the bodies in the multibody environment. This allows, for example, force-controlled robot-assisted drilling processes to be simulated together with robot dynamics models.

2.2 Determination of the drilling diameters

The first step is to determine the drilling diameters during the drilling process. If the drill does not come out of the material on the opposite side during drilling, only the outer diameter d_O is relevant. Otherwise, the inner diameter d_I is also important.

Collision detection is used to determine the drilling diameters during the process.

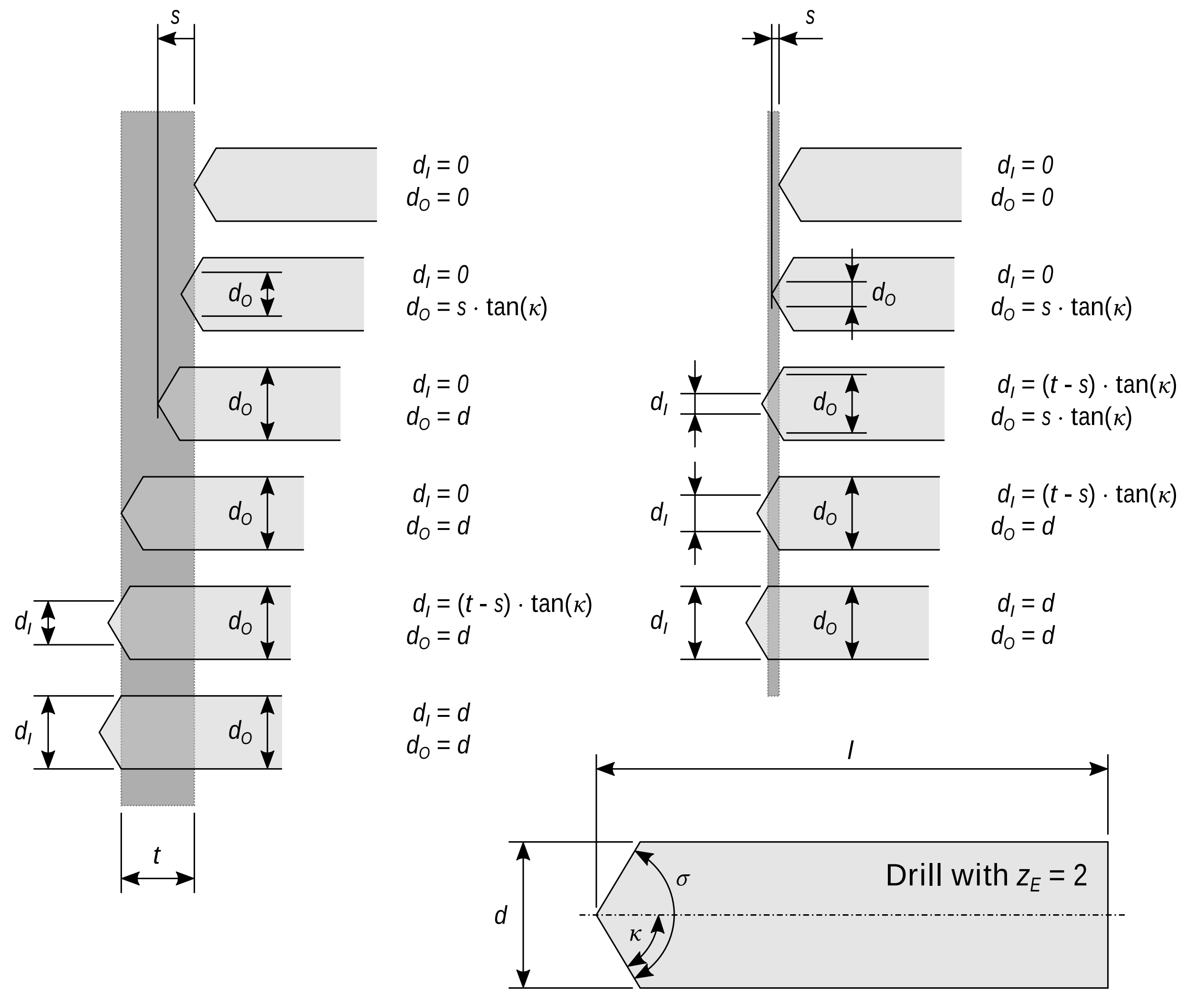

Figure 1: Drilling diameters for several states during the drilling process. A distinction is made as to whether the material is thicker than the height of the drill tip (left) or not (right). A drill is described by its length l, diameter d, and number of cutting edges z_E (shown in the bottom right), while the material is described by its thickness t.

The MPR algorithm is used in the developed model. It is connected to the multibody model in *Modelica* via an external library, similar to the method in Buse et al. (2023) [1].

Figure 1 shows the resulting drilling diameters for several states during the process. Collision detection is used to determine both the penetration depth of the drill and if the drill cone is penetrating the workpiece, is within the workpiece, or is leaving the workpiece. Depending on the state, different calculations are used to determine the diameters (see Figure 1). In addition, it is necessary to distinguish if the material is thicker than the height of the drill cone.

2.3 Kinematic model

The kinematic model uses the calculated drilling diameters from Section 2.2. Taking into account the drilling diameters, the cutting force per cutting edge F_{cz} is calculated with a modification of Equation (6) [2]:

$$F_{cz} = \frac{(d_O - d_I) \cdot f_z}{2} \cdot k_c \tag{10}$$

Based on the cutting force, the feed force F_f is calculated using Equation (8). The kinematic part of the developed drilling-force model has already been used in the *MFlex 2025* project [10].

2.4 Dynamics model with applied forces

A different approach is used for the dynamics model. The drilling forces are not applied directly to the bodies in the multibody model. Instead, a compliant contact model is applied to the drill body. This allows the drill to be pressed against the table even when it is not rotating. This also increases the numerical stability of the model. The collision detection provides the penetration depth s for the contact model.

The idea now is to make the feed force for the drilling F_f equal to the contact normal force F_N (see Equation (9)). The cutting force per cutting edge F_{cz} can then be calculated from this:

$$F_f = F_N \quad (11)$$

$$\Rightarrow z_E \cdot F_{cz} \cdot \sin(\sigma) = k \cdot s + d \cdot \dot{s} \quad (12)$$

$$\Rightarrow F_{cz} = \frac{k \cdot s + d \cdot \dot{s}}{z_E \cdot \sin(\sigma)} \quad (13)$$

Next, the feed per cutting edge f_z is calculated from the cutting force per cutting edge. This is done by combining Equation (10) and Equation (5):

$$F_{cz} = \frac{(d_O - d_I) \cdot f_z \cdot 0.001^z}{2 \cdot (f_z \cdot \sin(\frac{\sigma}{2}))^z} \cdot k_{c1.1} \quad (14)$$

$$\Rightarrow F_{cz} = \frac{(d_O - d_I) \cdot f_z^{1-z} \cdot 0.001^z}{2 \cdot \sin(\frac{\sigma}{2})^z} \cdot k_{c1.1} \quad (15)$$

$$\Rightarrow f_z = \left(\frac{F_{cz} \cdot 2 \cdot \sin(\frac{\sigma}{2})^z}{(d_O - d_I) \cdot 0.001^z \cdot k_{c1.1}}\right)^{\frac{1}{1-z}} \quad (16)$$

The feed per rotation f is then calculated based on f_z and the number of cutting edges z_E:

$$f = z_E \cdot f_z \quad (17)$$

This feed per rotation is now used to calculate the target velocity v_{tar} of the drill, based on the angular velocity ω of the drill, which is derived from the rotational frequency n of the drill:

$$v_{tar} = f \cdot n = f \cdot \frac{\omega}{2 \cdot \pi} \quad (18)$$

Finally, the target drill depth s_{tar} can be calculated by integrating the target velocity v_{target}:

$$s_{tar} = \int v_{tar} \, dt \quad (19)$$

This target drill depth is used as the reference depth for the calculation of the contact force. Equation (9) is modified to calculate the contact normal force F_N:

$$F_N = k \cdot \Delta s + d \cdot \Delta \dot{s} \quad (20)$$

$$\Rightarrow F_N = k \cdot (s - s_{tar}) + d \cdot v \quad (21)$$

The penetration depth s of the drill and the drill velocity v are still used, but now the contact surface of the workpiece moves based on the drilling process. Its position is defined by s_{tar}.

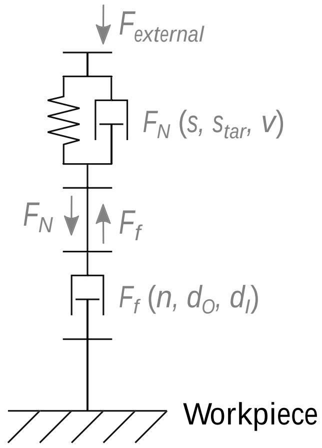

Figure 2: A substitute model of the drilling-force model. An external force is applied to the spring-damper element representing the compliant contact model. The contact force is equal to the feed force of the drilling-force model, here represented by a damper element, with the damping force dependent on the rotational frequency and the drill diameters.

A substitute model of the developed drilling-force model is shown in Figure 2. It can be seen as a series connection of a spring-damper element and a damper element.

The former describes the contact normal force and the latter the movement of the drill as a function of the rotational frequency and the drilling diameters.
Figure 3 shows a more detailed representation of the drilling-force model. It consists of three parts:

- A *DrillGeometry* model to calculate the drilling diameters and the penetration depth of the drill based on an external collision detection library (see Section 1.2 and Section 2.2).

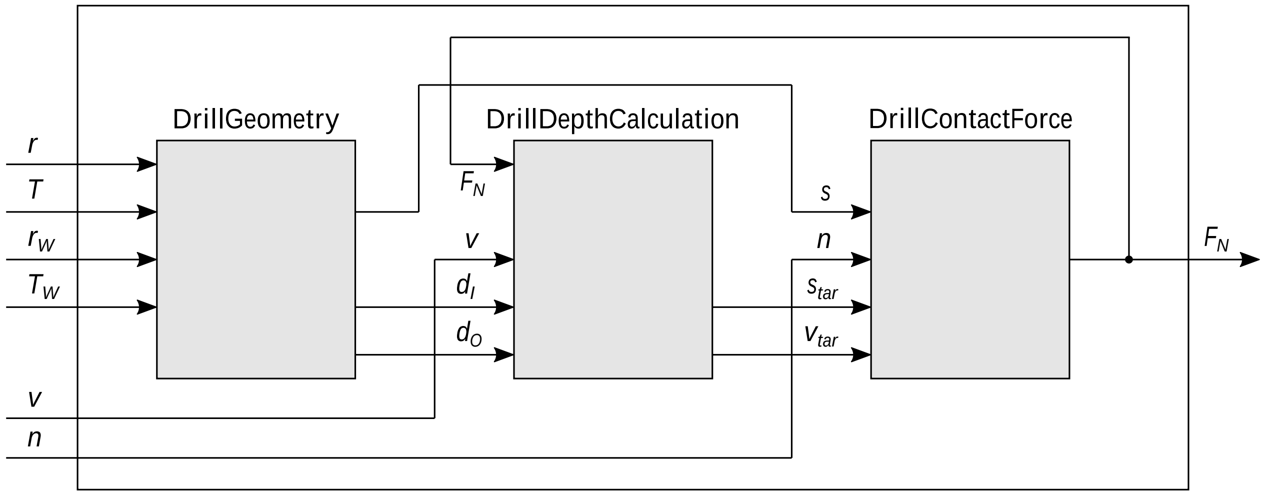

Figure 3: The developed drilling-force model with all models included. The drilling diameters and the drill penetration are calculated in the *DrillGeometry* model. The *DrillDepthCalculation* model provides the target position for the drill. The contact force is calculated in the *DrillContactForce* model based on the actual and target position of the drill.

- A *DrillDepthCalculation* model to calculate the target position of the drill. The calculation is based on Equations (11) to (19).
- A *DrillContactForce* model to calculate the compliant contact force based on the actual and target position and the velocity of the drill (see Equation (20) and (21)).

As mentioned above, the inputs to the drilling-force model are the velocity v and the rotational frequency n of the drill.

In addition, the position r and orientation T of the drill are required for the collision detection in the *DrillGeometry* model.

The same applies to the workpiece, described by r_W and T_W. Collision detection also requires the geometry of the drill and the workpiece.

3 Applications

In this section, two drilling processes are shown. One of them consists of drilling in a thin plate.

The kinematic model is used to calculate the forces involved. In the other process, the dynamics model is applied for a drilling process. This involves drilling into a material with a high material thickness.

3.1 Kinematic drilling into a thin plate

In the first example, the kinematic model is used for the drilling process of a thin plate. The plate is thinner than the height of the drill cone.

The material *34 CrMo4* is used for the workpiece (see [2, p. 19]):

$$k_{c1.1} = 2240 \frac{\text{N}}{\text{mm}^2} \quad (22)$$

$$z = 0.21 \quad (23)$$

A rotational frequency of $n = 9.28 \frac{1}{\text{s}}$ and a velocity of $v = 1.672 \frac{\text{mm}}{\text{s}}$ are used. The drill diameter is $d = 16$ mm with an angle of 118 degrees.

From this, the feed per cutting edge per rotation f_z can be calculated, resulting in a specific cutting force k_c of:

$$f_z = \frac{f}{z_E} = \frac{v}{z_E \cdot n} = \frac{1.672 \frac{\text{mm}}{\text{s}}}{2 \cdot 9.28 \frac{1}{\text{s}}} \approx 0.090 \text{ mm} \quad (24)$$

$$\Rightarrow k_c = \frac{0.001^z}{(f_z \cdot \sin(\frac{\sigma}{2}))^z} \cdot k_{c1.1} \approx 3836 \frac{\text{N}}{\text{mm}^2} \quad (25)$$

The calculated maximum cutting force is:

$$F_{c,\,max} = z_E \cdot \frac{d \cdot f_z}{2} \cdot k_c \approx 5524 \text{ N} \quad (26)$$

However, this value is not reached because the difference between the inner and outer drilling diameter is much smaller. The results are presented in Figure 4. The cutting force, the feed force, and both drilling diameters are shown. The maximum cutting force is $F_c = 986$ N and the maximum feed force is $F_f = 2917$ N (see Figure 4).

The simulation was run on a desktop computer with an Intel Core i7-11700K processor. A *Rkfix2* fixed-step solver with a fixed step size of 0.001 seconds was used. The computation time was 0.11 seconds for a simulation time of 10 seconds (real-time factor of 0.011). The simulation is real-time capable.

3.2 Drilling process using the dynamics model

The second example shows the dynamics model.

A *Modelica* model has been created for a drilling process. As in Section 3.1, the material used is *34 CrMo4*. The model is shown in Figure 5. An external force and angular velocity are generated with source blocks from the MSL. The drilling-force model is integrated into one block. This block is connected to a revolute joint, which in turn is connected to a prismatic joint. This allows a linear motion and a rotation. The drilling forces are applied directly to the frame of the model.

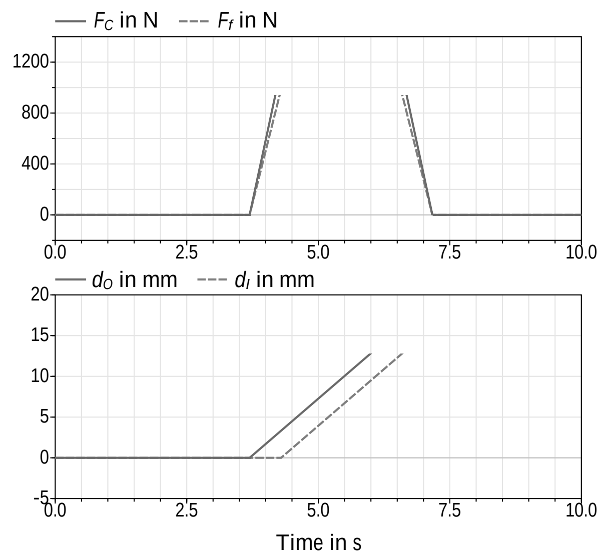

Figure 4: Results for the drilling process of a thin plate. The cutting force and the feed force are shown above. The drilling diameters are shown at the bottom.

The workpiece in the form of a plate is represented by a second block. Both the *DrillGeometry* model of the drilling-force model and this workpiece are modeled with components from a contact detection library. This allows multiple workpieces to be drilled in a multibody scenario without the need for predefined contact pairs.

The results are shown in Figure 6. The variable-step solver *Dassl* was used with a tolerance of 1e-8. It took 0.33 seconds to run the 40 seconds simulation.

As in Section 3.1, a desktop computer with an Intel Core i7-11700K processor was used. Fixed-step solvers are not suitable because the contact between the drill and the workpiece is very stiff and therefore very small step sizes are required at some points.

The actual and target position of the drill fit together well. The feed force and cutting force results match the manually calculated values. The specific cutting force is not defined for the full range of feeds (see Equation (5)). It is therefore limited.

When the feed is less than 1 mm, the specific cutting force does not increase any further. This increases the stability of the model.

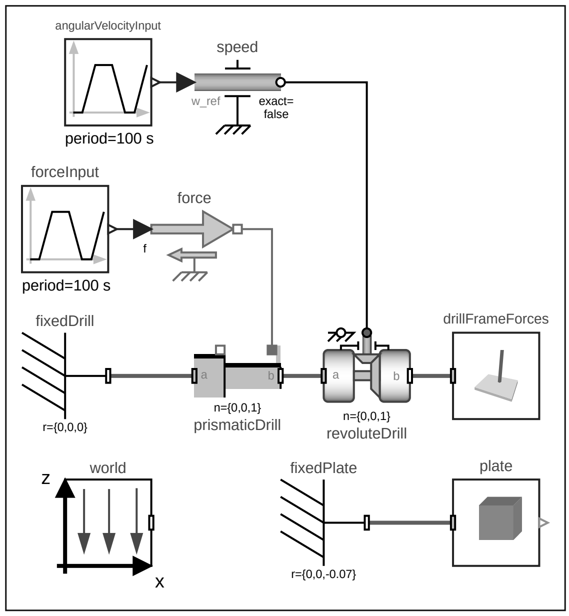

Figure 5: The *Modelica* model of the drilling process based on the dynamics model. The drilling model applies the forces directly to the frame. An external force and angular velocity are also applied to the frame.

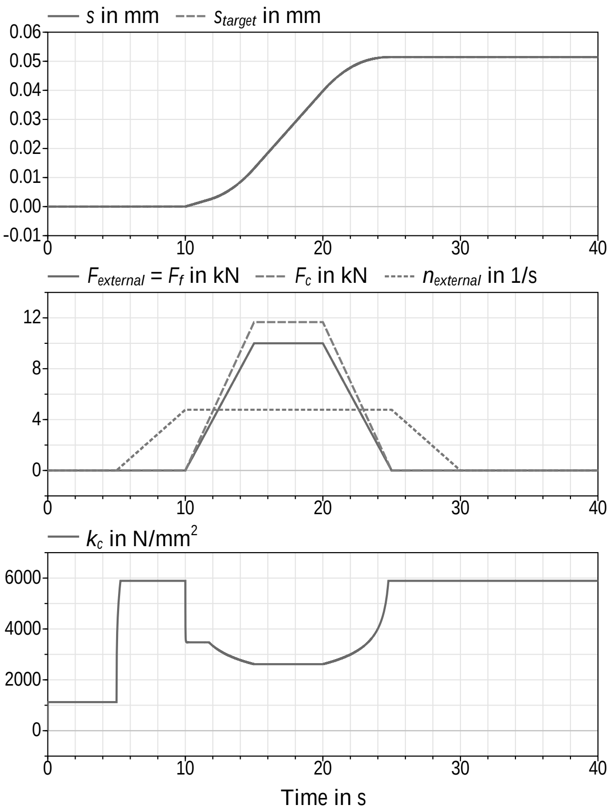

Figure 6: The results for the drilling process based on the dynamics model. The image shows the actual and target position for the drill (top), the external force, the cutting force and the rotational frequency (middle), and the specific cutting force (bottom).

4 Conclusion

In this work, a drilling-force model has been developed. It consists of two parts. A kinematic model can be used to calculate the forces of the drilling process without applying them. The drilling forces in the dynamics model are applied to the bodies in the multibody environment and can be used for body interaction.

The drilling-force model is based on drilling-force calculations, collision detection, a compliant contact model, and a method for applying the forces to the multibody environment. It can be used in system simulation environments such as *Modelica*. The capability of the developed model has been successfully demonstrated in two example drilling processes. However, the model has some limitations: Holes must be drilled at a 90 degree angle to the workpiece without tangential motion. And friction forces are not taken into account (for both the contact force and the drilling forces).

Possible further developments include the integration of a friction model. This would allow forces in the tangential direction to be considered for the contact model. Friction forces could also be included in the drilling-force calculation. Torques from the drilling process could also be considered, for example to model the drive of the drill spindle. In addition, the combination of the drilling-force model with force controlled robot models could be investigated.

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