Development of a Contact Model Adapted to Incremental Forming

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ABSTRACT: The objective of this article is to present the development of a new method for taking into account the contact between the tool and the blank during incremental forming. First, the need for such a model is justified. Then, the basic features of the adapted dynamic explicit scheme are presented, followed by the new algorithms proposed and their programming. Finally, some conclusions and perspectives are drawn.

Key words: Incremental Forming, Finite Element Method, Contact Model

1 INTRODUCTION

Incremental forming is a rather new sheet metal forming process and was developed in response to the observed deficiency in rapid prototyping in this field. It uses a standard smooth-end tool mounted on a numerically controlled multi-axis milling machine. This tool follows a complex tool-path and progressively deforms a clamped sheet into its desired shape.

Simulations of incremental forming processes often require very long computation time. Explicit strategy coupled with shell or brick element is one solution; however, the moving contact modeled by a penalty method decreases the accuracy.

Penalty methods usually check the contact at nodal points or integration points. This implies that for small tool radii, the size of the shell or the brick elements is strongly limited if a stable tool force representative of the actual process is intended. Indeed, when the element size is too large, the force history becomes dependent on the relative position of the tool and on the points where contact is evaluated, even though the mean deformation energy remains identical to the one computed with the refined mesh. Discontinuous forces modify the stress state in the sheet and in the material behavior when an accurate constitutive law with kinematic hardening is used.

This paper presents a new approach that allows one to take into account a contact anywhere inside a small number of elements without using a penalty method.

2 MOTIVATIONS

In a previous study, the forming of a 50-degree wall angle cone has been studied both experimentally and numerically [1,2]. The finite element code used was Lagamine, a code that has been developed at the University of Liège for 20 years. These simulations were static, implicit and used a penalty method to deal with the contact between the tool and the plate [3]. The type of elements used was an isoparametric 8-node brick element called BWD [4,5]. Several problems arose.

First, the choice of the penalty coefficient of the contact elements was critical: if chosen too high, some terms in the stiffness matrix were too high, leading to a bad convergence; if chosen too low, the interpenetration of the tool inside the sheet metal was too large.

Secondly, the size of the mesh had a great influence on the accuracy of the force. This was due to the fact that the contact was only taken into account at integration points, causing the force to decrease, and possibly drop to zero if the size of the mesh was too coarse, when the tool was between two integration points, and increase when it was on an integration point. This is shown in figure 1 where one can see that the force oscillates, instead of remaining constant as in the experimental results.

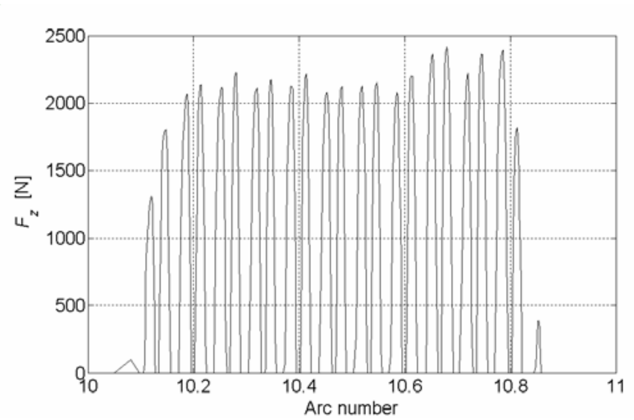

Fig. 1. Oscillations of the vertical force on the tool

Finally, even though the simulations were implicit, the time step remained relatively small because of the constant changes in the contact conditions. Moreover, most of the computation time was dedicated to the resolution of the system of equations, which can be avoided by using an explicit scheme.
For all these reasons, a new method needed to be developed.

3 PRINCIPLES

3.1 Dynamic explicit scheme

The developed method is based on a dynamic explicit scheme. This method is stable, provided that the time step is small enough. This leads to a huge number of steps but has the advantage that no system of equations needs to be solved.

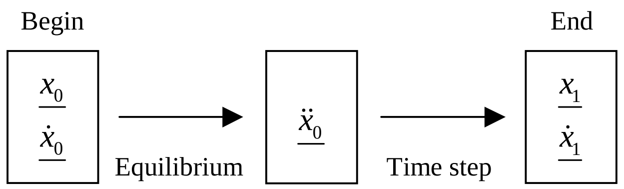

Fig. 2. Dynamic explicit time step

One dynamic explicit time step is presented in figure 2. At the beginning of each step, the position $\underline{x}_0$ and the velocity $\underline{\dot{x}}_0$ of every degree-of-freedom are known. The equilibrium equation is given by:

$$\underline{\underline{M}}\,\underline{\ddot{x}}_0 + \underline{\underline{C}}\,\underline{\dot{x}}_0 + \underline{F}_i = \underline{F}_{fixed} + \underline{F}_{contact} + \underline{F}_{ext} \qquad (1)$$

where $\underline{\underline{M}}\,\underline{\ddot{x}}_0$ = inertia forces,
$\underline{\underline{C}}\,\underline{\dot{x}}_0$ = damping forces,
$\underline{F}_i$ = forces equivalent to the stress state,
$\underline{F}_{fixed}$ = supporting forces,
$\underline{F}_{contact}$ = contact forces,
$\underline{F}_{ext}$ = externally applied forces.

This equation states that the internal forces must be equal to the external forces. The only unknown is the initial acceleration $\underline{\ddot{x}}_0$, which can be easily computed since the mass matrix is diagonal, its inversion being trivial.
The position $\underline{x}_1$ and the velocity $\underline{\dot{x}}_1$ at the end of the step can be computed using the well-known equations:

$$\begin{aligned} \underline{x}_1 &= \underline{x}_0 + \underline{\dot{x}}_0\,\Delta t + \underline{\ddot{x}}_0\,\frac{\Delta t^2}{2} \\ \underline{\dot{x}}_1 &= \underline{\dot{x}}_0 + \underline{\ddot{x}}_0\,\Delta t \end{aligned} \qquad (2)$$

where Δt is the time step.

3.2 Improvement

For the incremental forming process, the contact between the tool and the sheet metal only takes place in a small region. The vector containing the forces due to the contact is then mainly composed of zeros. This leads to the idea that the solution to the equilibrium equation has two contributions that can be summed:

$$\underline{\ddot{x}}_0 = \underline{\ddot{x}}_0^* + \underline{\Delta\ddot{x}}_0 \qquad (3)$$

The first contribution doesn't take the contact forces into account:

$$\underline{\underline{M}}\,\underline{\ddot{x}}_0^* = \underline{F}_{fixed} + \underline{F}_{ext} - \underline{\underline{C}}\,\underline{\dot{x}}_0 - \underline{F}_i \qquad (4)$$

The size of this system of equations is the number of degrees-of-freedom in the whole structure. The initial acceleration can be computed, as well as the position and velocity at the end of the time step:

$$\begin{aligned} \underline{x}_1^* &= \underline{x}_0 + \underline{\dot{x}}_0\,\Delta t + \underline{\ddot{x}}_0^*\,\frac{\Delta t^2}{2} \\ \underline{\dot{x}}_1^* &= \underline{\dot{x}}_0 + \underline{\ddot{x}}_0^*\,\Delta t \end{aligned} \qquad (5)$$

The second contribution is due to the contact forces, which only concern a few degrees-of-freedom:

$$\underline{\underline{M}}\;\underline{\Delta\ddot{x}_0} = \underline{F_{contact}} \tag{6}$$

The size of this system of equation is then very limited. The contribution to the position and velocity at the end of the time step is:

$$\begin{aligned} \underline{\Delta x_1} &= \underline{\Delta\ddot{x}_0}\,\frac{\Delta t^2}{2} \\ \underline{\Delta\dot{x}_1} &= \underline{\Delta\ddot{x}_0}\,\Delta t \end{aligned} \tag{7}$$

4 ALGORITHM

The main advantage of this new method is that the contact elements, and in particular the use of the penalty method, can be removed, as it will be explained below. This section will mainly focus on the contribution due to the contact forces. It supposes that the other terms have already been computed.

4.1 Contact search

During the incremental forming process, the tool is moving around the plate. The location of the contact point(s) constantly changes but will follow the same trend as the tool path. Because, during a small time interval, the change in location will remain small, the contact search can be focused around the location of the previous contact point. The strategy is the following:

- Find the elements in a neighborhood around the previous contact location using an oil-stain method (i.e. adding successive elements from neighbor to neighbor). The size of the neighborhood is a function of the tool radius and the elements' size.

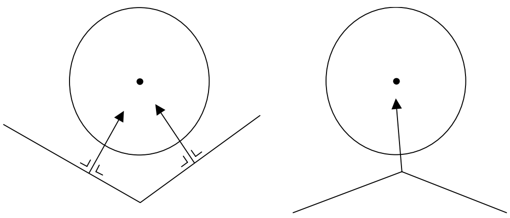

Fig. 3. Definition of the potential contact points

- Among these elements, search for potential contact points, which can be anywhere inside, on an edge, or on a corner of the elements. As shown in figure 3, a potential contact point is defined as the point for which the perpendicular to the element surface goes through the tool center. This is only valid if this point is inside the element. If it is outside the element, the potential contact point is on an edge or a corner if all the elements adjacent to this edge or corner indicate a contact there. In that case, the normal direction is defined as the direction going from the contact point to the tool center and is no longer necessary perpendicular to any of the elements.

4.2 Equivalent nodal forces

The next step is to compute the nodal forces equivalent to three unitary forces (one normal force and two tangential forces in case of friction between the tool and the blank) at every potential contact point using the interpolation functions of the elements. These nodal forces will be related to the second contribution to the initial nodal accelerations, using equation (6), hence, to the position and velocity of the nodes at the end of the step, using equation (7). The summation of equations (5) and (7) gives then the nodal position and velocity at the end of the time step as a function of the intensity of the contact forces:

$$\begin{aligned} \underline{x_1} &= \underline{x_1^*} + \underline{\Delta x_1} \\ \underline{\dot{x}_1} &= \underline{\dot{x}_1^*} + \underline{\Delta\dot{x}_1} \end{aligned} \tag{8}$$

Finally, using the interpolation functions again, these are transformed back into quantities related to the contact points, i.e. the distance and relative velocity with respect to the tool. At this stage, the intensity of the contact forces and the type of contact (rolling, sliding or no contact) are still unknown.

4.3 Intensity of the contact forces

The following conditions are required at every contact point:

- For a rolling contact: zero distance, positive contact pressure and no relative velocity between the tool and the sheet metal;
- For a sliding contact: zero distance, positive contact pressure and friction forces proportional to the contact pressure, in agreement with Coulomb's law;
- If no contact: positive distance, zero contact pressure and zero friction forces.

Given an assumption on the type of contact, a system of equations linking the distances and relative velocities at the contact points to the intensities of the contact forces can be formulated. As this system only concerns a small number of forces (three for every potential contact point), its size is very limited. If, after solving the equations, some contact requirements are not satisfied, a small number of iterations might be needed in order to find the correct contact assumptions.

5 IMPLEMENTATION

This method has been programmed and integrated into the finite element code Lagamine. The results on a small academic simulation are promising as far as the computation time is concerned. Moreover, the oscillations in the force and displacement due to the discrete number of point where the contact was taken into account have been removed since the contact can now happen anywhere in the elements. Since the programming of this method is relatively new, further detailed comparisons need to be performed and will be published later.

6 CONCLUSIONS

In this article, the need for developing a new method for simulating the incremental forming process, and especially for taking the contact into account, has been emphasized. A solution to this problem, based on a dynamic explicit scheme, has been proposed and implemented in a finite element code. This method can model a moving contact anywhere on the element surface without the use of a penalty method. Instead, a first computation is made ignoring the contact forces. Then, the solution is corrected by adjusting the intensities of the contact forces in order to fulfill geometric conditions.

Further studies will be dedicated to the comparison of the accuracy of the new method as well as the reduction of computation time with respect to the classical approach.

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