Transfer Die System Timing and Parameter Optimization According to an Obstacle Map

by

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Abstract

For complex sheet metal parts, multiple stamping stages are needed in a sequence. In today's industry, intermediate parts are transferred between stages automatically by feeding as a strip (progressive die) or a blank (transfer die). Although progressive/transfer dies are highly automated, transfer system parameters need to be predefined. These parameters must ensure that the part is transferred to next stage quickly and safely. However, due to highly complex geometry and motion in the die system, these parameters are conventionally finalized manually according to designers' experience.

In this thesis, algorithms are proposed to optimize transfer system parameters in transfer die, according to the geometry and motion restrictions of the entire system. Two algorithms are proposed to complete a two-step optimization process.

In the first step, the geometry of the die set and parts are analyzed. Based on Siemens NX software and customized kinematic model, motions of die components are simulated, an "Obstacle Map" is generated to record the potential collisions between parts (and grippers) and die set during the part transfer process. Obstacle map can be regarded as an inherent property of the entire die system geometry, which can be utilized not only for the optimization algorithm proposed in the second step, but also for future research.

In the second step, with obstacle map, motions of the transfer system are analyzed. According to system motion capacity and freedom of modification in practice, transfer system parameters are optimized. The core of the algorithm in this step is to apply overlap between motions to reduce the transfer duration. Lift stroke and press stroke are also optimized when modifications are allowed. The optimized transfer system parameters result in improved strokes per minute, while all the obstacles in the obstacle map are bypassed.

One case study for a typical transfer die system with 14 initial SPM is performed to show the effectiveness of the proposed algorithms. Four levels of optimization are conducted with increasing freedom of modification: initial speed -> maximum speed -> allow lift stroke modification -> allow press stroke modification. The results show that the proposed algorithms are valid, SPM can be improved (22.9 -> 26.52 -> 26.61 -> 27.99) in different situations. Some topics can be further addressed based on the works in this thesis, future works can focus on algorithm expansion to progressive die, and algorithm improvements for more complex cases.

Preface

This research project is conducted with help from Longterm Technology Services Inc. (LTS). LTS provided working environment, market survey and other background support. The industrial facts, rules of thumb in industry in Chapter 3 and customized kinematic model in Chapter 4 were provided by LTS.

I developed the concepts in 4.3 for the analysis in this research. I'm also responsible for the algorithm and program development for Chapter 5 and Chapter 6. Raw information of the case study in Chapter 7 is provided by LTS, while I'm responsible for the analysis, optimization and result generation.

For the project, kinematic model utilization, namely the obstacle mapping process in Chapter 5, is tested under Siemens NX 10.0.3.5 software environment.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AHP	Analytic Hierarchy Process
API	Application Programming Interface
CAD	Computer Aided Design
DOD	Die Open Duration
FOD	Feed Only Duration
LFL	Lift-feed-lower process
LSA	Lower Scrap Area
LTS	Longterm Technology Services Inc
MAT	Medial Axis Transform
MCC	Minimum Clearance for Clamping
MCF	Minimum Clearance for Feeding
OBC	Open-back-close process
OEM	Original Equipment Manufacturer
PDW	Progressive Die Wizard
PLM	Product Lifecycle Management
SPM	Strokes per minute
USA	Upper Scrap Area

Acknowledgements

“Stepping out of comfort zone” is what the whole project was about, not only for designers and manufacturers in the industry, but also for myself. Leaving my hometown to Canada, transferring my program from course based to research based, travelling from Vancouver to London, Ontario for the research project, every step takes a lot of courage. Especially the last one, leaving the beautiful campus of UBC, the great city of Vancouver, friends and relatives caused a serious hesitation. The hesitation was all about the fear and anxiety of new situations, challenges, and possibilities of failure. These negative emotions shaded the positive side of the whole thing – irreplaceable experiences, self-improvement, and the opportunity of creating something really useful for the society – which I have all gained during the last several months.

I would like to offer my enduring gratitude to my supervisor, Professor Hsi-Yung Feng, who offered me the opportunity for this project, and moreover, the continuously encouraging and guidance throughout the project.

I would like to acknowledge my colleagues in LTS, A.Guo, F.Cheng, C.Gautam, S.Liu and B.Murphy, for their help to my research and my life in London, it was a wonderful experience to work with these intelligent and warm hearted persons.

I would like to thank Doctor Nagamune and Professor Sassani, for their attendance to my thesis defending.

Many people encouraged, and helped me to take the first step out, but I want to dedicate my special thanks to my parents. Your wise advices, firm support and eternal love was, and will be the decisive part of all the previous, present and future success in my life.

To My Parents

1 Introduction

1.1 Background

Sheet metal parts are everywhere in our daily life, they can be as small as a key, or as big as a vehicle frame. Stamping, as one of the major processing methods in sheet metal forming, is widely used in industry. Stamping die production line can produce at high speed with high product consistency. These advantages make stamping especially suitable for today's high demand and increasingly automated industry.

Because automotive industry is one of the most important aspects of mechanical engineering, the market of automotive component stamping is large. Nowadays, components like bumpers, doors, frames and body panels are all produced through stamping process. Essentially, there are thousands of stamped components on a car. According to market reports [1] [2], after the trough in 2009, the automotive industry is recovering quickly while pushing the business and technology to the next generation. It is predicted that automotive metal stamping market will worth over one hundred billion dollars by 2024. The reason behind such prediction is the rising demand and decreasing manufacturing costs.

However, apart from the positive outlook, the stamping industry is also facing serious challenges. Productivity and cost issues give huge pressure to manufacturers and push them to improve. Particularly, for vehicle components, it is common for products to have complex shapes, hence multiple stamping steps and multiple stamping machines are often needed in a sequence to make one product. Traditionally, human operators do the transfer work by hands, which result in low efficiency, labor cost and misfeeding, and sometimes even cause safety issues.

Progressive die and transfer die were developed to solve the above issue. A progressive die set uses coil metal in feeding, metal strip travel along the multiple stage production line. On each stage, the strip will be punched once and features will be added to the product, each stage will conduct a part of the work, and in the last stage, a final product will be cut from the strip. Therefore, part transfer between stages is conducted by the metal strip and feeder.

A transfer die set uses sheet metal stack (usually blanked from coil steel) in feeding, each piece of metal will end up as one product. Robotic arms and fingers are used to transfer

parts between stages, simply simulate the human operators' work, but in a faster and more accurate way. Transfer die can handle more complex features on the part, because parts are physically independent.

The concepts of progressive/transfer die are not new, but many manufacturers did not pay enough attention to them until they are facing such pressure in improving their technology today. Transformation from labor-intensive to knowledge-intensive industry has redefined stamping plants. With machine operation, productivity and consistency can be improved, labor costs and hazard can be reduced. For some of the most automated plants, workers only need to feed the raw material to the production line at the beginning of production, then they can just stand at the end of the line and pack products.

It is noted that progressive/transfer die also have their specific challenges. In order to transfer parts automatically, part design, die design and transfer system design need to fit such objective. For progressive die, since the part must be carried by the strip, additional strip width is needed to sit on the "slide way". Clearance between parts may also be more than necessary when the die cannot be made compact enough. For transfer die, although it can handle complex products in operation process, the transfer process is tricky. Since there is no "slide way" to assist the transfer process in transfer die, robotic arms and fingers in transfer die must be carefully designed, their motion must be carefully defined to ensure a smooth, safe and quick transfer process.

Geometry design and motion pattern in progressive/transfer die will greatly affect the productivity and cost, which are the key factors in automotive components stamping industry. New technologies focused on these factors have become the main drive of the improvement of this industry, and will continuously be highly demanded.

1.2 Motivations

Progressive/transfer dies are widely used in the industry, it is of great value to develop and apply new technologies in this area. As the market reports, cost and productivity are decisive factors in progressive/transfer die. Since the production of one progressive/transfer die system is huge, minor changes can result in large difference. For example, one percent more scrap area can cause large material waste, and one more product produced per minute can make a lot of profit.

Therefore, researchers should pay attention to the growing demand of new technologies in order to reduce cost and improve productivity. For cost side, research can be focused on lower cost materials, lower operation cost and less raw material. For productivity side, since progressive/transfer die already replaced human operators with machine transfer system, the transfer system efficiency will be a key factor for productivity.

As a quantitative indicator of productivity, strokes per minute (SPM) is the major concern in real cases. On the control panel of each press machine, there will be a place to set or view SPM (and/or cycle time which equals to 60s/SPM). SPM indicates how many products the production line can produce per minute. This vital factor, however, currently largely depends on engineers' experience. The reason is, in today's industry, division of designing and manufacturing work makes it difficult for any single person to have a good understanding of the whole die set. For progressive/transfer die, there are multiple stages, the scale of the whole system can be huge, it is almost impossible to have only one designer for all the stages. Hence the difficulty for progressive/transfer die review is significant. Conventionally, die review is done by using the exploded view. For each critical timing, a corresponded exploded view needs to be created, this process is time consuming and error-prone. However, even with these views, reviewers still need to imagine the interactions between components, not to mention if there is any modification in die design, the related process must repeat. Therefore, running strategy of progressive/transfer die can only be finalized by designers' experience if there is no tool to help analyzing the motion regarding the overall geometry of whole production line.

It is conceivable that there is a need for this kind of system, which can help designers or manufacturers to decide optimum SPM. In this thesis, motion analysis regarding part and die geometry will be conducted. For specific projects, the unique geometry property can be obtained and recorded, from which optimum SPM can be derived.

1.3 Objectives

It should be noted that SPM can be modified in multiple situations. Commonly, the design team decides SPM after die review. During the design stage, it is possible for designers to be given an expected SPM, so the die will be designed to meet the requirement, at this stage, not only SPM, but also the die design can be modified to suit each other. Even at the production stage, it is still possible to modify SPM by changing settings in the transfer

system after a few trial runs. At this stage, however, the die is already made and it is usually not suggested to change the design – counting the time to redesign and remanufacturing, the overall productivity can be even lower. In this case, only the transfer system parameters can be modified (e.g. timings, speeds).

Therefore, first of all, a system for progressive/transfer die SPM optimization should be able to recognize the die design and extract information from its geometry. Secondly, since the technical concerns mainly focus on the interactions between multiple moving components, the system must consider the motion characteristics of these components. Thirdly, the proposed system should be able to deal with different requirements for motion analysis, and provide multiple options regarding different cases in practice.

In this context, this thesis is dedicated to developing such a system that can do geometry and motion analysis for progressive/transfer die. The proposed system will be able to access the geometry of the die and product – most likely to be the CAD part/assembly file – and be able to extract necessary information. It will also be able to set or get motion parameters for progressive/transfer die, and optimize these parameters regarding different requirements. In order to conduct the above functions, the following works are necessary:

1. Develop a method that can analyze geometric information of progressive/transfer die system, it should contain a reliable kinematic model for transfer die. Progressive die can be considered as a simplified case of transfer die, so this will also solve the kinematic model for progressive die. Particularly, for a given motion strategy, the system should be able to simulate the movement and output required information.
2. Develop a method that can utilize the output information from the above method. With this information and other user inputs, calculate optimum transfer system parameters regarding the following factors: kinematic constraints (motion capacities, dwell time, etc.), mechanical constraints (collision etc.), and user intentions (freedom of modification, clearance etc.).

After the above optimization process, two constraints can be obtained. The first is about geometry: at which stage, which particular die/part geometry becomes the constraint of higher SPM. The second is about motion: when trying to speed up producing, which motion capacity will become the constraint of higher SPM. With these information, users will have a better understanding of their die project, and be able to make changes according to their freedom of modification.

1.4 Thesis Structure

The following of this thesis will be arranged as follows:

Apart from the introduction in Chapter 1, there will be one more chapter that reviews the previous studies in progressive/transfer die. The literature review in Chapter 2 will finalize the background knowledge of this thesis.

Then, the prerequisites of this thesis will be introduced. The basis of motion analysis in this thesis is the motion curves and die components, which will be introduced in Chapter 3. In Chapter 4, the kinematic model for progressive/transfer die will be presented, since the kinematic model is closely related to Siemens NX™ and DYNMIK DESIGN™ software, they will be introduced as well.

In Chapter 5, one of the core concepts of the proposed system – obstacle map – will be introduced. Plus, the mapping strategy and method will be addressed. With the obstacle map for a particular die set, optimization of transfer system can be conducted, the method for such optimization will be shown in Chapter 6.

In chapter 7, one case study will be presented to show how the proposed algorithms in this thesis can improve SPM for a transfer die project. Finally, in Chapter 8, contributions of this thesis will be discussed, plus, the observed or remaining issues will be presented, thus the topics for future research can be clarified.

Figure 1.1 shows the thesis structure as a flow chart.

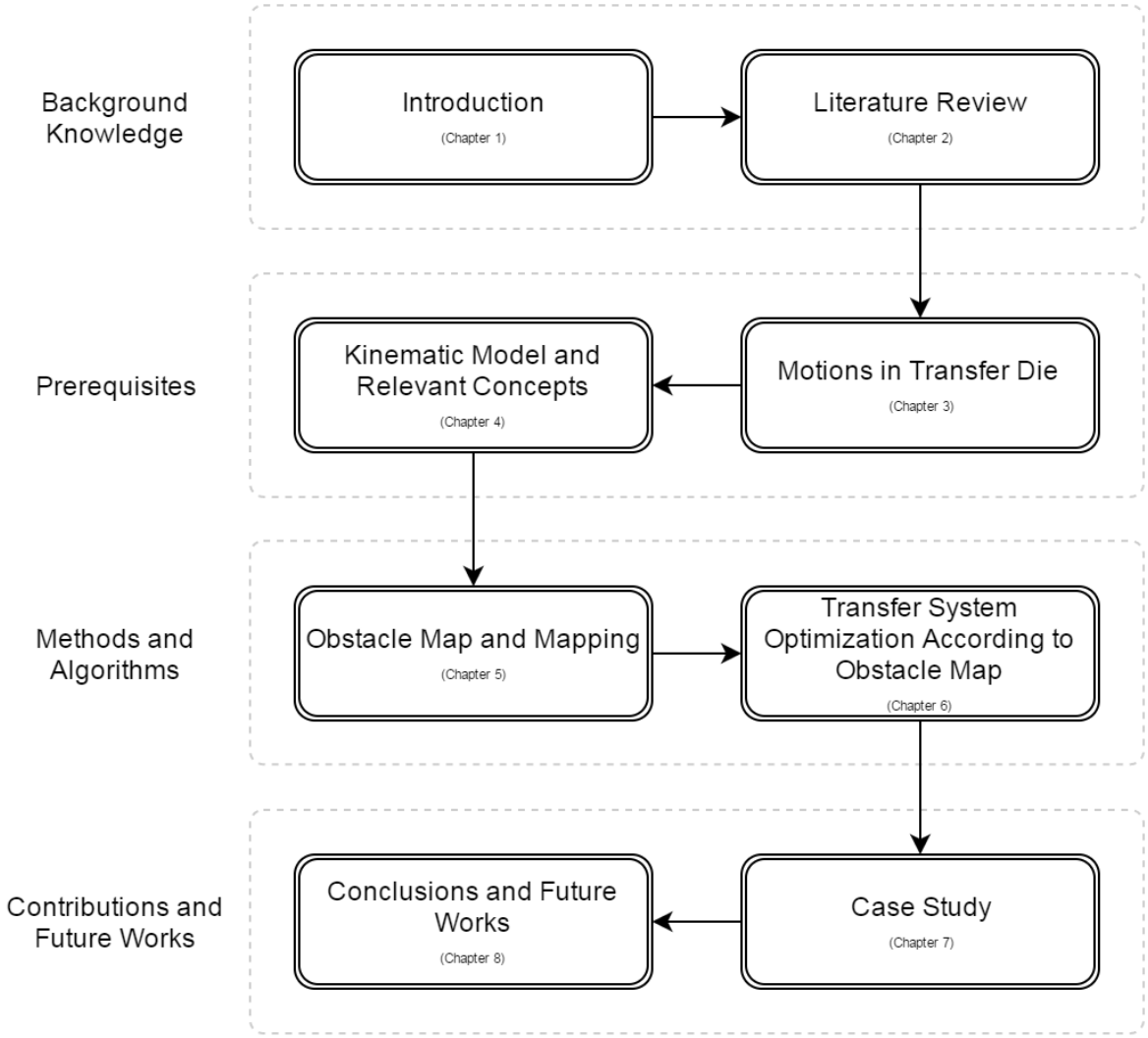


Figure 1.1: Thesis Structure

2 Literature Review

2.1 Reduce Cost and Improve Productivity

Sheet metal parts are widely used in our daily life, the geometry of sheet metal parts varies. Some very simple parts can be manufactured with just one punch, but for some complex parts, multiple stamping operations must be conducted.

Instead of several simple dies conducted on separate press machines, progressive die or transfer die combines these operations into one press machine with multiple stages. A progressive die system operates on a sheet metal strip along stages, while a transfer die system operates on several sheet metal blanks and transfer them between stages. Therefore, different stages of part production can be performed simultaneously within one punch. In the first station, the raw material (strip/blank) is sent into the production line, in the final station, completed parts are collected from the production line. This process enables high productivity and high product consistency.

However, the progressive/transfer die facilities are often complex and expensive. Reducing operation cost and increasing productivity are two reasonable ways to increase profit from a progressive/transfer die production line,

It was found that among operation costs, raw material cost dominates other costs [3]. The reason is that materials are fed as a metal strip in progressive die, or as blanks in transfer die. The material utilization strongly depends on the shape and orientation of unfolded part. For a given product model, unfolded blank shape can be obtained naturally, but blank orientation is changeable. To determine the optimum blank orientation, namely, blank layout, for maximize material utilization and minimize scrap, is important for cost reducing.

The productivity of a die set can be presented by strokes per minute (SPM). A cycle of one stroke can be subdivided into the following steps: die open -> stripper frees the blank -> blank move from the current station to the next station -> stripper holds the blank at the next station -> die close. It can be found that this process is simply moving the blank between two stages during the die open period, and from common sense, the time of this process is depended on distance and speed. Moreover, for progressive/transfer dies, the blank must be located at the exact position, so piloting system, as another factor, is essential. Distance between two stations is called pitch, this factor is related to blank orientation and product

design. Speed is a property of strip feeder in progressive die, or a property of the gripper driver in transfer die. And the piloting system, which is a part of die geometry, has a lot of interactions with blank layout design.

The remaining of this literature review will be focused on methods to reduce cycle time and improve productivity for progressive/transfer die. Cost reducing issue will also be addressed because some topics about improving productivity have already considered cost reducing issue. In section 2.2~2.4, literature reviews on “Blank/Strip layout”, “Piloting system” and “Kinematics” will be presented. In section 2.5, some other approaches will be discussed. Conclusions and comments will be given in 2.6.

2.2 Blank/Strip Layout

By unfolding a model of stamped metal part to a flat pattern, and nesting the pattern on the metal sheet, a blank layout can be generated. Then, operations can be identified and managed, the sequence planning can be generated and will result in a strip layout. Design of blank and strip layout is a highly experience-intensive task. Traditionally, they are conducted by experienced stamping engineers. During decades, researchers keep trying to simplify this task by developing tools to assist designers, or even automatically solve the task by simulating designers’ activities.

2.2.1 Blank Layout

Blank layout is directly related to the distance between stations. And it is one of the most important design tasks for material utilization. Because the flat pattern of a product usually contains complex 2D features, the previous works on blank layout tend to surround the flat pattern with a polygon, and try to find the optimum layout of the polygon.

Adamowicz, M et al. [4] can be considered as pioneers of this aspect. They packed the flat pattern to a minimum rectangle, and repeat the rectangle along the strip. The drawback of their method is obvious: a rectangle is far from the real contour of the flat pattern, and it will result in large material waste. Singh, R et al. [5] developed a system for 2D part blank layout modelling with low cost. Their nesting algorithm can generate more complex polygons. Venkata Rao et al. [6] proposed an analytic hierarchy process method (AHP) to compare different strip layouts. Five factors: material utilization, die cost, operation cost, production rate and job accuracy are

considered with relative weight factors. However, the above algorithms are still at the primary stage, while the orientation of blanks was not considered.

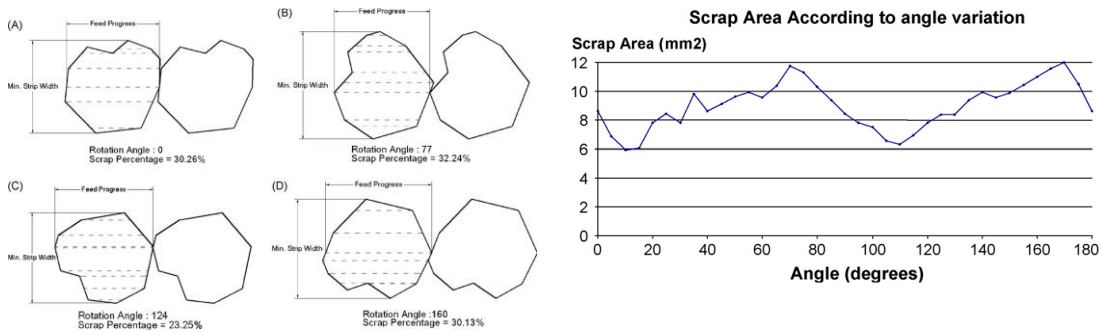


Figure 2.1: Rotate the sketch and find the angle that minimizes scrap area [7]

In order to determine the optimum blank orientation, Ghatrehnaby, M et al. [7] introduced a method which automates the nesting of different parts according to minimum scrap strategy. The method is also capable for selecting direct pilots (if there are any) or creating semi-direct or indirect pilots for the strip. In their method, the nesting part is done basically by rotating the sketch and detecting contact between current and next part (Figure 2.1), then find the angle that minimizes scrap area.

2.2.2 Operation Sequence Planning

After the blank layout is generated, the remaining task is to produce the part of the blank. There are a lot of available stamping operations in today's industry. Typically, these operations can be grouped into three categories: shearing, bending and forming [8]. Shearing is to separate the material using shearing force, this is the most common and necessary operation. Hole punching, blanking, trimming are all shearing operations. Bending is to generate local deformation along the bend line, which includes L-bend, U-bend and others according to the bending shape. Forming operation includes drawing, embossing and other operations that generate deformation on the entire punching area.

Sequence planning is of great importance in die design. First of all, the stampability must be considered, no collision is allowed. Secondly, some operations can be done in one station and some operations must be, or better to be conducted in a sequence. Balancing, accuracy, piloting, spring back etc. are also noticeable factors.

Lin, Z et al. [9] and Tumkor, S et al. [10] focused on unbalanced moments in progressive die. They proposed methods in sequence planning to reduce unbalanced moments. It is concluded by Lin, Z et al. [9] that it is better not to mix operations in different categories. Most shearing operations should be done consecutively, then bending and forming. Changing the sequence of categories is acceptable, for example, conduct forming first and then shearing and bending. But a mixed sequence, for example, shearing-bending-forming-shearing-bending… is not suggested.

Kumar, S et al. [11] developed a rule-based expert system approach of Artificial Intelligence for automation of strip-layout design. Chu, C. et al. [12] [13] developed a method for stamping operation sequencing by presenting two graphs, operation adjacency graph and operation precedence graph. Their method is based on feature tree, however, it has a couple of drawbacks. It is possible that a stamping process regard to design tree is not the best process in manufacturing, some separately designed features may actually be able to be combined into one station. The repeatedly revised model may also result in non-optimal feature tree.

Tor, S. B. et al. [14] tried another approach, case-based methods, to generate strip layout for progressive die. By retrieving similar and successful cases from case library, solutions for new case can be generated. A case-based reasoning system is faster than knowledge-based systems, and it can learn from past mistakes. However, for a case-based method, it is difficult to complete case library for all possible cases. In Tor, S. B's later work [15] [16] [17], hybrid systems and blackboard-based systems are developed. The blackboard system is like several specialists discussing the problem with one blackboard, everyone can modify data on the blackboard, and discussion may happen when "modify" event happens. Hence different methods can be combined (Figure 2.2).

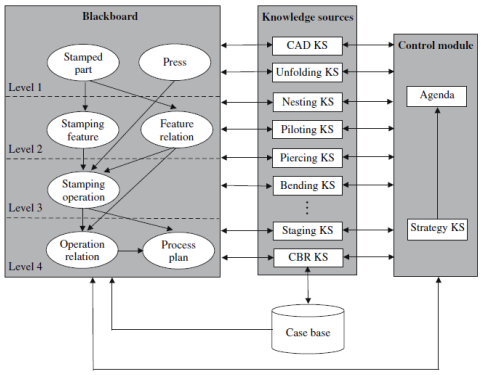


Figure 2.2: Blackboard architecture for stamping process planning [17]

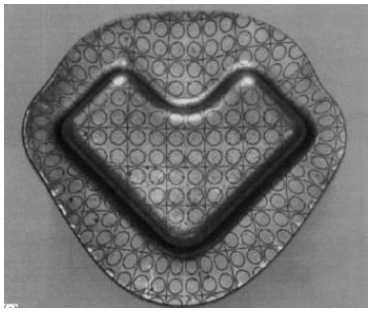


Figure 2.3: Photograph of L-shape cup drawing from a circular blank [18]

Forming process, especially the drawing process, is usually planned separately, because unlike shearing and bending, as shown in Figure 2.3, drawing process causes a large deformation on the whole blank. Some defects like wrinkling and necking must be avoided in drawing process. Effective factors for this process are studied by researchers, and it can be summarized that blank material [19], tool shape [20] [21], tool material [22] and blank holding force [20] [23] can affect the performance in drawing process. It is conceivable that many deep drawing products do not contain a lot of operations of other categories, because large deformation caused by drawing is harmful for other existing features.

2.2.3 Strip Layout

The result of blank layout and sequence planning is the strip layout. Figure 2.4 shows a typical strip layout for a product which contains shearing and bending operations. Blanking operations are conducted in the first few stations, and followed by bending operations. Some punches are combined to reduce the number of stations. And pilot holes are manufactured in the very first station. The piloting system will be discussed in section 2.3.

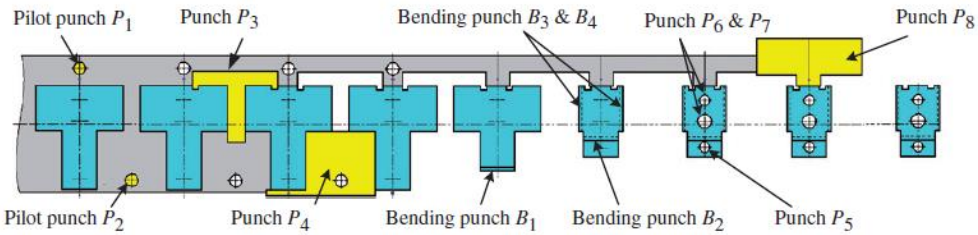


Figure 2.4: Strip layout of a typical progressive die product [8]

2.3 Piloting

Piloting system is important for progressive/transfer die. For multiple stations, strip/blank must be located in the right position accurately. This is vital for the quality of product. To achieve this, pilot holes are often needed.

Generally, there are three kinds of piloting in progressive dies – direct, indirect and semi-direct. Direct piloting is to directly use holes of product for piloting purpose. Indirect piloting is to create holes outside the blank area for piloting. And semi-direct piloting is to find a circular area in a non-circular hole of the part, create holes in the area for piloting, and finish the non-circular hole after piloting task is done (e.g. in the last station).

2.3.1 Pilot Hole Designing

Designing of piloting system is a relatively straightforward task, when the strip layout is well done, the scrap area should be limited, and there will not be too many options for indirect piloting. For direct or semi-direct piloting, the options are also limited because of the part geometry. Therefore, some researches on blank/strip layout have already taken piloting system into consideration. In Ghatrehnaby's method for blank layout [7], the piloting part is done by comparing all three strategies (direct, semi-direct, indirect piloting) and chooses the one which has the least scrap, if scrap amount is same, indirect piloting is preferred for reducing wear on the product. Kumar, S et al. [11] also considered piloting system in their system for strip layout design, but their method only considered direct piloting.

In order to obtain an accurate mathematical solution for pilot hole design, Ghatrehnaby, M et al. [24] developed a method based on medial axis transform (MAT) to design pilot holes automatically. The shape of part is described by its MAT and three types of pilot holes can be accurately calculated mathematically.

Figure 2.5 and Figure 2.6 shows how the MAT method designs indirect pilot holes. By applying MAT to upper and lower scrap area, their MAT presentation can be generated. Set a threshold of minimum pilot hole radius, then the valid part of MAT presentation can be obtained (Figure 2.6). Finally the centre of pilot holes is chosen to be the points with minimum Y value in upper scrap area (USA) and maximum Y value in lower scrap area (LSA), which will results in minimum increase in strip width.

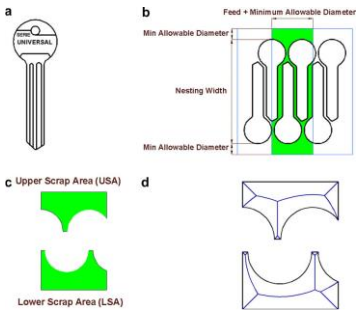


Figure 2.5: Determine MAT [24]

(a) An example workpiece.
(b) Nesting template.
(c) USA & LSA.
(d) Medial axis for USA & LSA

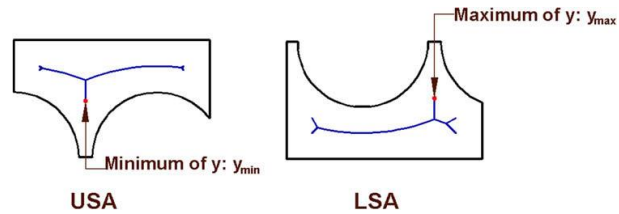


Figure 2.6: Solve pilot holes from MAT [24]

The points with minimum Y value in USA and maximum Y value in LSA results in minimum increase in strip width

A drawback of MAT method is the high requirement for the computer's geometrical ability. For some complex edges, the mathematical form of medial axis can be very complex and very difficult to solve. Moghaddam, M. J et al. [25] proposed another method for piloting system design. The highlight of this method is that features are translated into coordinates. Hence geometrical ability of modelling software is not the decisive factor, calculation time can be reduced. This method is limited by the size of the pixels and largest deviation will be one pixel length. Although the algorithm is easy to apply, decrease size of the pixels will increase the amount of calculation.

2.3.2 Pilot Hole Utilizing

High precision is the goal of piloting system, because feeding accuracy is directly related to the product quality. Vallance, R.R et al. [26] developed an analytical model to estimate the pitch distance between pilot holes, which considered potential errors in piloting system and piloting process. They concluded that errors may come from clearances between pilot pin and its related tools and holes, as well as errors generated when punching a new pilot hole.

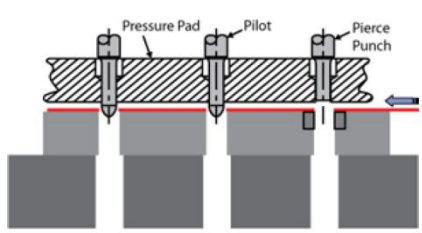


Figure 2.7: Proper feed release procedure [27]

In order to reduce cycle time and increase productivity, quickness of piloting system is equally important. Art Hedrick [27] studied the procedure in piloting system, when blank or strip is entering one station, the feeder must free the part before pilot pin enters the pilot hole. However, if feeder frees the part too early, it can pull the strip out of position. Art Hedrick then suggested a proper feed release procedure (Figure 2.7). The feed release must be timed so that the bullet nose of the pilot pin partially enters the pilot hole. Therefore, when the part is freed, the shift will not be out of control. By doing so, not only the piloting speed can increase, but also pilot pin wear can be reduced.

2.4 Kinematics

Some kinematic issues have been addressed in previous sections. For example, moment balancing of punch and die is related to strip layout design, feed release timing is related to pilot hole utilization. There are some other issues in progressive/transfer die kinematics, like stamping speed and strip/blank feeding rate, collision avoidance, motion characteristics and accuracy are also related to kinematics.

2.4.1 High-Speed Feeding and Stamping

Feed speed and stamping speed is directly related to productivity. For feed speed, Al Lochtefeld [28] illustrated several factors in high speed feeding such as grip force, coefficient of friction and inertia. However, although manufacturers can provide product lines with 1000-SPM servo-driven feeds or 2000-SPM cam-driven feeds, the operation speed is actually limited by stamping speed rather than feed speed.

For stamping speed, Osakada, K et al. [29] reviewed mechanical servo press technology. They showed that mechanical servo press combines the advantages of mechanical press (high speed, accuracy and reliability) and hydraulic press (flexibility, controllability), which has bright prospects in stamping industry.

2.4.2 Blank Holding and Collision Avoidance

Similar to strip feeding in progressive die, blank holding and blank transfer have a large effect on transfer die. Research on blank holder and collision avoidance in the transfer process are of great value to increase productivity and quality.

Yagami, T et al. [30] proposed an algorithm to control the blank holder motion and blank holding force to reduce wrinkling in deep drawing. Ming-Chang Yang [31] introduced a modified design for barrel cam in transfer die which can reduce impact force during transfer and increase transfer speed. These works on blank holder have common defects that they only work for one particular task or specific parts.

There are multiple ways to avoid collision. Firstly, increasing accuracy of feeding system can be one way because a lot of collisions are due to misfeeding. Advanced piloting system and strip design (e.g. pitch notch) can be beneficial. The second approach is to install sensors. Kate Bachman [32] showed that by introducing four sensors (misfeed sensor, overfeed sensor, part-exit sensor and stripper sensor), the possibility of die crash can be greatly reduced (from twice a week to every six months). However, it is conceivable that this method is costly.

The third way, which is increasingly important in today's industry, is to simulate the processes virtually. Uncovering potential collisions before production starts can save a lot of work and retooling cost, and reduce downtime [33]. This opens the topic of motion simulation, which is also the main topic of this thesis.

2.4.3 Motion Simulation

Simulating the stamping process virtually has become very useful in practice. In today's industry, Computer Aided Design is widely used, all the design features are stored in part and assembly files. With Product Lifecycle Management (PLM) software, stamping process simulation can be conducted right after the designing. Designers can see how the components will move and interact, they can also analyze the interactions using the powerful tools provided by the software. This method is becoming increasingly preferred in today's industry.

2.4.4 Cam Motion

As the previous contents addressed, there are multiple ways to achieve required motions in press machine. However, although hydraulic or servo press can achieve high speed or stability, there motion curves are still following the traditional cam motion. After all, press machine is moving up and down in one dimension, so theoretically its motion can be simply described by the motion of a cam follower. And the characteristics of its motion can be solved mathematically.

For analyzing cam motion characteristics, SVAJ diagram is often used. While S is the displacement, V, A and J are first to third derivative. So V is velocity, A is acceleration, and J is jerk. A typical SVAJ diagram of a Uniform Motion cam is shown in Figure 2.8.

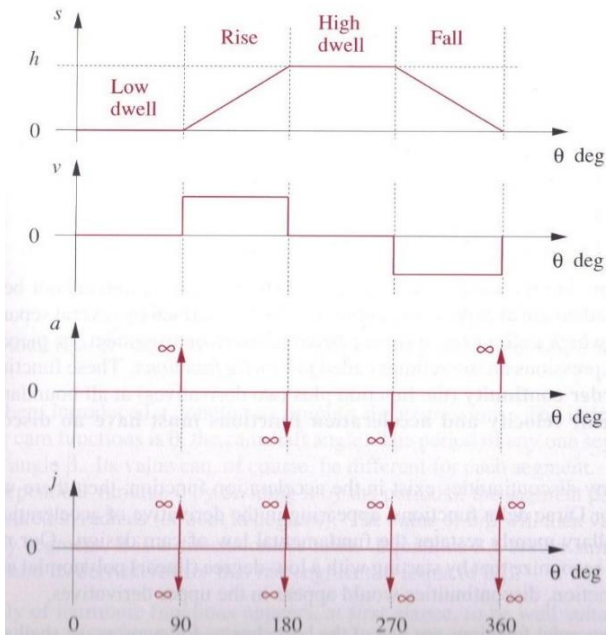


Figure 2.8: SVAJ Diagram of Uniform Motion [34]

It is very straightforward that SVAJ diagram can show that uniform motion is not a good cam design. Velocity has discontinuities, acceleration and jerk have infinite value at certain degrees. Hence, this design is rarely used in reality. There are several existing cam motions which have better properties. They are shown in Figure 2.9.

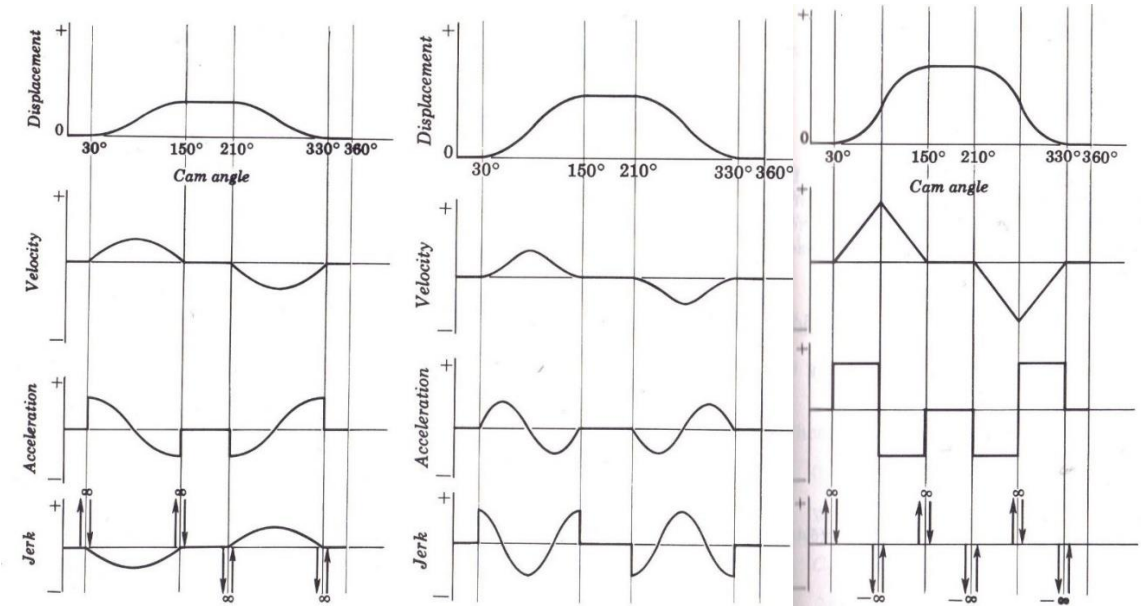


Figure 2.9: SVAJ Diagram of Simple Harmonic (left), Cycloidal (middle) and Parabolic (right) Cam Motion [35]

Norton, Robert L. [34] summarized previous studies and experimental results in cam motion, then stated that a good cam function must be continuous in SVA diagram, and hence must be finite in Jerk diagram. Waldron, Kenneth J. [36] also notes that an infinite jerk should be prevented because it can cause vibrations in the system. Based on the above rule, according to Figure 2.9, Simple Harmonic motion ($s = \frac{h}{2} - \frac{h}{2} \times \cos(\theta)$) and Parabolic motion ($s = C\theta^2$) causes infinite jerk so they are not acceptable. Cycloidal motion ($s = h\left(\frac{\theta}{\alpha}\right) - (\frac{h}{2\pi})\sin(\frac{2\pi\theta}{\alpha})$) is considered to be an acceptable design.

There are some other good cam motions that fulfill the above rules, like Modified Trapezoidal, Modified Sine, but the one which is more often used in today's industry is Polynomial Motion ($s = C_0 + C_1x + C_2x^2 + C_3x^3 + C_4x^4 + \cdots + C_nx^n$). It can be found from its equation that polynomial motion has several advantages. The coefficients are easy to solve from given boundary conditions, meanwhile, from given coefficients, it is easy to calculate the derivatives. Hence a polynomial curve is more versatile to handle even stricter rules for the motion. A 5-order polynomial motion can have a continuous SVA diagram and finite Jerk diagram. Moreover, a 7-order polynomial motion can even have a continuous Jerk diagram.

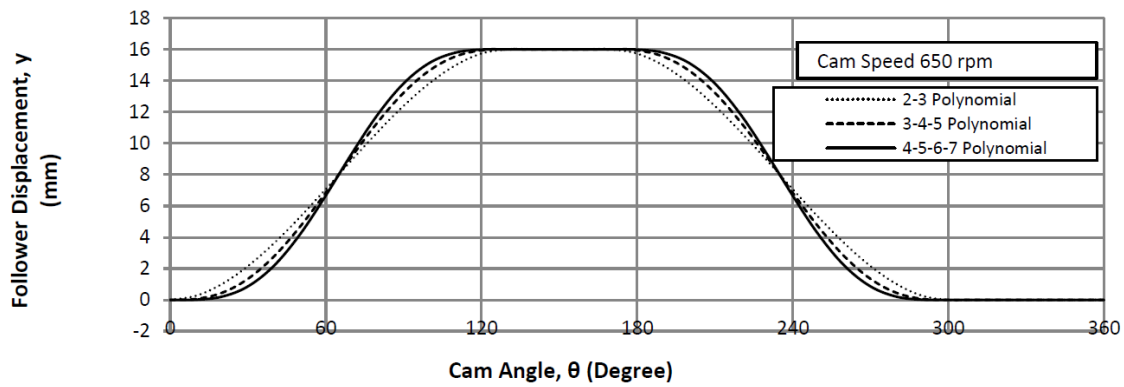


Figure 2.10: Follower motion for various polynomial cam profiles [37]

Kiran et al. [37] studied multiple polynomial cam profiles from 3-order to 7-order. And concluded that 2-3 polynomial cam profile show discontinuous in acceleration. 4-5-6-7 polynomial cam profile have smooth jerk property, but the opening period becomes smaller and peak velocity is higher, which means the kinetic energy consumption is higher. 3-4-5 polynomial curve shows good SVAJ property and shows an overall advantage among other polynomial curves.

2.5 Other Approaches

The material of punch, die and blank is also a noticeable factor. Kumar, S et al. [38] proposed a system which can give expert advice on material selection for progressive die components, but they didn't consider stamping speed. When punch speed becomes higher, oscillation problem becomes more severe. Hirsch, M et al. [39] tried two light metals (Al, Mg) instead of steel, as plate materials. The experimental result shows that light metal can reduce the effect of oscillation. But they didn't show the durability of light metal which is doubted. Hot stamping has been a popular research topic recently. By heating to Austenite, steel will have better formability, and by forming and quenching to Martensite, the product will have ultra-high strength. This technology has very good prospects. But the existing heating methods are not able to ensure heating speed and homogeneity at same time [40].

2.6 Comments

As the above literature review shows, sheet metal forming has become an important manufacturing process in many aspects. Progressive/transfer die, as highly automated systems, has been increasingly popular in today's industry. However, progressive/transfer die facilities are often complex and expensive, operation cost is also a major issue. Therefore, manufacturers are keen to make more profit from their progressive/transfer die production line by reducing operation cost and increasing productivity.

Researchers have been trying to boost progressive/transfer die industry for decades. Many research has been done in improving blank/strip layout, so the material cost (scrap area) can be reduced. Moreover, a good blank layout will lead to better operation sequence planning. By dividing operations into different categories, and arrange them regarding to several factors (knowledge, experience, user intention, etc.), the optimum operation sequence can be generated.

Piloting system will largely affect the product quality, and must be carefully designed. Direct piloting is to directly use holes of product for piloting purpose, this is easy to design but has the largest impact on product. Indirect piloting is to create holes outside the blank area for piloting, thus the impact product is minimized, but it may result in an additional scrap area. Semi-direct piloting is to create temporary holes in the area for piloting, and finish the non-circular hole after piloting task is done, it is very limited in use because of high requirements for the product geometry.

Some of the above issues have already taken kinematic issue into consideration. Yet there are still other issues within this category. In current industry, with the popularization of CAD software, designers can show their design in 3D and simulate the motions virtually. This raises the possibility to observe a "bad" design and fix problems before the die is manufactured.

It can be found that most research on progressive/transfer die are focused on progressive die. However, transfer die is more often used in today's vehicle component manufacturing because in this area the product geometry is more complex, and scrap area is more difficult to control. Researches on transfer die is very limited.

Plus, the majority of current research is focused on designing stage, the application or manufacturing stage, however, has not drawn enough attention among researchers.

Researches on kinematics issue are highly scattered. Even professional CAD software does not provide detailed solutions.

Lack of linkage between academic research and manufacturers is one of the reasons for this situation. In manufacturing stage, there are many case specific issues, many of them are resolved manufacturers themselves and the solution was not shared. However, in many cases, the methods they are using to solve problems are still based on experience, or simply sacrificing efficiency for safety.

For example, in vehicle component industry, decision for SPM currently is largely depended on engineers' experience, or tables from OEM – while the data in tables are from OEM's engineers' experience. None of them can generate optimum SPM for specific projects based on a convincible analysis of the projects. While SPM is such an important parameter in progressive/transfer die manufacturing stage, which can directly affect the productivity and hence the profit, there is a need for this kind of system, which can automatically calculate SPM and optimize it for specific projects.

In this thesis, the above desired system will be proposed. With motion analysis based on part/die geometry, the optimum system timing and parameters for specific projects can be obtained. These optimum settings can give maximum SPM without collision according to the factors considered in this thesis. The proposed system will be focused on transfer die, however, it can be easily expanded to progressive die.

3 Motions in Transfer Die

The concept “motion curve” in this thesis is the distance-time (s-t) graph of transfer die components. The term “distance” can be replaced as other equivalent terms like “height” or “stroke”. The term “time” can also be replaced as “degree” in some situations. It should be noted that this concept should not be confused with another concept “motion profile”, which means the actual trace that a component move along.

3.1 Motion Curve Assumption

As previously introduced, there are multiple acceptable cam motions for the stamping industry. According to SVAJ diagram, both cycloidal and polynomial motions have second order continuity (velocity and acceleration), and finite third order (jerk). Essentially, a 345 polynomial curve looks very similar to the cycloidal curve [34]. Therefore, in industry, the press and transfer system are usually tailored to have these kinds of motion curves.

Comparing to cycloidal curve ($s = h\left(\frac{\theta}{\alpha}\right) - (\frac{h}{2\pi})\sin(\frac{2\pi\theta}{\alpha})$), polynomial curve ($s = C_0 + C_1x + C_2x^2 + C_3x^3 + C_4x^4 + \cdots + C_nx^n$) is more versatile to handle different boundary conditions. Plus, the mathematical analysis of polynomial curve will be easier than cycloidal curve.

As a company who provides technical support for a wide range of progressive/transfer die manufacturers, Longterm Technology Services (LTS) Inc., has also adopted 345 polynomial curve in their commercial software for progressive/transfer die motion simulation. The feedbacks from LTS’s customers show that 345 polynomial curve reflects the actual motion curves accurately.

Therefore, in this project, 345 polynomial curve is assumed to be the motion curve for transfer die components.

It should be noted that although the above assumption is made, the algorithms proposed in this thesis can be applied not only with 345 polynomial curve, but also with other motion curves in industry. For the proposed algorithms, calculations will regard to properties of 345 polynomial curve, however, with the same idea, it is easy to expand to other motion curves like 4567 polynomial curve or cycloidal curve. In further developments, it is even possible to analyze motion with mixed motion curves (e.g. 345 for advance, cycloidal for return). This topic will be further discussed in Chapter 8.

3.2 Properties of 345 Polynomial Curve

It is given [34] [35] [36] that the basic equation of 345 polynomial curve is:

$$y = 10x^3 - 15x^4 + 6x^5 \quad \textbf{(1)}$$

The parameters of the above equation give several useful properties for 345 polynomial curve. These properties will be regularly used in later parts of this thesis. The SVAJ diagram of the above curve is shown in Figure 3.1.

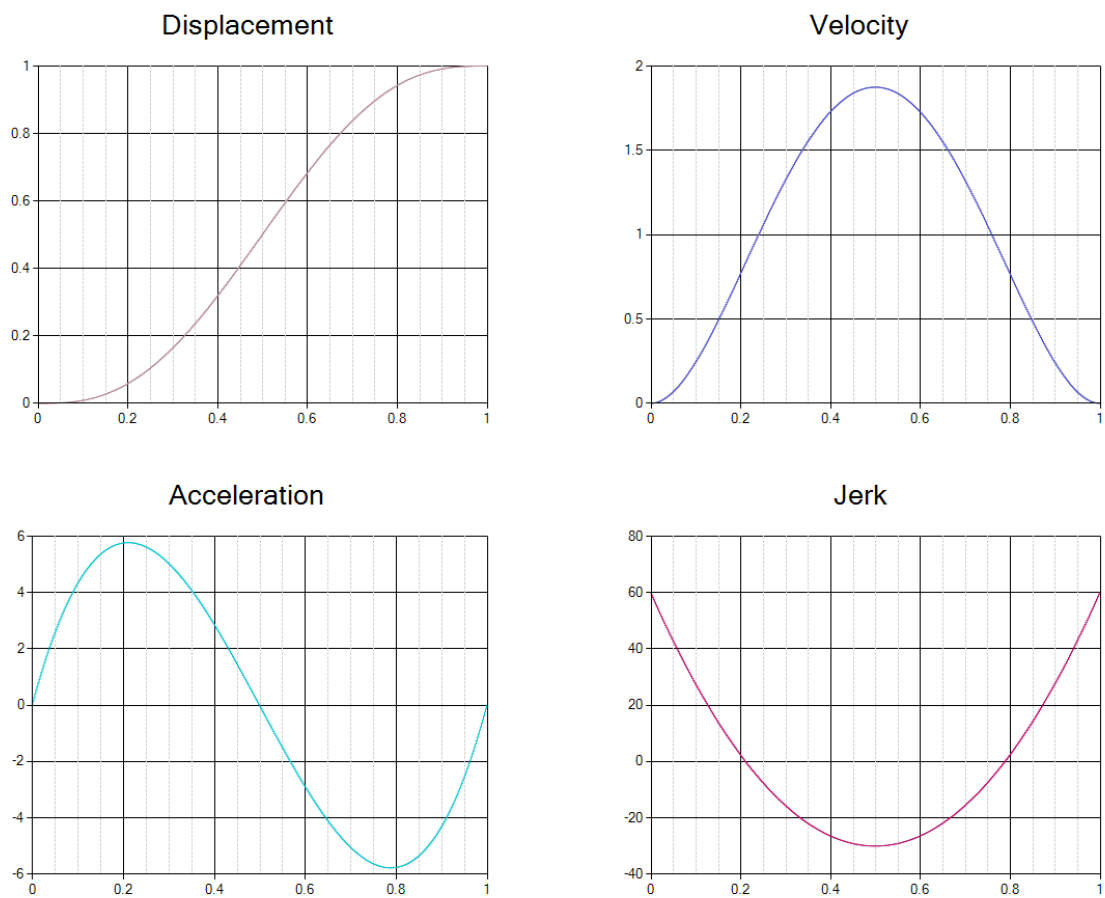


Figure 3.1: SVAJ Diagram 345 polynomial curve

From SVAJ diagram and its equation, the following properties of 345 polynomial curve can be observed:

①. When x increase from 0 to 1, displacement monotonically increasing from 0 to 1.

This property makes the original curve a unit size. For any curve derived from 345 polynomial curve, the shape of the curve will be simply stretching the original one by

adding parameters to x and y. For example, a top shoe rise from 0 to 150 mm in 0 to 180 degree, using 345 polynomial curve, the equation will be:

$$\frac{y}{150} = 10(\frac{x}{180})^3 - 15(\frac{x}{180})^4 + 6(\frac{x}{180})^5 \quad \textbf{(2)}$$

Moreover, given any duration (t) and height (h), the equation will be:

$$y = h \times \left[10\left(\frac{x}{t}\right)^3 - 15\left(\frac{x}{t}\right)^4 + 6\left(\frac{x}{t}\right)^5\right] \quad \textbf{(3)}$$

Because the curve is monotonically increasing, there is one to one correspondence between x and y, thus gives the possibility to make a lookup table for both x to y and y to x. This is particularly important for 345 polynomial curve and the algorithms in this thesis. In later parts of this thesis, solving x from y will be a regular task, but generally a 5-order function is unsolvable, therefore, a lookup table is created to conduct the solving task.

②. Position and value of peak velocity and acceleration can be easily calculated.

One of the advantages of 345 polynomial curve is the smooth start and end. The velocity and acceleration diagram both start from zero and end with zero, gives no immediate force at begin and end of the motion.

The position and value of maximum velocity and acceleration can be easily calculated. Equations of velocity and acceleration are:

$$v = y' = 30x^2 - 60x^3 + 30x^4 \quad \textbf{(4)}$$

$$a = y'' = 60x - 180x^2 + 120x^3 \quad \textbf{(5)}$$

Moreover, given any time duration (t) and height (h), the equations will be:

$$v = \left[30\left(\frac{x}{t}\right)^2 - 60\left(\frac{x}{t}\right)^3 + 30\left(\frac{x}{t}\right)^4\right] \times \frac{1}{t} \times h \quad \textbf{(6)}$$

$$a = \left[60\left(\frac{x}{t}\right)^1 - 180\left(\frac{x}{t}\right)^2 + 120\left(\frac{x}{t}\right)^3\right] \times \left(\frac{1}{t}\right)^2 \times h \quad \textbf{(7)}$$

The above equations can be easily solved, the result is:

	Timing	Value
Peak Velocity	$x_{maxv} = \frac{t}{2}$	$maxv = \frac{15h}{8t}$
Peak Acceleration	$x_{maxa} = \left(\frac{1}{2} \pm \frac{\sqrt{3}}{6}\right) t$	$\lvert maxa \rvert = \frac{10\sqrt{3}h}{3t^2}$

Note: t is the total time, h is the travel distance

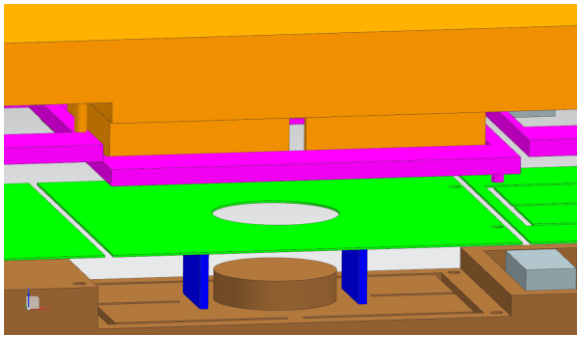
Table 3.1: Peak velocity and acceleration of 345 polynomial motion

It can be found that the peak velocity and acceleration occur at certain position along the total time, plus, the value of peak velocity and acceleration can be presented by total distance and total time. This gives the possibility to solve any of these elements from a given set of other elements. For example, from a given maximum velocity, and given distance, the time required will be: $t = \frac{15h}{8 \times maxv}$

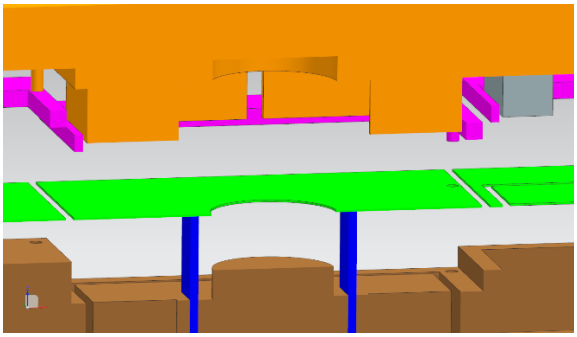
3.3 Component Classification and Motion Priorities

It is assumed in 3.1 that the moving components in progressive/transfer die system all follow 345 polynomial curve. These components can be divided into several categories, each category has its own rules of motion.

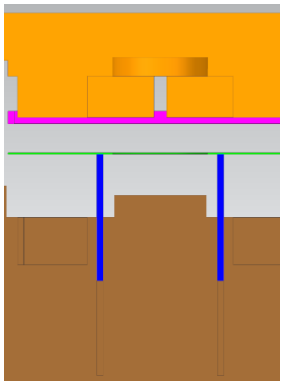
For example, at each stage, the part must be lifted to a certain height for the grippers to pick it up, the component which lifts the part is the lifter. Meanwhile, stripper, which is mounted on the top shoe is used to keep the part at the required position during die close, it is also responsible for some of the stamping operations. When die is closing, both stripper and lifter will finally be compressed, but the lifter will be compressed prior to the stripper. This is one of the many motion rules in transfer die.



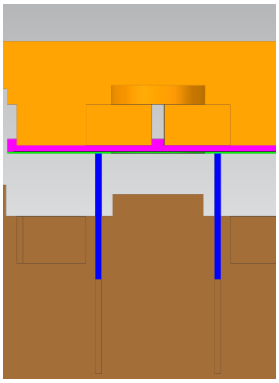
a: Sample die stage



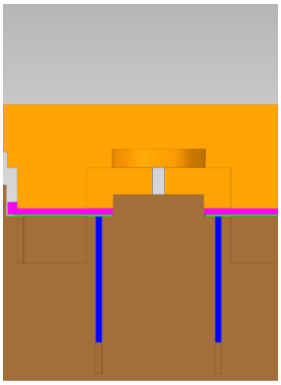
b: Sample die stage section view



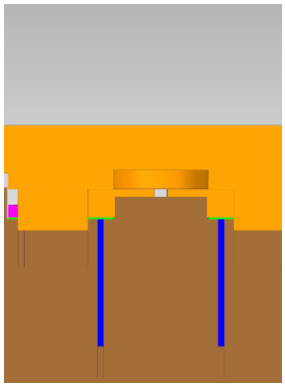
c1: Die open position



c2: Stripper touches part



c3: Lifter will be pushed down firstly



c4: Die close position

Figure 3.2: Component interaction from die open to die close

Figure 3.2 shows a sample transfer die stage with typical components – top shoe (orange), lower shoe (brown), stripper (pink), lifter (blue) and part (green). The process from die open to die close reflects the priority of motion.

4 Kinematic Model and Relevant Concepts

As the previous chapter introduced, the motions of components in progressive/transfer die follows specific rules. In order to conduct motion analysis, it is necessary to have a reliable kinematic model which implements these rules.

4.1 NX Progressive Die Wizard Tooling Validation

NX (UG) is the core of Siemens PLM Software. It has the application Progressive Die Wizard (PDW). With the Tooling Validation application, the basic motion simulation and analysis for progressive die can be conducted. As literature review in Chapter 2 has introduced, the developments can be focused on the following topics:

1. Transfer die kinematic model. Because most of car component stamping die industry are using transfer die.

2. Increase category of components for more advanced die systems.

3. Increase number of components for more complex die systems.

4.2 DYNMIK Design for Die

For the topics addressed in 4.1, *DYNMIK Design*™ has been developed by Longterm Technology Services (LTS) Inc.

4.2.1 DYNMIK Kinematic Model

DYNMIK integrates both the kinematic model and control data calculation. With part/assembly file of progressive/transfer die, the kinematic model can be applied and control data can be generated from DYNMIK algorithms according to 345 polynomial motion curve and component motion rules introduced in Chapter 3. Then, the motion simulation can be conducted.

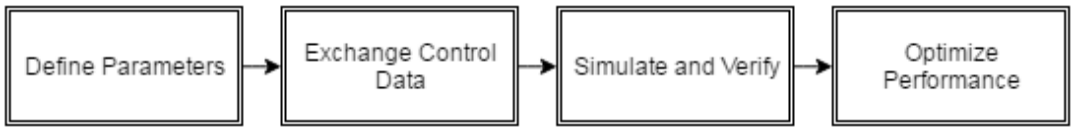


Figure 4.1: DYNMIK Workflow

Figure 4.1 shows the flow chart of DYNMIK.

4.2.2 Basic SPM Calculation Module

There is a basic SPM analysis module in DYNMIK. Users are required to input the system parameters into the software, as well as motion capacities. The software then will calculate the maximum velocity, acceleration for top shoe and each gripper. For SPM analysis, it will add SPM from 1, and see at what SPM value the maximum velocity or acceleration excess the limit.

The above method is undeveloped, it does not require any information from NX, which means it does not refer to die geometry. This can also be observed from Figure 4.1 – all the geometry information is stored in NX, but there is no flow coming from NX and end at DYNMIK.

The above contents indicates that the current DYNMIK software cannot provide motion analysis for specific progressive/transfer die systems because of its inability to access the geometry information. As a result of this fact, the SPM analysis module is fairly immature.

In later parts of this thesis, a method “Obstacle Mapping” will be proposed to extract geometry information of die assembly. Then the “Transfer System Optimization According to Obstacle Map” algorithm will be proposed to replace the previous SPM analysis method. However, before entering these two topics, some relevant concepts need to be clarified. Some of these concepts are used in progressive/transfer die industry daily, some are created for this research and will be used regularly in this thesis. So it is necessary to introduce these terms firstly.

4.3 Relevant Concepts

4.3.1 Progressive/transfer Die System Parameters

Some concepts, like press stroke, lifter travel, are commonly used in progressive/transfer die industry. Plus, usually the die designer will align the feeding direction x-axis and lift up direction as z-axis.

There are some other parameters which are commonly concerned by manufacturers:

Motion capacity: This is the maximum motion that one component can achieve during the whole cycle. It contains the limit of velocity and acceleration, sometimes

jerk is also considered. This term usually applies to self-driven components in die assembly, namely the top shoe and gripper.

Cycle time: Time for one stroke, which means the time needed for top shoe to start from die open position (press stroke), lower down to die close position, and return to die open position.

SPM: Strokes Per Minute, equals to 60s/Cycle time.

Gripper timings: In industry, one cycle is divided into 360 degrees. Die open is 0 or 360, die close is 180. All the event timings are presented as start/end angles. For transfer die, the transfer system has x, y and z-axis motion, each axis has an advance and a return motion, and each motion has a start and end angle, thus there are 3x2x2=12 critical timings.

4.3.2 Clearances

The following concepts will be regularly used in later parts of this thesis.

- **Clearance**: The concept “clearance” itself need to be clarified. As progressive/transfer die has multiple stages, each stage has their own lifter/stripper, and each lifter/stripper has their own travel distance (zero if the stage has no such component). So, when die is open, the clearance between lifter and stripper are different from stage to stage.

  The term “clearance” in this thesis is the minimum clearance among these stages. In practice, it is the stage with the largest sum of “lifter travel” and “stripper travel”. In later analysis, “stripper” and “lifter” will also be the component of this stage.

  By doing so, when clearance is not zero, it means at all the stages, strippers are detached from parts, all strippers and lifters are fully extended.

- **Minimum clearance for feeding (MCF)**: This is the minimum clearance between stripper and part, which allows the part to be safely fed.

  For example, assume a transfer die system at 320 degree, top shoe is at 250 mm height and is still moving up (say press stroke is 300 mm so at 360 degree it will reach 300 mm). Stripper travel is 50 mm so stripper is at 200 height at this angle. And part is already picked up by the gripper, which is at 120 mm height.

Although there is an 80 mm clearance between top shoe and part, assume there is a 40 mm pin on top shoe, and a 50 mm bending feature on the part, as Figure 4.2 shows, it may still result in collision when feeding. 80 mm clearance is not safe, 90 mm probably works for this example, so MCF should be 90 mm.

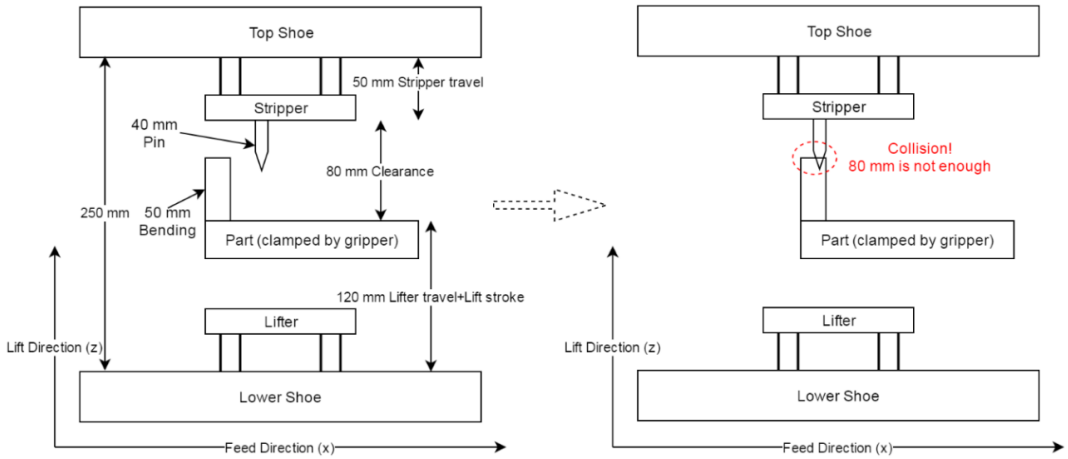


Figure 4.2: Minimum Clearance for Feeding (MCF)

- **Minimum clearance for clamping (MCC) and Danger Zone:** Similar to MCF, when gripper is moving along y-axis to clamp the part, it also needs to consider collision issues since gripper also has thickness and geometry.

  Use the same example for MCF, assume the system at 290 degree, top shoe is at 180 mm and is still moving up, with 50 mm lift height and 30 mm part thickness, it has a 50 mm clearance between part and stripper. However, as Figure 4.3 shows, since gripper has thickness, it will still result in collision if gripper clamp the part at this moment. So 50 mm is not safe, 60 mm MCC probably will be just enough for this example.

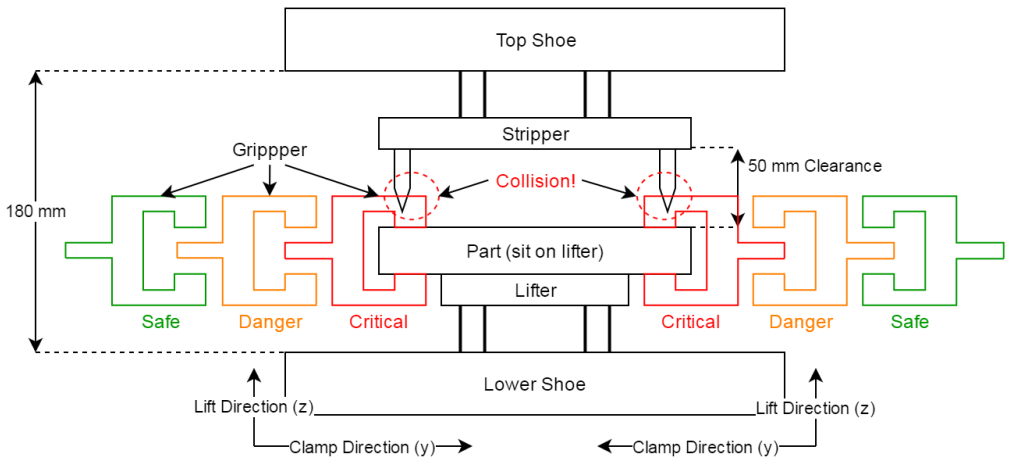
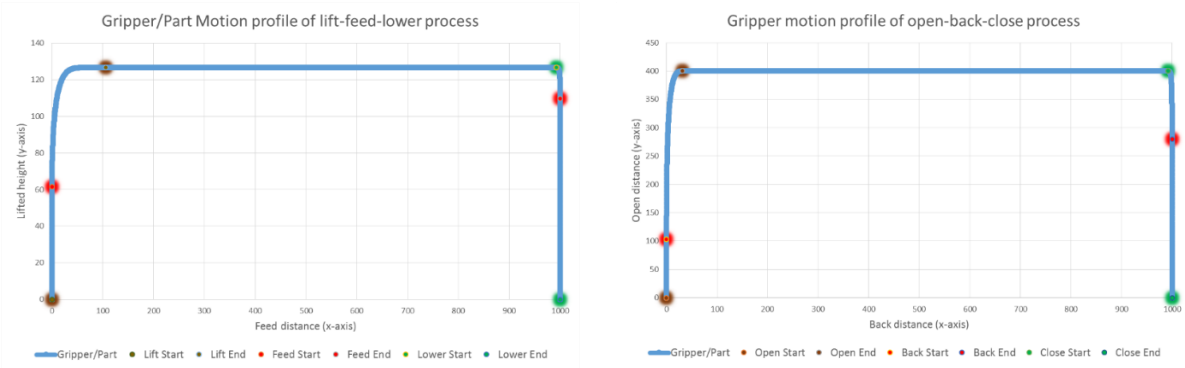


Figure 4.3: Minimum Clearance for Clamping (MCC) and Danger Zone

It should be noted that although it is unacceptable for the gripper to pick the part at this moment, it does not mean the gripper cannot move. While gripper is moving along y-axis, it may collide with other components, but the degree of danger varies. The closer gripper move towards the part, the more danger it faces. Therefore, MCC only valid when gripper is in the danger zone, and the length of danger zone is also an important parameter.

4.3.3 Motion Profile, Overlap and Overlap Percentage

With moving distance and start/end timings, the motion of a transfer system can be fully defined. Hence the motion profiles of components are able to be created. In these motion profiles, the motion profiles of gripper/part are most important ones.



a: Lift-feed-lower (x-z plane) b: Open-back-close (x-y plane)

Figure 4.4: Transfer die gripper motion profile

Figure 4.4 shows a typical gripper motion profile of a transfer die system. During die open period, gripper will **close** in to clamp the part, and **lift** it up from lower die or lifter, then **feed** the part to the next stage and **lower** down, and finally **open** to escape from the danger zone. During die close, gripper will **back** to the previous stage for the next pick up event. So the cycle of a gripper will be …-close-lift-feed-lower-open-back-close-…

In later part of this thesis, "lift-feed-lower process" can be called **LFL**, and "open-back-close process" can be called **OBC**. In practice, there is also another set of terms – advance move and return move – for all the three axis motions (see Table 4.1).

	Advance Move	Return Move
x	Feed	Back
y	Open	Close
z	Lift	Lower

Table 4.1: Term "Advance Move" and "Return Move"

In 4.3.1, it was introduced that there are 12 gripper timings, in Figure 4.4, these timings are also shown. It can be found that these timings do not have to follow the sequence of events strictly, for example, feed event can start before lift event ends, lower event can start before feed event ends. This is called **Overlap**, which means the duration of two consecutive events partially overlap each other. In later parts of this thesis, the portion of a y or z-axis event being overlapped by an x-axis event will be called "**Overlap Percentage**". For example, if lift event is from 0~2s, feed event is from 1~4s, lower event is from 3.5~5.5s, then the lift-feed overlap percentage is:

$$\frac{t_{lift\_end} - t_{feed\_start}}{t_{lift\_end} - t_{lift\_start}} \times 100\% = \frac{2-1}{2-0} \times 100\% = 50\%$$

Feed-lower overlap percentage is:

$$\frac{t_{feed\_end} - t_{lower\_start}}{t_{lower\_end} - t_{lower\_start}} \times 100\% = \frac{4-3.5}{5.5-3.5} \times 100\% = 25\%$$

It is conceivable that overlap is the reason that the motion profile appears to be a curve, not straight lines with sharp corner. The curved connection between mutually perpendicular linear motions also results in smoother direction change and hence

better kinematic performance. Plus, the more motion overlapped, the more total transfer time can be saved.

Although from above contents it appears that the more overlap the better, there should be limits for the increment of overlap percentage. From Figure 4.4 (a), it can be found that more overlap in lift motion means not only a smoother change in moving direction, but also earlier feed start timing.

However, whether it is safe to start feeding as early as Figure 4.4 (a) shows, is a question. Consider a pilot pin at the beginning, if the gripper starts feeding before it lifts the part high enough (i.e. free from pilot pin), the pilot pin will obstruct the feeding motion. Such obstruction will cause sudden stuck to transfer system, large stress to pilot pin and part, or simply say, damage to the die system.

In order to avoid the obstruction, the existence of the pilot pin must be recognized before creating the motion profile. More generally say, not only the pilot pin, but also all the die geometry that may cause collision during transfer must be recognized. In the next chapter, this will be achieved by the process called “Obstacle Mapping”, and the outcome “Obstacle Map” will be the basis of further analysis in this thesis.

4.3.4 Motion Curve Chart and Clearance Curve Chart

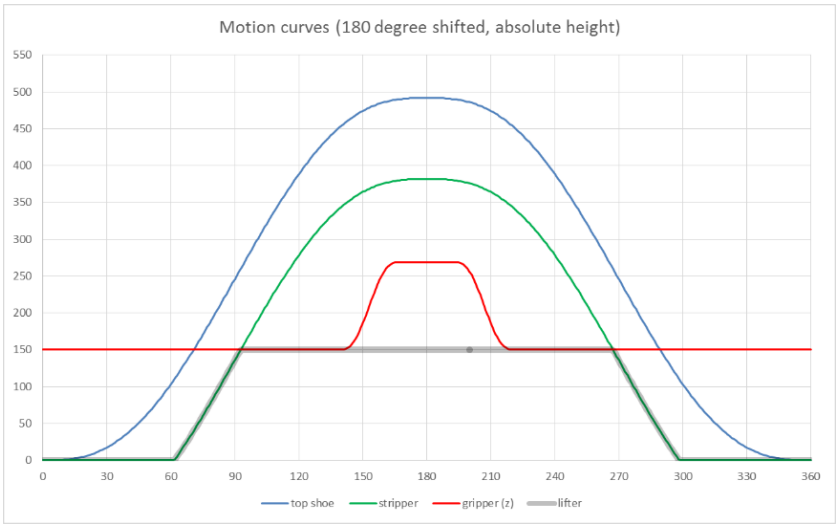
With the concepts of motion curve and clearances, the motion curve chart and clearance curve chart for the 360 degrees press cycle can be generated.

In industry, the motion curves are usually set to start from die open position, so at 0 degree, the top shoe is at the highest position, and at 180 degree, it is at 0 height which is die close position. This is convenient for analysis of forming process during die close. However, in this thesis, the topic is more about the transfer process during die open, so in this thesis the motion curve charts will set die close as 0 degree, and die open as 180 degree, namely, 180 degree shifted from commonly used charts.

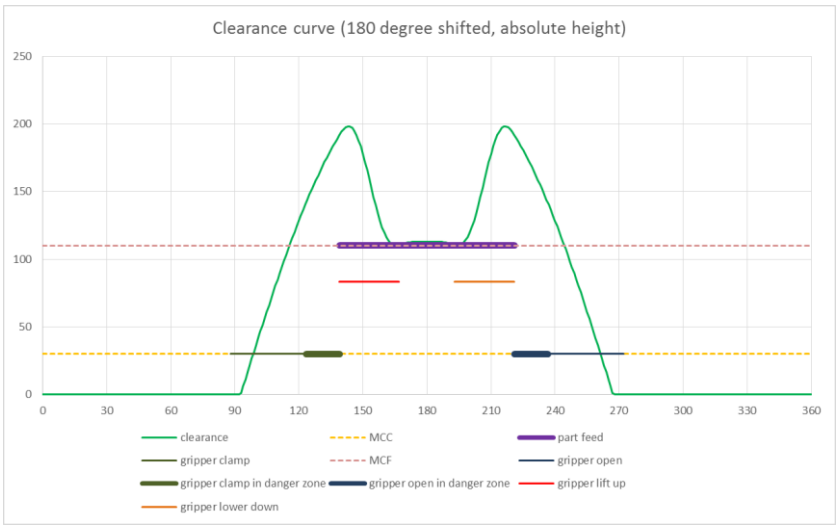
For example, as Figure 4.5 (a) shows, the blue curve is the motion curve of top shoe, it rises from die close (0 & 360 degree) to die open (180 degree), and fall down to die close. Its motion is following 345 polynomial curve.

Green curve is for the stripper, the value is the height of top shoe minus stripper travel, but the value will not be negative because stripper will be stopped by lower die. Lifter (gray bold curve) has lower priority than stripper so it will be driven by the

stripper, but its height will not excess its lifter travel. Red curve is the z-axis motion of gripper, it will pick the part and lift it after stripper and lifter separates, it dwells for some time at its lift stroke height because during this period it will feed the part along x-axis.



a: motion curve chart



b: clearance curve chart

Figure 4.5: Motion Curve Chart and Clearance Curve Chart

The clearance between gripper (and part, during transfer) and stripper is the key factor. However, this clearance only valid when the die is open. From Figure 4.5 (a), it can be found that between around 90 and 270 degree, the stripper and lifter separates, clearance between stripper and lifter is positive, hence the clearance between stripper and gripper is valid. Plot the clearance (green minus red) and it

results in Figure 4.5 (b). The green curve shows the clearance between gripper and stripper. Bold lines show the duration that the related motion take place (e.g. part feed is from around 135 to 215, shown as thick purple line from 135 to 215). Dash lines show the minimum clearance (MCC/MCF) needed to conduct related motions.

It should be noted that the term “gripper clamp/open in the danger zone” is just a portion of gripper clamp/open motion. As introduced in 4.3.2, clamping motion can start before clearance is higher than the MCC, but the clearance must be higher than MCC before it enters the danger zone.

For the example shown in Figure 4.5, clearance is just enough for safe feeding, because in Figure 4.5 (b) it shows that around 160~200 degree the clearance between gripper and stripper is just higher than MCF.

Figure 4.6: Motion curve with required stripper height (dashed line)

By transforming MCC and MCF in their valid period back to motion curve chart, Figure 4.6 shows the motion curve with minimum required stripper height. The stripper height (green line) must be higher than the required height (dashed line). The transfer between motion curve chart and clearance curve chart are shown in Appendix 0.

5 Obstacle Map and Mapping

It is already clarified that die geometry should be considered in the decision of transfer system parameters. Moreover, the part and gripper's geometry should also be considered. In this chapter, the pivotal geometries will be extracted from NX part/assembly file, and create the database which will be the basis of later optimizations. The database is called "Obstacle Map" and the process to obtain it is called "Obstacle Mapping".

5.1 Obstacle Map

5.1.1 Obstacle

Consider a simplified model in 2D. As shown in Figure 5.1, a part with multiple bending features is going to be picked and fed to the next stage. All other die components are hidden except part and lower die. It can be found that at multiple position, collision between part and lower die can happen.

Imagine a position recorder is "hanging" at the bottom left of the part, and record its position when some features are just about to touch (or detach) each other. The recorded points will be like what Figure 5.1 shows.

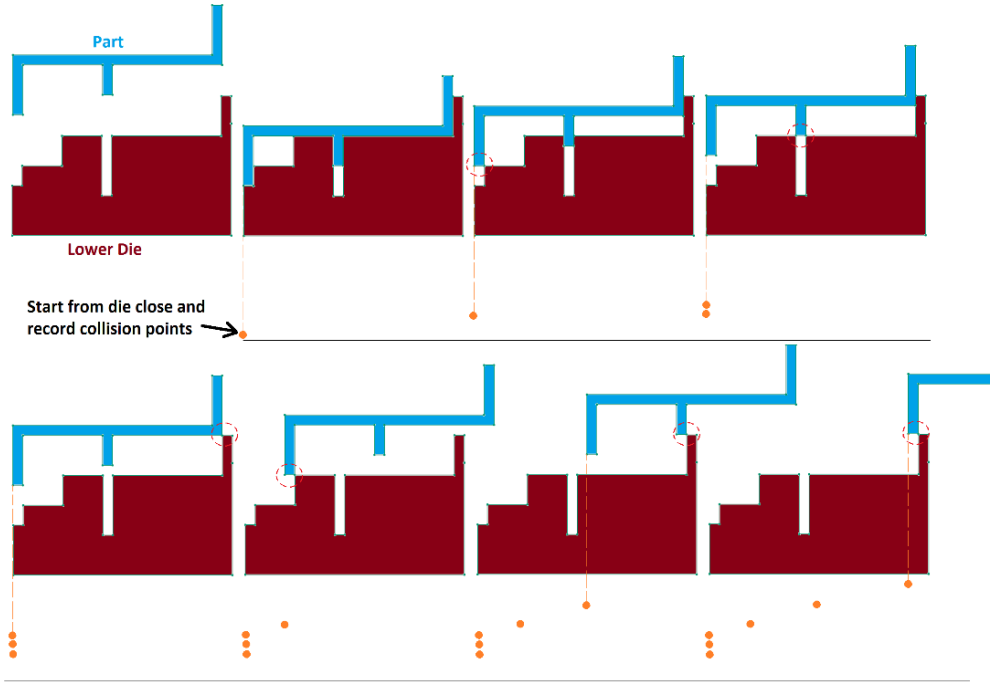


Figure 5.1: Collision points and obstacle pixel

It should also be noted that there are multiple bending features on the part, meanwhile, there are multiple blocks on lower die. Hence, one bending feature may collide with multiple blocks at different position, and one block may collide with multiple bending features at different position.

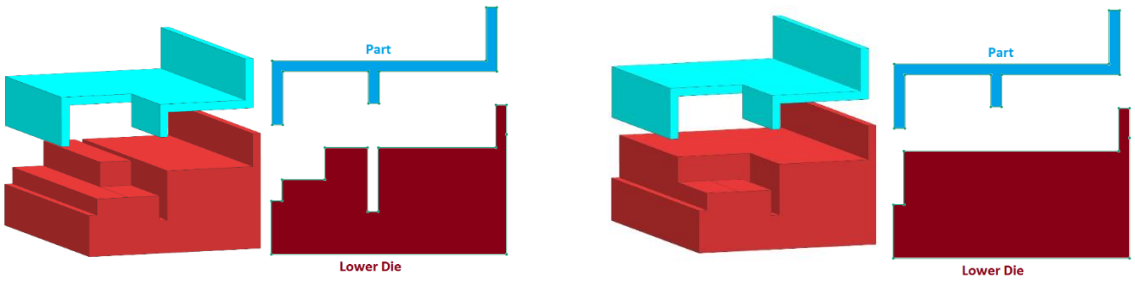
The collision points are shown as orange pixels and their positions are recorded, the details of the collisions should also be recorded (i.e. which feature collide with which block). The combination of collision location and collision details is called an "Obstacle Pixel". And a collection of obstacle pixels is called the "Obstacle Map". Since the part transfer is just between two stages, the length of the map will be the distance between two stages, which is the transfer pitch.

Different stages can have different obstacle maps. The following sections will show more concepts under obstacle map, and how these concepts further developed to the useful foundation of later optimizations.

5.1.2 Obstacle Map of One Stage

Consider the above example in 3D. As Figure 5.2 shows, the part contains multiple bending features, which are distributed at different y-axis positions (x-axis is feeding direction, z-axis is lifting direction).

As Figure 5.2 (a) shows, the side view reflects the critical geometries well, the obstacle map can be created simply refer to the side view.



a b

Figure 5.2: Obstacle Map for one stage

However, for the same part, the lower die geometry may (and more likely) appear to be the one shown in Figure 5.2 (b). The side view cannot show the geometry on the lower die for one of the bending features. In real case, this happens at almost every stage, yet the mapping work can still be done – although the geometry is in 3D, the

motion profile is in 2D, hence the obstacle map is still in 2D. For lift-feed-lower process (LFL), only x and z-axis motion exist, it does not matter at what y-axis position the collision happens. Moreover, the part is moved as a whole, the position of obstacle pixel can be uniquely expressed as its current position relative to the initial position. Therefore, as Figure 5.3 shows, by mapping for different section views and combine all the section obstacle maps, the obstacle map for one stage can be obtained.

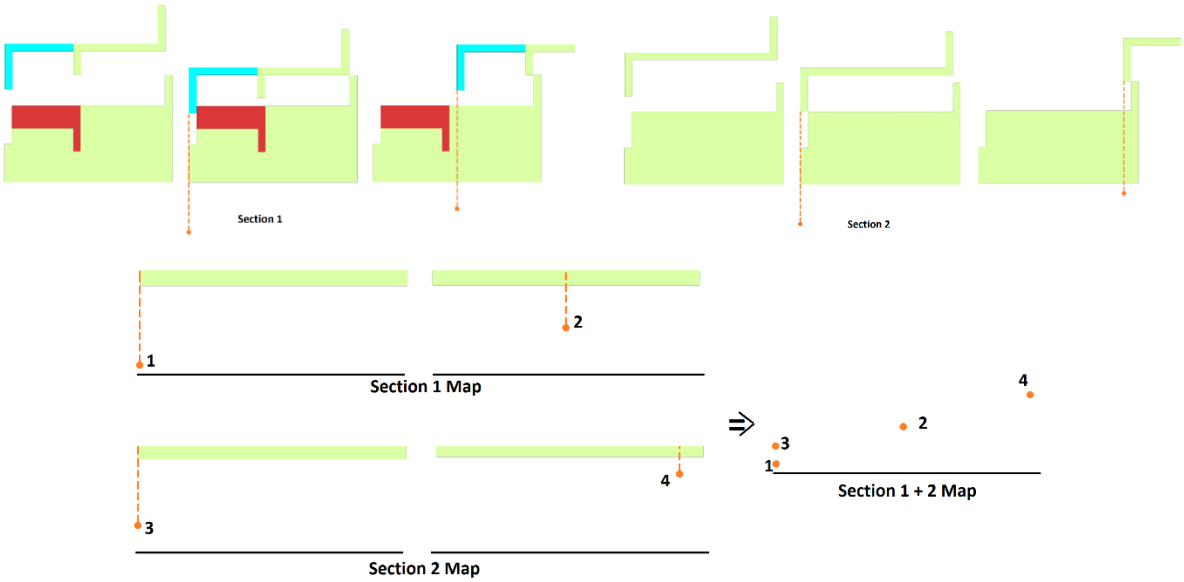


Figure 5.3: Obstacle Map for one stage

5.1.3 Obstacle Map of Whole System

Not only a single part, but also all the parts in the system, will be moved as a whole. After the parts are picked up, the relative position between them will not change until grippers free the parts. Therefore, mapping for the whole system is similar to mapping for one stage.

For example, as Figure 5.4 shows, part 4 and 5 (other parts are hidden) will be lifted and fed together, collision may happen on part 4 or 5. However, the obstacle pixels registered will only regard to the position relative to initial position – no matter part 4 or part 5. Hence, the multiple stages will only result in one obstacle map. Because the part feeding distance equals to transfer pitch, the valid length of the obstacle map will also be that value.

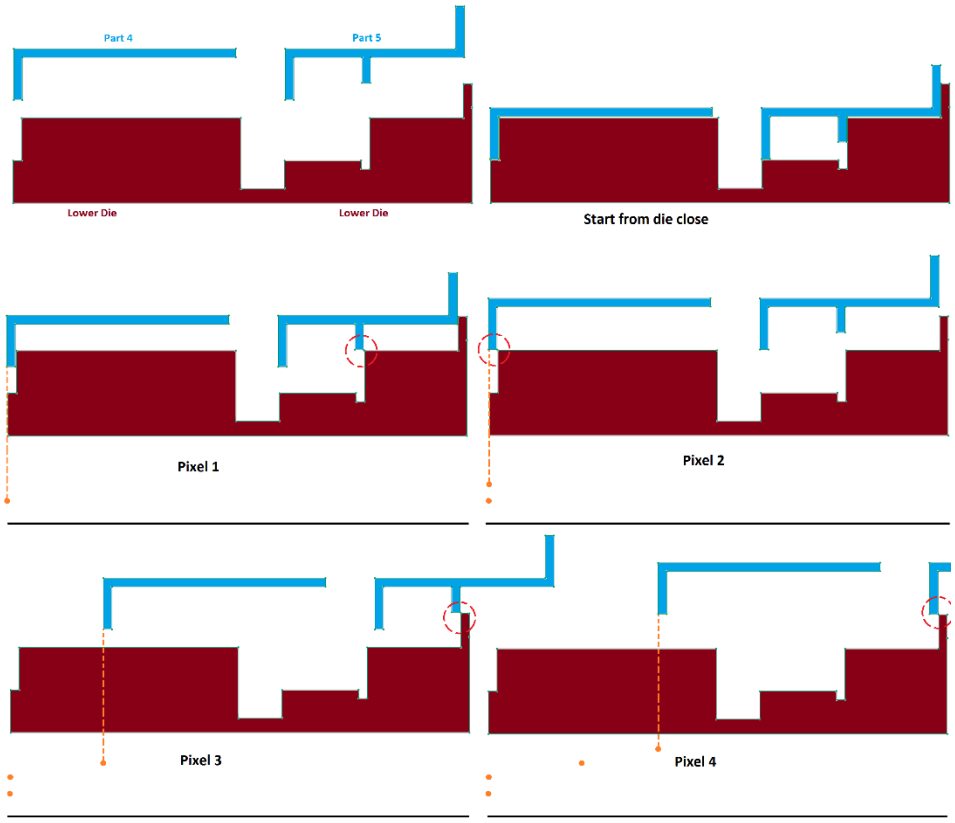


Figure 5.4: Obstacle Map for whole system

In 5.1.2, it is clarified that for 3D parts, the mapping for one stage can be done by combining all its section view maps. Since for one part, all the sections are obviously moving together, so they only result in one obstacle map. In this section, it is also clarified that for the whole system, all the parts are moving together, it is conceivable that the obstacle pixels of the whole system can be obtained by combining the map for all the stages and all sections. Hence, it can be said that:

All the information about possible collisions in lift-feed-lower process (LFL) can be demonstrated by a single obstacle map, the length of which equal to one pitch distance.

5.1.4 Forward Map and Backward Map

The above statement is made for LFL. After the parts are freed, before top shoe lower down for stamping operation, grippers will move along y-axis to escape from die operation area (danger zone). When the operation is being conducted, grippers move along x-axis, back to initial position. Then after the operation is done, grippers

again move along y-axis to pick the part up. This process is called open-back-close process (OBC).

Because parts are freed before OBC, this process is only for gripper motion. But it is still possible to have collision between the gripper and side of lower die. Follow the same idea introduced in previous contents, the obstacle map of OBC can also be generated.

Obstacle map for lift-feed-lower process (LFL) is called “Forward Map”.

Obstacle map for open-back-close process (OBC) is called “Backward Map”.

In common transfer system, there are two grippers. Their y-axis motions are usually reversed – in open process, one move along +y, the other move along –y. The mapping work for backward map is actually needed for both grippers. However, because the pair grippers have exactly mirrored motion, it is again similar to previously introduced concepts, by combine the two obstacle maps (+y gripper and –y gripper), the unique backward obstacle map can be obtained.

Therefore, the following statements can be made:

For the whole transfer system, all the information about possible collisions can be contained in two obstacle maps – Forward (LFL) Map and Backward (OBC) Map.

5.1.5 Full Map and Side Map

If an obstacle map is well generated without missing any possible obstacle pixel, the following inference can be made from the above statement:

If the motion profile can bypass all the obstacles in obstacle map, there will be no collision for such motion.

The term “bypass” means, for any x-axis position, the z value (LFL) or |y| value (OBC, both +y and -y considered) of motion profile is larger than such value of the obstacle pixel at same x position. For example, for LFL, an obstacle is at x=50 mm, obstacle height is 100 mm, if the motion profile is higher than (50,100), then this obstacle is bypassed.

In LFL, the part will firstly be lifted till the height reaches lift stroke, it will not lower down before the lift motion is completed. So in lift-feed process, the motion profile will not go downward, similarly, in feed-lower process, motion profile will not go upward. This fact makes it possible to simplify the obstacle map.

Consider the motion profile and obstacles as Figure 5.5 shows, there are 8 obstacles with different position and height. It can be found that the motion profile (blue curve) bypassed all the obstacles, which means there is no collision during this LFL process.

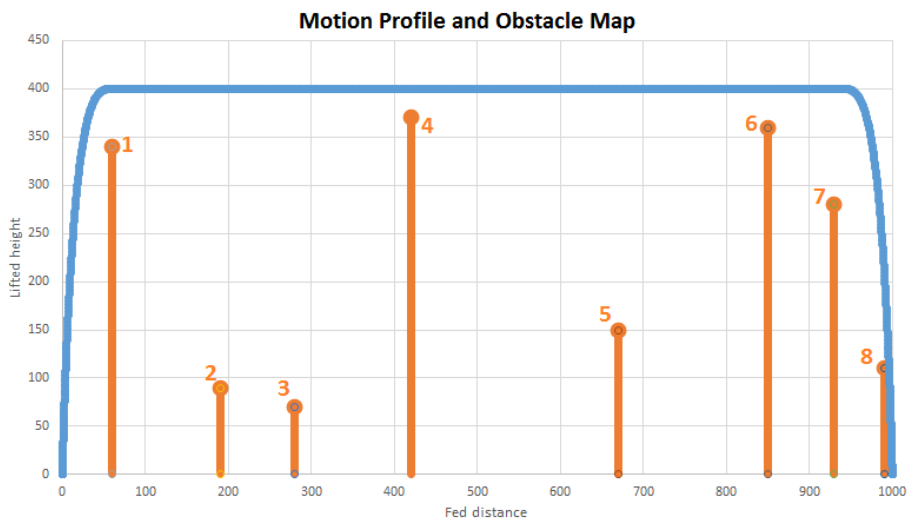


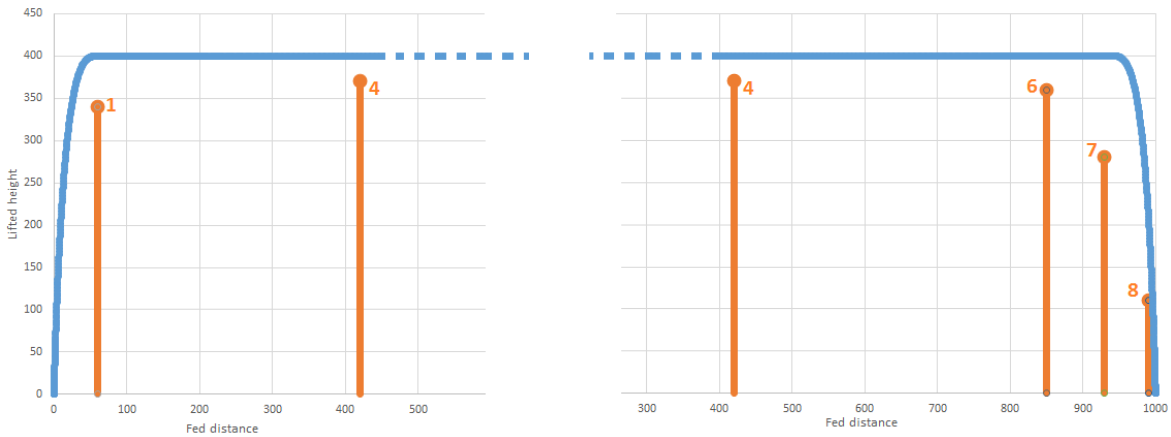
Figure 5.5: Obstacle Map simplification – Full Map and Side Map

To simplify the obstacle map, obstacle 2 and 3 should be noted. In lift-feed process, part will go upward until it reaches lift stroke. So, during lift-feed process, if an obstacle is already bypassed, any later obstacle that is lower than this one can be ignored.

In the above example, at around 60 fed distance, obstacle 1 is bypassed, after that, part lift height will not go downward until feed-lower process. Therefore, obstacle 2 and 3 can be ignored, there is no collision concern until the part arrive an obstacle higher than obstacle 1 (obstacle 4 in the above example).

Essentially, since obstacle 4 is the highest obstacle in the map, for lift-feed process, all the obstacles after that can be ignored. So for lift-feed process, only obstacle 1 and 4 need to be concerned. Similarly, for feed-lower process, only obstacle 4,6,7,8 need to be concerned, obstacle 5 can be ignored.

The above analysis introduces the concept “Side Map”. For both LFL and OBC, there is one advance move and one return move (e.g. lift-feed and feed-lower). For each move, some obstacles can be ignored, actually, the whole obstacle map can be divided to two sides by the highest obstacle. One side is for advance move, the other side is for return move.



a: Lift-feed (advance) Side Map b: Feed-lower (return) Side Map

Figure 5.6: Separated Side Maps

Figure 5.6 shows the separated side maps of the above example. With side map, motion profile optimization task can be further divided.

For each transfer system, there are two full maps – one is forward map, the other is backward map. For each full map, it can be divided to two side maps – advance side and return side. For each side map, there are two motions that are concerned – one is along x-axis, the other is along y or z-axis – the overlap percentage between which can be solved regard to obstacles in the side map.

Table 5.1 below summarizes the recent sections.

Full Map	Side Map	Related Motions and Overlap
Forward Map (LFL Map)	Lift-feed side	x advance – z advance
	Feed-lower side	x advance – z return
Backward Map (OBC Map)	Open-back side	x return – y advance
	Back-close side	x return – y return

Table 5.1: Full Map, Side Map, Related Motions and Overlap

5.2 Mapping Strategy

The obstacle map contains all the possible collisions in transfer system, it can be fairly useful in transfer motion analysis. Yet it must be carefully generated, because any missed or incorrectly positioned obstacle pixel may result in fatal mistakes in optimization result. With DYNMIK kinematic model and NX collision checking, obstacle maps can be obtained.

5.2.1 Preparations Before Mapping

For algorithm development in NX, Siemens provides NX Open API as a tool for custom application developments. In this thesis, this tool is utilized to realize the obstacle mapping work by the following steps:

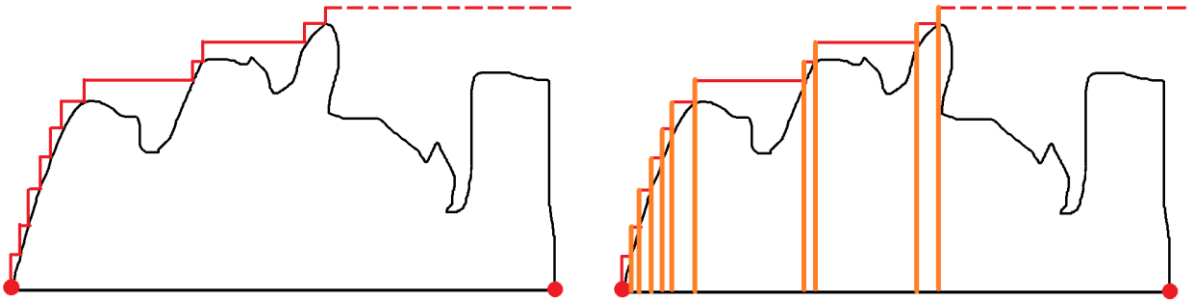
- Access geometry in NX: With NX Open, the geometries (i.e. solid bodies) of defined components (top shoe, gripper, etc.) in kinematic model can be accessed.
- Extract geometry for later operations: Hence the geometry data extraction from NX internal to public use is done in this step.
- Initialize component position: In industry, as a rule of thumb, designers usually design the die assembly at die close position. This step is to initialize them to die open position.
- Initialize collision check: For LFL and OBC, collision checking is done differently, the collision checking settings should be set in this step.

After initialization, a temporary die assembly can be created, later operations will be done with the temporary assembly and initial data will not be affected.

5.2.2 Zig-zag Mapping

In section 5.1.5, it was introduced that the side map only care about obstacles that is higher than previous ones. This idea can be applied in mapping strategies.

Simply run the part in the feeding direction. When it touches the obstacle (collision detected), lift it for a step distance, and try to feed again. The motion profile of the part will be like zig-zag.



a: zig-zag motion profile b: generated obstacle map (advance side)

Figure 5.7: Zig-zag mapping

For example, assume the geometry between two stages on lower die is like the black lines in Figure 5.7, part is to be fed from the red point on the left side to red point on the right side.

Run the part like the red zig-zag, do collision checking after each step, when a collision is detected, move the part upward a until the collision is cleared, then feed forward again until the next collision happens. The orange bars in Figure 5.7 (b) are the obstacles detected, their height and distance from the origin will be recorded and thus can construct an obstacle map.

As Figure 5.7 shows, the mapping motion profile is just one zig-zag line, if the feeding step and lifting step are same, with given pitch distance and height of highest obstacle, the maximum number of collision checking will be:

$$Num.Checking = \frac{Pitch}{Step} + \frac{Height}{Step} \quad \textbf{(8)}$$

However, it is possible for zig-zag mapping to miss obstacles.

This situation is not very common in real die assemblies. Although the die itself may have concave geometry, when taking part geometry into account, the small concaves are usually crossed over. Yet it is still necessary to develop a more reliable mapping strategy.

5.2.3 Column-scan Mapping

Multiple solutions were considered to overcome this situation. One is shown in Figure 5.8, which is similar to rotating a bar (or a circle, concepts are similar) along the obstacle and detect collision. However, it still has a possibility that even a dangling obstacle may exist.

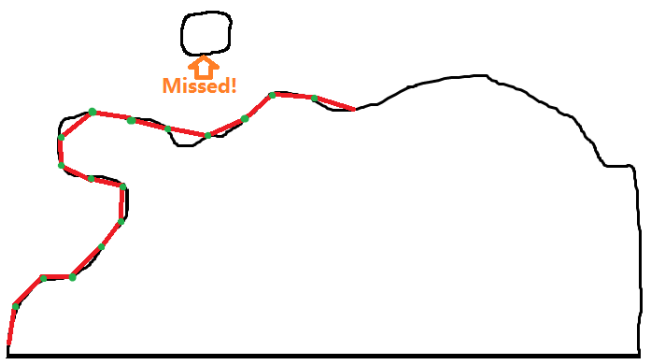


Figure 5.8: Bar rotation mapping and its drawback

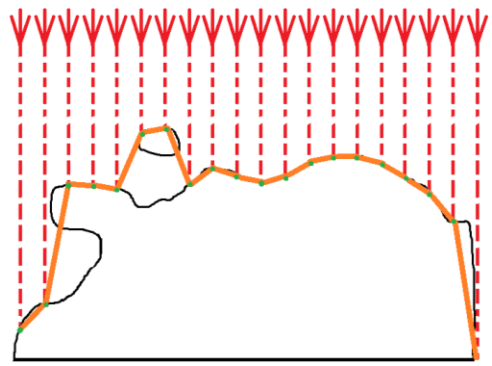


Figure 5.9: Column scan mapping

Finally, it is clarified that there is no shortcut to mapping obstacles both accurately and efficiently. And the most reliable strategy is proposed, which is called column-scan.

Process of column-scan mapping is also straightforward – “dropping” the part from a safe height (e.g. press stroke), and check collision at each step, stop when any collision is detected and register obstacle pixel, then move to next column.

By scanning the obstacle column by column, the chance to miss an obstacle can be minimized. And the outcome obstacle map geometry can well reflect the actual needed geometry for later analysis. Moreover, according to density of scan lines, the accuracy of outcome can be controlled. If time is not a significant concern, it should be preferred to conduct a very fine scan and obtain the most accurate obstacle map.

Not like zig-zag mapping, the result from column-scan mapping will not ignore any obstacle during mapping, all the obstacles will be reflected on the full map. So the process from full map to side map (and simplification) will be needed.

The efficiency of column-scan mapping is considerably lower than that of zig-zag mapping. For zig-zag mapping, the checking positions are along a one dimensional zig-zag line, while for column-scan, collision checking must be done on a two dimensional plane. Given the pitch distance, dropping height and same lifting/feeding step, the maximum number of collision checking will be:

$$Num.Checking = \frac{Pitch}{Step} \times \frac{Height}{Step} \quad \textbf{(9)}$$

Time consumption is the main drawback of column-scan mapping. Although in practice, time is not the major concern compare to accuracy, it will help a lot if the mapping task can be done in shorter time.

5.2.4 Segmenting Mapping Task

To save the mapping time, the most intuitive way is to put more computers into the mapping task. This may not be possible in zig-zag mapping because the part motion in zig-zag mapping depends on its previous motion, plus, it is not necessary to apply such idea in zig-zag mapping for its high efficiency. However, for column-scan mapping, this idea is applicable – there is no relationship between column and column, it is definitely possible to scan each column separately and combine them to create the obstacle map. Actually, this is exactly how the column-scan mapping is done even on one computer.

Therefore, by segmenting the mapping task to multiple segments, running simultaneously for these segments on different computers or NX sessions, and combining the result, the mapping time can be reduced.

Moreover, this segmentation also gives the possibility to assign different steps for each segment. In transfer system, the most concerned areas are the starting and ending of the transfer, assigning shorter step in these areas is beneficial. Plus, the designers may not clearly know at which position what collision may happen, but they should roughly have an idea about the danger parts in their design, for these parts, it is also beneficial to have finer scans. Then, for segments that are considered relatively “safe”, step distance can be larger to save time.

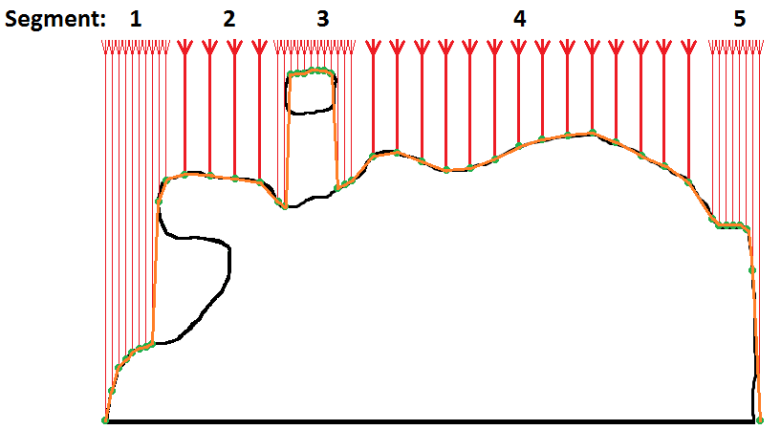


Figure 5.10: Column-scan mapping segmentation

As Figure 5.10 shows, the segmented column-scan mapping can handle different areas of the map with different step distance, which can both improve accuracy in certain areas and shorten the overall process time.

The only drawback of this method is the requirement of multiple computers. However, this should not be a significant issue in practice, because in progressive/transfer die industry, the design team will have multiple and powerful computers. Anyway, there are surely more ways to improve accuracy and efficiency of obstacle mapping, and this can be one of the future work topics. But in this thesis, the exploration on this topic will not go further.

Table 5.2 summarizes and compares the advantages and disadvantages of the proposed mapping strategies.

	Advantage	Disadvantage
zig-zag mapping	great efficiency, directly output side map	bad accuracy in some cases, may miss obstacles
column-scan mapping	good accuracy	bad efficiency
segmented column-scan	flexible accuracy, good efficiency	require multiple computers or NX sessions

Table 5.2: Advantages and disadvantages of different mapping strategies

5.2.5 Manual Mapping

Although programming with NX can automate the obstacle mapping work dramatically, manual mapping will never be excluded from the options. Removing an

obstacle in the map is rare, but adding or modifying an obstacle can be common. For example, if an extra clearance is to be applied between a certain pair of components at a certain position, the obstacle at that position should be revised.

There are some components that will not be shown in the part/assembly model (e.g. electric cables). These components should be considered in obstacle mapping, and they can only be added manually since there is no model for automatic mapping program to recognize.

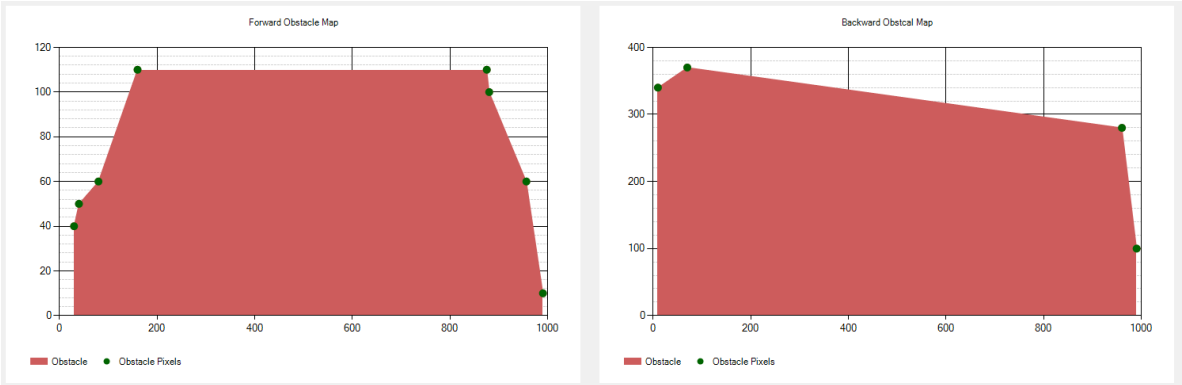


Figure 5.11: Obstacle map display template in later contents

In later contents, transfer system optimization will be based on the obstacle map obtained by methods introduced in this chapter. Figure 5.11 shows the display template of obstacle maps. Obstacle pixels will be shown as dark green points, using these points as vertex, polygons can be displayed to represent the obstacle map. The polygons will be filled with Indian red color.

6 Transfer System Optimization According to Obstacle Map

A review of previous chapters:

- 345 polynomial curve can reflect the real motion curve in progressive/transfer die system accurately. Hence 345 polynomial curve is assumed to be the motion curve of the components in this thesis.
- The property of 345 polynomial curve ensures that with given moving distance, maximum velocity or maximum acceleration can be solved directly from moving duration, and vice versa.
- Motion of gripper in transfer die contains two phases, lift-feed-lower process (LFL) and open-back-close process (OBC). The shape of motion profile is decided by the "overlap" between two motions – lift and feed, feed and lower, open and back, back and close.
- It is beneficial to increase overlap percentage, because a smoother motion profile can help to reduce the total transfer time, thus reduce cycle time and improve SPM. However, increasing overlap percentage without recognizing the die geometry is dangerous, it may cause collisions.
- By mapping the obstacles in the die system, die geometry information can be extracted and obstacle map can be generated. If the motion profile can bypass all obstacles in the obstacle map, there will be no collision.

In this chapter, based on the fact that collision can be avoided by bypassing all obstacles, the algorithm of gripper motion profile optimization will be proposed. With optimized motion profile, timings and parameters of the transfer system can be optimized. The optimization will result in better kinematics during part transfer, shorter transfer time, and finally result in a shorter cycle time and improved SPM.

6.1 General Methods and Concepts

The basic idea to reduce cycle time is to run the top shoe faster. However, running top shoe faster will reduce die open time for part transfer, therefore, the first mission is to reduce transfer time.

There are two ways to reduce transfer time. The first is to run the gripper as fast as it can. This is, namely, trying to utilize the maximum velocity and acceleration of gripper on each axis motion so for each axis motion the total time can be minimized. The second way, which can be used simultaneously, is to apply larger overlap between motions. Consider LFL, the motion contains one x-axis motion (feed) and two z-axis motion (lift & lower), the total time is:

$$t_{LFL} = t_{x-f} + \left(1 - P_{lift}\right)t_z + (1 - P_{lower})t_z \quad \textbf{(10)}$$

Where P_{lift} and P_{lower} are the overlap percentage for lift-feed process and feed-lower process. t_{x-f} is the feed time, t_z is lift time and lower time. It should be noted that t_x may have two values, because for LFL grippers have to carry the part, while for OBC they do not. But for t_y (always not carrying the part) and t_z (always carrying the part), there will be no difference.

Once t_{LFL} is minimized, the speed of top shoe can increase, hence SPM can be improved.

In later part of this thesis, time for OBC will also be used. t_{LFL} will be the critical variable of cycle time calculation, then with cycle time, t_{OBC} can be calculated:

$$t_{OBC} = t_{cycle} - t_{LFL} \quad \textbf{(11)}$$

6.1.1 Initial Target Value

Although it is just clarified that reduce t_{LFL} can reduce cycle time, quantitative analysis is needed. The concept “Target Value” is introduced to describe the height of top shoe, at which the part can be fed safely. According to previous contents, the initial definition of target value will be:

$$Initial\ Target\ Value = S_S + S_L + S_{Gz} + MCF \quad \textbf{(12)}$$

Where S_S is travel distance of stripper, S_L is travel distance of lifter, S_{Gz} is travel distance of gripper z-axis, which is lift stroke. MCF is minimum clearance for feeding introduced in 4.3.2. In later contents, definition of target value will change and the term “initial” here is to separate the different definitions.

While top shoe moving upwards from die close to die open, the suppressed components extend to their die open position in a sequence according to their priority. Firstly stripper, then lifter and the related part, which are the first two terms in Eq. (12). After stripper and lifter separates, gripper close in to clamp the part, then lift the part to lift stroke, which is the third term in the equation. And finally, regarding the sum of the above three terms, top shoe still needs to go up for some distance to make clearance for feeding, which is MCF.

Stripper travel, lifter travel and MCF can be known from die geometry, or simply given by the designer. Lift stroke can be obtained from transfer system parameters, or given by calculated results. Hence the initial target value can be determined.

6.1.2 Open Portion and Die Open Duration

The motion curve of top shoe is a 345 polynomial curve. As 3.2 introduced, once the polynomial curve is determined, solving y from x or x from y is not a problem. For top shoe and the target value, once the press stroke and target value is known, the portion during which top shoe is higher than target value can be solved.

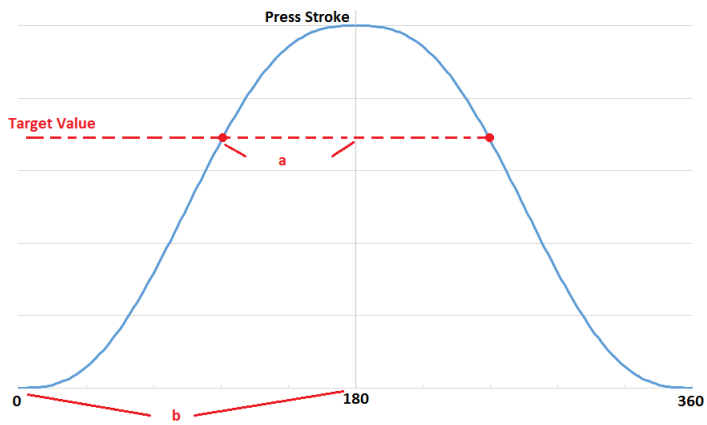


Figure 6.1: Solve open portion from press stroke and target value

As shown in Figure 6.1, the open portion is a/b, it can be solved from lookup table. Since the motion is symmetric, the whole open portion during the cycle is the same value. Die open duration (DOD) is simply the time during which top shoe is higher than target value.

$$DOD = t_{cycle} \times \frac{a}{b} = t_{cycle} \times f(\frac{target\ value}{press\ stroke}) \quad \textbf{(13)}$$

Where *f(x)* is the result of solving (1-x) from y in basic 345 polynomial curve (Eq. (1)). From the properties of 345 polynomial curve, it is known that *f(x)* is monotonically decreasing in the range [0, 1]. Which means, the smaller target value, the larger portion that top shoe is above target value.

With determined target value, the relationship shown in Eq. (13) indicates that when reducing cycle time, die open duration will also be reduced. However, reduction in DOD must have a limit, the limit is, DOD must be sufficient for part to be fed from current stage to the next one.

6.1.3 Let Feed Duration Equal Die Open Duration

Use the properties of 345 polynomial curve again. With motion distance (transfer pitch), and motion capacity (maximum v or a), the required time duration can be calculated.

From velocity:

$$t_{req\_from\_v} = \frac{15 \times Pitch}{8 \times v_{max}} \quad \textbf{(14)}$$

From acceleration:

$$t_{req\_from\_a} = \sqrt{\frac{10\sqrt{3} \times Pitch}{3 \times a_{max}}} \quad \textbf{(15)}$$

Eq. (14) and Eq. (15) can be referred to equations in Table 3.1.

Feed duration then can be calculated. The calculation result from velocity and acceleration may be different, the larger one should be regarded as the feed duration to ensure that none of the motion capacity is exceeded.

From the definition of target value, it can be found that within DOD, the clearance between stripper and part is larger than MCF. Because part can only be fed when clearance is larger than MCF, the following statement can be made:

Die open duration (DOD) must be longer than or equal to the duration in which part is fed at lift stroke height.

The above statement gives the limit of reduction in DOD. Since the shorter DOD, the shorter cycle time, it is conceivable that the best strategy is to let DOD equal to feed duration so DOD can be minimized.

6.2 Top Shoe Optimization

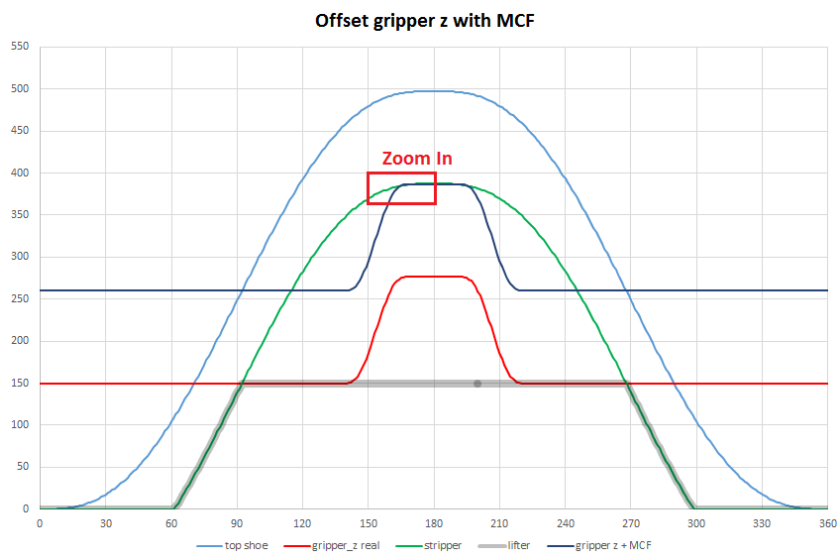
6.2.1 Consider Clearance for Overlap and MCF

Back to the definition of target value, it is initially assumed that part will be fed after it is fully raised by the gripper (lift stroke). However, in practice, when overlap is applied in LFL, the situation will change. A lift-feed overlap means feed start before lift is finished, a feed-lower overlap means lower start before feed is finished. When both overlap exists, the feed duration will not change, but the duration in which part is fed at lift stroke height is changed.

$$Feed\ Only\ Duration\ (FOD) = t_{x-f} - P_{lift}t_z - P_{lower}t_z \quad \textbf{(16)}$$

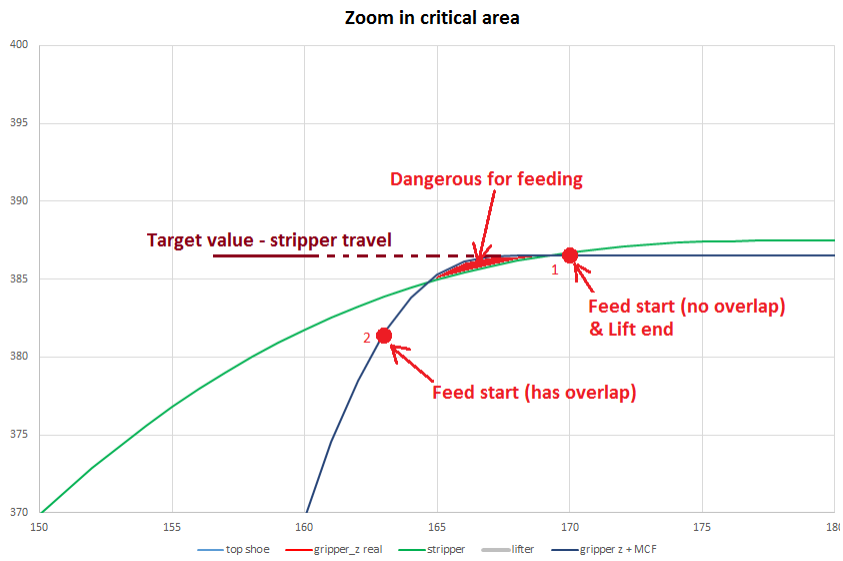
The term Feed Only Duration (FOD) means the duration in which gripper feed the part without lifting or lowering it. During FOD, the gripper is at the highest position and only have x-axis motion. So, when overlap is applied, although feeding duration stays the same, FOD is shortened. So DOD can be further reduced, and then cycle time can be further reduced – this also shows why overlap is beneficial in reducing cycle time. However, when trying to apply the above process, some problem arises.

By offsetting the gripper z-axis motion curve with MCF, it will result in better display to show whether the clearance is enough or not.

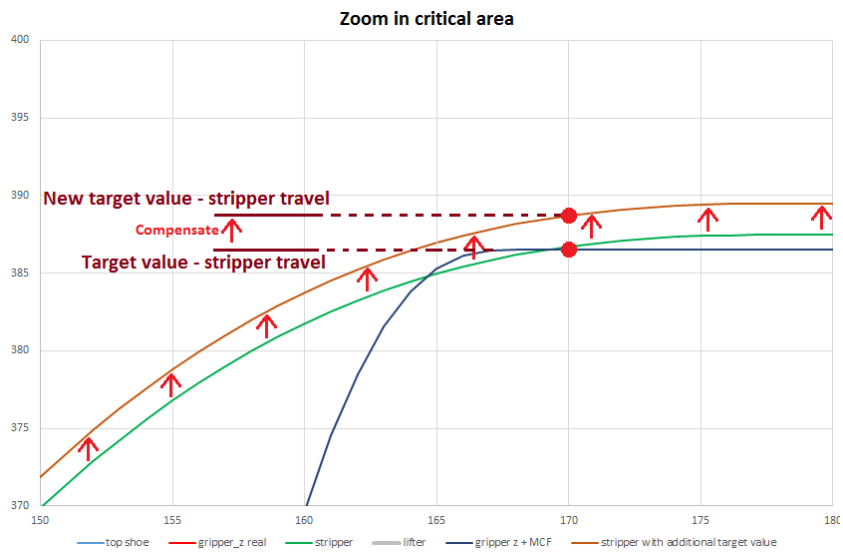


a: offset gripper z motion curve

b: zoom in to show the danger



c: danger when feed start early



d: additional target value is needed

Figure 6.2: Need Additional Target Value for overlap

As Figure 6.2 (a) and (b) shows, lift the gripper z-axis motion curve with MCF (red -> dark blue), it can be found that at the end of lifting and beginning of feeding, the clearance between stripper and gripper become critical.

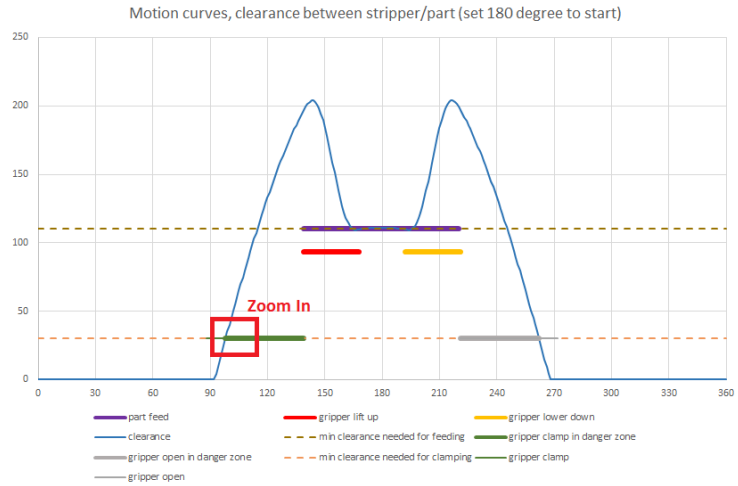
From the definition of MCF, it can be inferred that only when the lifted gripper z-axis motion curve is lower than the stripper motion curve, part can be fed safely. If there is no overlap, as one red point (No.1) in Figure 6.2 (c) shows, simply let DOD equal to feed duration (which equals to FOD if there is no overlap), then solve other parameters. This can lead to a result that lift end and feed start at the same time.

However, if an overlap is applied, as another red point (No.2) in Figure 6.2 (c) shows, the part feed will start before lift end, at the end of lifting event, the clearance will be dangerous for feeding.

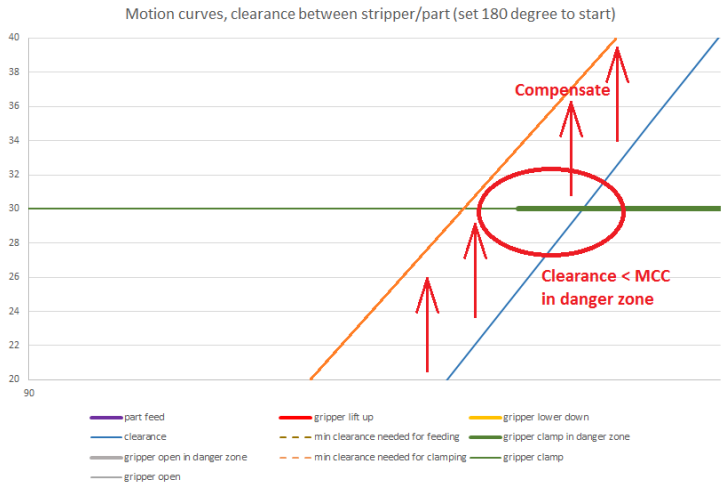
The reason behind such phenomenon is related to the motion of top shoe and gripper. During the whole 360 degrees cycle, top shoe will go upward during 0~180 and downward during 180~360. It takes 180 degree for top shoe to travel its specified travel distance (press stroke). For gripper z-axis, it will take only 20~40 degrees to lift the part. This will result in the motion curves in Figure 6.2 (c), while the local speed of gripper is faster than stripper (which is mounted on top shoe). The clearance between stripper and gripper decreasing so fast that top shoe has no enough time to reserve clearance, yet the feeding already start. Finally, the clearance is down to MCF but gripper is still rising fast, hence there will be couples of degrees that clearance is less than MCF, which is dangerous for feeding.

6.2.2 Consider Clearance for MCC

Consider the clearance chart and focus on MCC. It was clarified in chapter 4 that when gripper is moving along y-axis, becoming closer and closer to the part, at one point it will enter the danger zone, where it may collide with top shoe components. Within this danger zone, the clearance between gripper and stripper must be higher than MCC to ensure safety in the clamping process. This concept can be displayed by clearance chart, the bold lines which indicate “clamping in danger zone” must be covered by the clearance curve.



a: Clearance curve and MCC required in the danger zone



b: Adjustion for MCC

Figure 6.3: Need Additional Target Value for MCC

As Figure 6.3 shows, when clearance curve cannot fully cover the gripper motion in danger zone, the clearance curve must be lifted. The reason for this phenomenon is related to gripper y-axis motion parameters and the definition of the danger zone. When the geometry of die assembly is wide, and the gripper clamp stroke is short, the majority of the whole clamp stroke can be in danger zone. Plus, gripper y-axis motion is faster than top shoe, which may result in no enough time for top shoe to create enough clearance. Similar to the issue introduced in 6.2.1, additional target value is needed to lift the curve and increase clearance.

6.2.3 Target Value Compensation

To overcome the problems in 6.2.1 and 6.2.2, additional target value is applied to compensate the clearance. As Figure 6.2 (d) and Figure 6.3 (b) shows, compensation will be added to target value, and the calculation will follow the same route “top shoe must be higher than target value during FOD”. Since target value is increased, more clearance will be reserved so the clearance will never drop to a value lower than MCF.

$$Target\ Value = S_S + S_L + S_{Gz} + MCF + S_{Comp} \quad \textbf{(17)}$$

Where S_{Comp} is the compensation of target value, it may also be referred as “additional target value” or “additional clearance”. Eq. (17) is the new definition of target value, which will be used in later parts of this thesis.

6.2.4 Solve Speed vs. Solve Press Stroke

If target value and required feed duration are solved, top shoe motion optimization can be conducted by letting FOD equal to DOD. For a given target value, there are two factors that affect the DOD – speed and press stroke. Equations for cycle time calculation are:

From velocity:

$$t_{cycle} = \frac{15 \times Press\ Stroke}{8 \times v_{max}} \quad \textbf{(18)}$$

From acceleration:

$$t_{cycle} = \sqrt{\frac{10\sqrt{3} \times Press\ Stroke}{3 \times a_{max}}} \quad \textbf{(19)}$$

Similar to the equations used to solve feeding duration, Eq. (18) and Eq. (19) can be referred to equations in Table 3.1.

For speed, it is intuitive that speed up the die system at will reduce all the time durations in the system, including DOD. Higher speed means both higher velocity and acceleration, as the above equations have shown, one of them will be the boundary condition.

For press stroke, if the motion capacity of top shoe is fixed, cycle time can be solved from press stroke by Eq. (18) and Eq. (19). Then, with press stroke and target value, DOD can be decided based on Eq. (13).

Optimization for top shoe is to do the above process reversely. Both increasing running speed and decreasing press stroke can reduce cycle time and improve SPM, but both will also reduce DOD. Therefore, make DOD equal to FOD is the basic idea of optimization about top shoe. According to different cases in practice, the optimization can be solving speed (v & a) from fixed press stroke, or solving press stroke from given motion capacity (max. v & max. a).

From velocity:

$$FOD = \frac{15 \times Press\ Stroke}{8 \times v_{max}} \times f\left(\frac{target\ value}{press\ stroke}\right) \quad \textbf{(20)}$$

From acceleration:

$$FOD = \sqrt{\frac{10\sqrt{3} \times Press\ Stroke}{3 \times a_{max}}} \times f\left(\frac{target\ value}{press\ stroke}\right) \quad \textbf{(21)}$$

As Eq. (20) and Eq. (21) shows, the relationship between FOD, target value, press stroke, and speed (peak v and peak a) can be used to solve any one of them

according to others. No matter which kind of optimization will be conducted, target value and FOD are necessary inputs for the algorithm.

Since *f(x)* is monotonically decreasing, with calculated FOD regarding to lower shoe geometry, the guidance of top shoe optimization can be stated as:

The smaller target value, the shorter cycle time.

Because target value is the sum of several die parameters which are constant, plus a variable compensation value, the compensation should be as small as possible.

6.3 Optimization Guideline

With the equations and concepts introduced in previous contents, the optimization guideline for reducing the cycle time can be summarized.

With FOD equal to DOD, and DOD is related to press stroke and target value, cycle time can be solved from FOD, target value and press stroke:

$$t_{cycle} = FOD/f(\frac{target\ value}{press\ stroke}) \quad \textbf{(22)}$$

Where *f(x)* is monotonically decreasing, the result of which can be solved from the lookup table of 345 polynomial curve. Combining Eq. (16) and Eq. (22), FOD can be presented by the overlap percentages and motion durations in LFL:

$$t_{cycle} = (t_{x-f} - P_{lift}t_z - P_{lower}t_z)/f(\frac{target\ value}{press\ stroke}) \quad \textbf{(23)}$$

From gripper motion velocity, acceleration and moving distance, $t_{x\text{-}f}$ and t_z can also be solved, so the objected of decreasing cycle time can be transferred to finding the maximum overlap percentage and the minimum target value.

Overlap percentage must ensure that the obstacles in obstacle map are bypassed, while target value must ensure that the clearance requirements for MCC and MCF are fulfilled.

Then, after the cycle time is solved, with Eq. (18) and Eq. (19), velocity and acceleration of top shoe can be solved from press stroke, or press stroke can be solved from known velocity and acceleration, depends on the situation.

It should be noted that the parameters will affect each other and the optimization must consider the entire system as a whole. For example, although in the equation it appears that

increasing $t_{x\text{-}f}$ and t_z can decrease cycle time, they actually should be minimized because the increment of them will affect the overlap percentage and the target value, and the overall effect will be an increased cycle time. Also, the increment of overlap percentage can also lead to the increment of target value, which will be further discussed in 6.5.

In the following sections of this chapter, three different optimization levels that are developed in this research will be introduced. Target value, Overlap percentage optimization, FOD calculation, and top shoe optimization of each optimization level will be discussed.

6.4 Level 1 – Optimize Overlap Only

In practice, product design, die design, transfer system supply, press machine supply, actual production, are all separated tasks. Some company have one-stop business which can cover most of the product lifecycle, any design change or production plan change can be applied within the cooperation with related departments.

However, it is also possible that for a given product, die design and machine supply are from different specific companies, manufacturers receive all these materials and produce in their plant. In this situation, any change in design or plan may affect the whole supply chain, which is very difficult to handle.

Another situation is, for a die set which is already in production, if parameter or design is modified, manufacturer needs to stop the press machine, replace die sets, and do the trial run again. This process costs so much that in practice it rarely – if ever – happens.

Therefore, it is possible that the die design and transfer system parameters are already fixed. The room for optimization is very small – actually, for manufacturers in plant, there are only a few things they can change on the control panel for a die set.

In this section, the extreme case will be discussed. Even when the die design and transfer system parameters are all fixed, it is still possible to improve SPM by applying overlap and optimizing the motion profile.

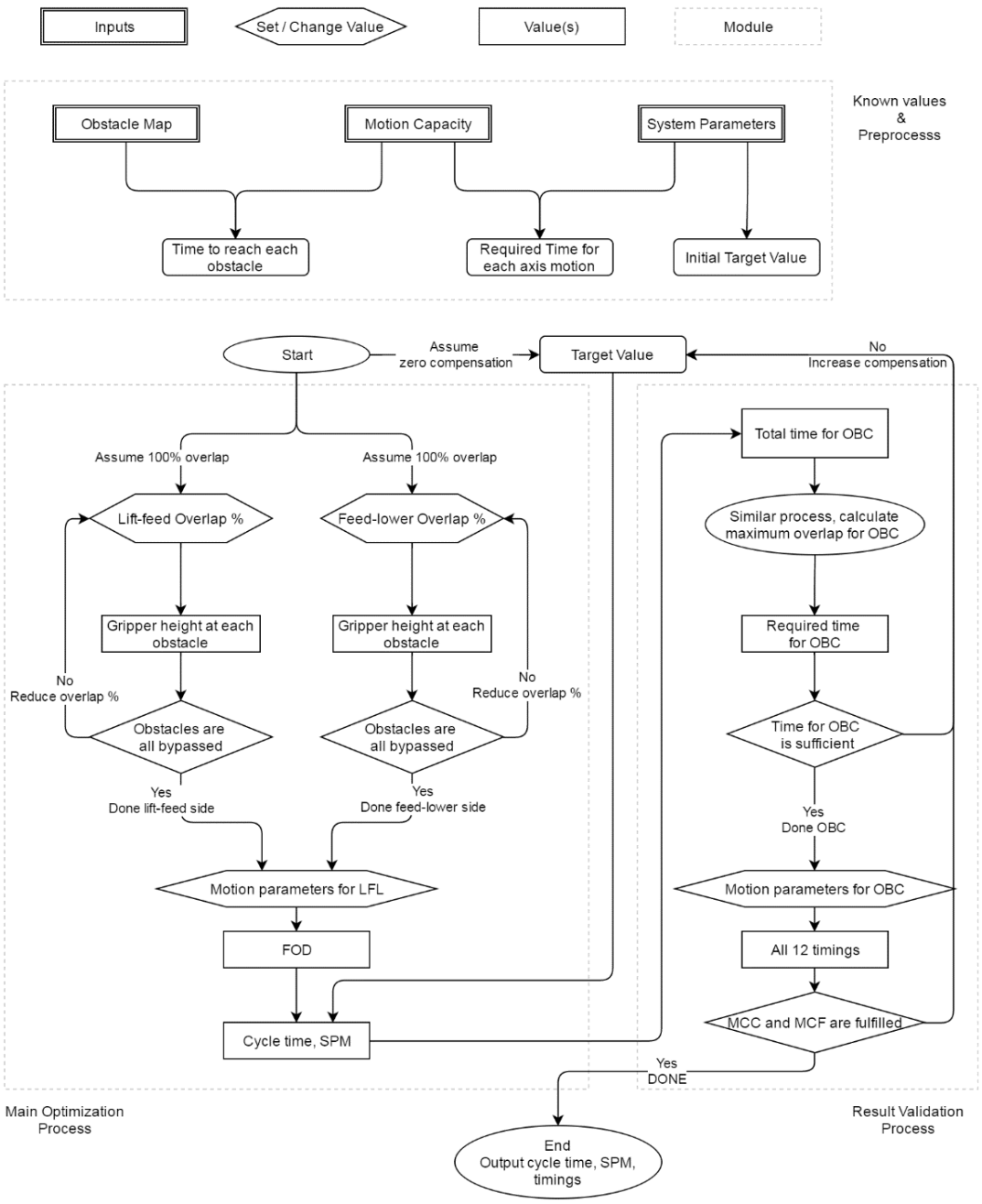
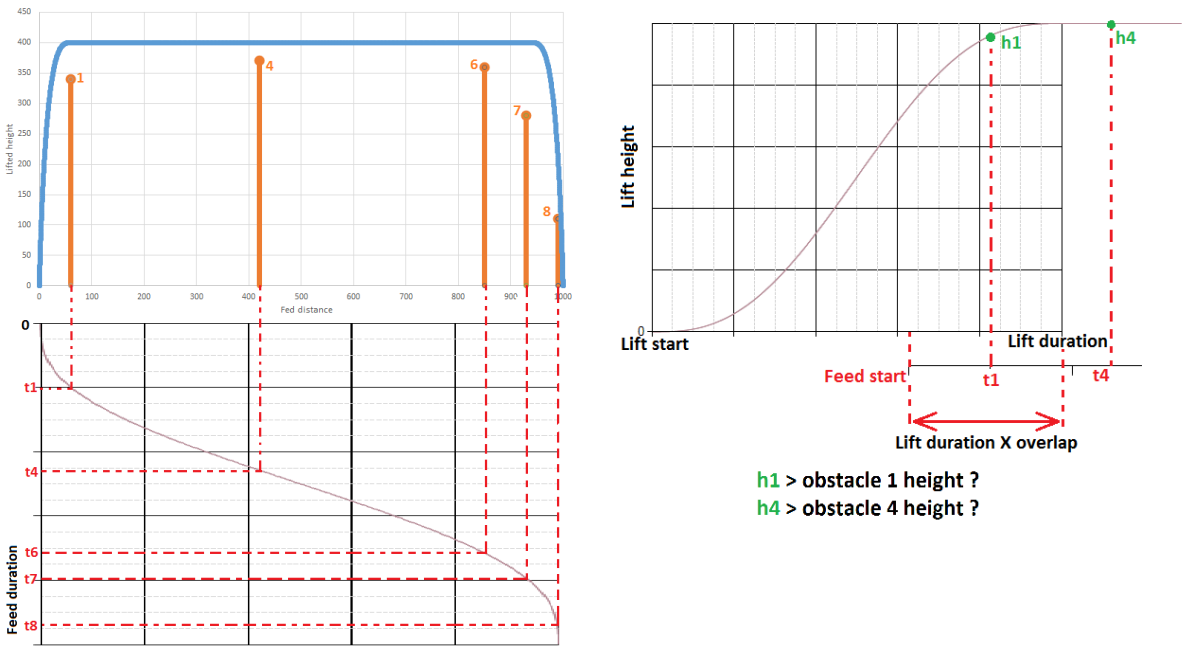


Figure 6.4: Flow chart of optimization level 1

Figure 6.4 shows the flowchart of optimization for the above case. The idea is straightforward, LFL motion will be optimized firstly, because it only related to the geometry of lower die, hence FOD can be calculated. With FOD, target value compensation can be assumed and result in a trial target value, hence trial cycle time and SPM can be calculated. Then do the checking process to validate trial results, if validation is passed, output the results. Details of the process will be introduced in the following.

Firstly, obstacle map, motion capacities and gripper motion parameters will be used as inputs. Required time for feeding/return (x), clamp open/close (y) and lift/lower (z) can be calculated. Moreover, with obstacle map, the timing to reach each obstacle can also be calculated. As Figure 6.5 (a) shows, since the motion curve of feeding process is 345 polynomial curve, with total feed time, timings to reach each obstacle can be solved.



a: timings to reach each obstacle b: lift height at each obstacle (one side)

Figure 6.5: Overlap optimization concerning obstacles

Then, solve the optimum overlap percentage from these timings. As Figure 6.5 (b) shows, with timings to reach each obstacle and assumed overlap, lift height at each obstacle can be solved. For example, in the above figures, gripper will reach obstacle 1 at t1, and obstacle 4 at t4. When increasing overlap percentage, h1 and h4 will decrease. But h1 and h4 must be larger than the height of obstacle 1 and 4, or it will result in collision, therefore, overlap has a maximum value which can be solved from this information.

Figure 6.5 only shows the lift-feed side, feed-lower side can be solved similarly. Hence, with lift-feed overlap and feed-lower overlap, FOD can be calculated using Eq. (16).

Target value should be as small as possible, this means the compensation should be as small as possible. At the beginning, the compensation is assumed to be zero. So, with FOD, cycle time can be calculated using Eq. (20) or Eq. (21) (both will be used and one result in larger cycle time will be critical). Total time for LFL can be calculated from Eq. (10):

$$t_{LFL} = t_{x-f} + (1 - P_{lift})t_z + (1 - P_{lower})t_z$$

And then the total time for OBC can be obtained from Eq. (11):

$$t_{OBC} = t_{cycle} - t_{LFL}$$

The next step is to conduct the similar process to OBC – assume 100% overlap and see if collision exists, if yes, decrease overlap percentage until all the obstacles are bypassed. However, not like the process for LFL, for OBC the t_{OBC} is calculated from Eq. (11) and fixed as an input, while for LFL the t_{LFL} was the output. This may result in the situation that, t_{OBC} is not sufficient for the gripper back motion, hence it is definitely not sufficient for OBC. Such situation is actually rare, because for common die design and transfer system, LFL is more critical, time is more pressing for LFL. If the outcome cycle time can fulfill LFL, it usually can fulfill OBC automatically. Yet it is still possible that t_{OBC} is not sufficient. When this happens, compensation should be increased to increase cycle time, hence to give more time for OBC until it is sufficient.

After OBC is also optimized, all 12 timings can be finalized ($3\ axis \times advance\&return \times start\&end$). Then, as the considerations discussed in 6.2.1 and 6.2.2, clearance must be validated to ensure that MCC and MCF are fulfilled in their valid durations. If clearance is not fulfilled, target value compensation should be increased to create more clearance until it is fulfilled.

Finally, when all the validations are passed, the outcome result can fulfill all the requirements with the shortest cycle time.

6.5 Level 2 – Optimize Overlap and Lift Stroke

For manufacturers, it is not easy to modify the die design, but modifying transfer system is feasible. In 6.4, method has been introduced to modify timings of transfer system, hence overlap can be applied and SPM can be improved. In this section, the situation with more freedom of transfer system parameter modification will be discussed. In additional to timings, if lift stroke can be modified as well, the optimization result can be further improved.

6.5.1 Minimum Lift Stroke

In transfer die, lifter will lift the part to pick up height, then part will be clamped by the gripper. Gripper will further lift the part, then feed along x-axis to the next stage. The

distance that gripper will travel along z-axis after clamping the part, is called lift stroke.

The meaning of lift stroke is to bypass the geometry on lower die or lifter. The larger lift stroke, the longer time that gripper will need to lift the part. In practice, lift stroke is given from transfer system default settings, or modified according to designers' experience. Lift stroke obtained from this method may not be optimum, if manufacturer have more freedom than just modifying timings, optimize lift stroke should be considered.

With obstacle map, the minimum lift stroke can be easily determined. Since the obstacle map shows all the possible collisions, the minimum lift stroke to bypass all the obstacles is exactly the height of the highest obstacle (in mapping process, a clearance equal to one mapping step is already applied).

6.5.2 Additional Lift Stroke – Consider Simple Block Obstacle

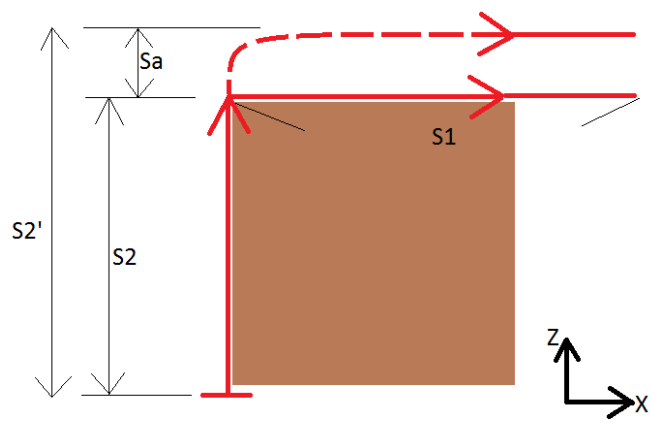


Figure 6.6: Additional Lift Stroke

Consider the above movement, the brown block is the obstacle right at the beginning of LFL. *S2* is the minimum lift stroke to clear the obstacle, *S1* is the transfer pitch. If gripper simply moves *S2* upward, then stop at the corner, and start again on x-axis for *S1*, the total travel distance is minimized, however, minimum travel distance does not mean minimum time.

If gripper moves an additional distance (*Sa*) on z-axis and make the motion profile a round corner, it can start its x-axis motion right after passing the sharp corner – which means an overlap between lift and feed motion. So its average speed on *S2* segment can be increased. Therefore, travel time on *S2* segment is reduced, and

total time for LFL (t_{LFL}) is reduced. But if *Sa* is very large, the drawback of increasing z-axis motion duration will gradually dominate, and t_{LFL} will increase again. So there must be an optimum value of *Sa*.

By conducting experiments and studying the properties of 354 polynomial curve, it is clarified that *Sa = 15% S2* result in the minimum t_{LFL} no regardless of value of *S1* and *S2*. This means:

For an obstacle right at the beginning of LFL, lift stroke equals to 115% of the obstacle height can result in the minimum t_{LFL}.

The 15% additional lift stroke will result in 27.4% overlap percentage.

The process of obtaining the number "15%" and related discussions can be found in Appendix 0.

6.5.3 Additional Lift Stroke – Consider Obstacle With Distance

The goal of lift stroke optimization is to minimize the LFL duration t_{LFL}. In 6.5.2, an obstacle right at the beginning of LFL is considered. But in real cases, the obstacle may locate at some safe distance from the beginning.

When safe distance is zero, it is already clarified that the optimum additional lift stroke is 15% of initial lift stroke, and result in 27.4% overlap.

When safe distance is infinity, it is conceivable that 0% additional lift stroke and 100% overlap percentage can be achieved. This means the part can start feeding immediately when it is being lifted. And no additional lift stroke is needed to speed up lifting process because the space on x-axis is enough.

After running experiments with changing safe distances and additional lift strokes, the following results are concluded:

For known motion capacities, transfer pitch, obstacle height, the optimal strategy of bypassing the obstacle changes while safe distance changes.

Starting from zero safe distance (say S0), which result in 15% additional lift stroke and 27.4% overlap.

Until a certain distance (say S1), the additional lift stroke remains 15%, but overlap percentage increase from 27.4% to 100%. So at S1, the optimal strategy is 15% additional lift stroke with 100% overlap percentage.

Then, continuing increasing safe distance from S1, until another certain distance (say S2), overlap percentage remains 100% (it cannot be higher), but additional lift stroke decrease from 15% to 0%. So at – and after – S2, optimal strategy is 0% additional lift stroke with 100% overlap percentage.

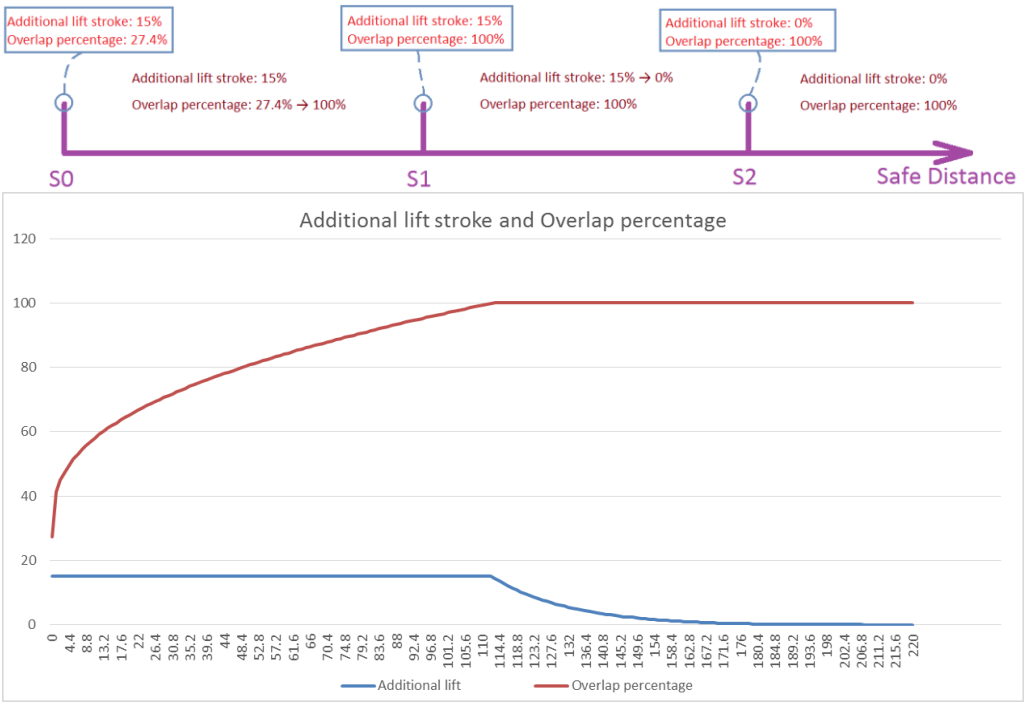


Figure 6.7: Optimum strategy for different safe distance

The above strategy ensures that when obstacle has distance from S0, the modification will firstly be applied to overlap percentage. So that the total transfer time can be minimized.

Moreover, the above strategy also gives the idea to further simplify obstacle map. For multiple obstacles, the optimal strategy will be identical to the strategy for one particular obstacle, which is called “equivalent obstacle”. As Figure 6.8 shows, moving the highest obstacle toward the start (lift-feed) or end (lift-lower) of LFL, the motion profile will be optimized regarding to their safe distance. At one particular distance, the motion profile will bypass all the other obstacles, hence the equivalent obstacles (green dashed line) can be obtained to represent the whole obstacle map.

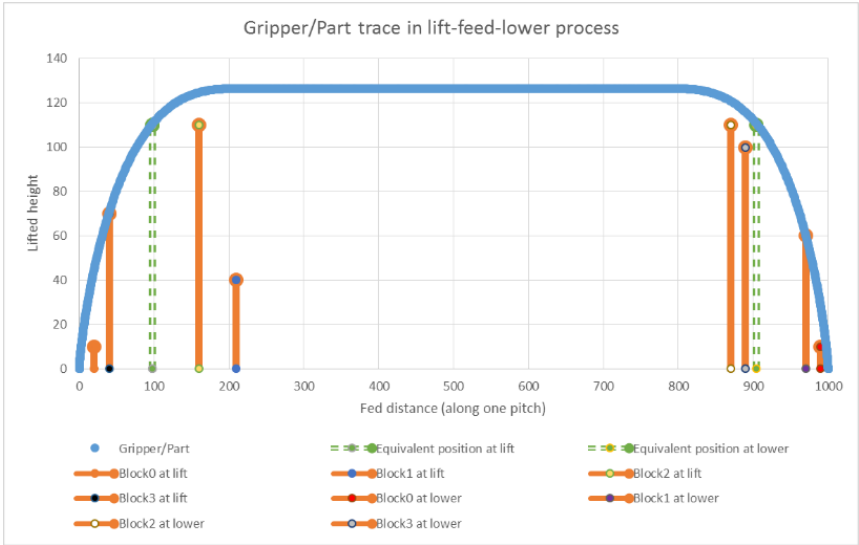
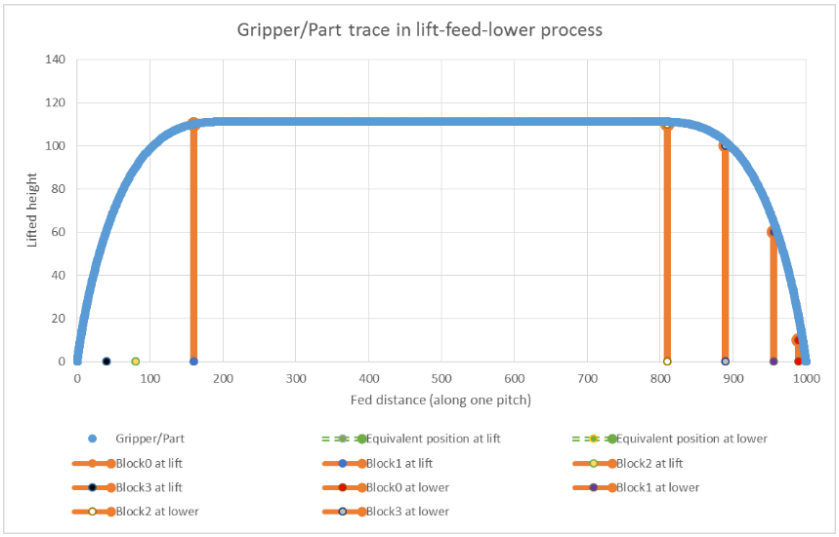


Figure 6.8: Equivalent obstacles for LFL

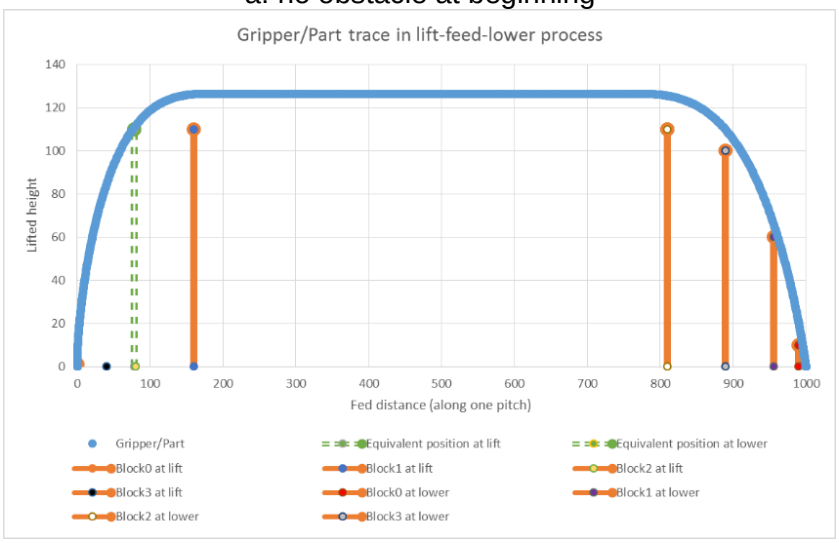
6.5.4 Additional Lift Stroke – Consider Effect on Top Shoe

Consider the case shown in Figure 6.9 (a), the critical obstacles are far away at lift-feed side, the additional lift stroke is small as it can be found that the lift stroke just slightly larger than the highest obstacle.

When there is a tiny obstacle (say 1mm) at the beginning, with the strategy introduced in 6.5.3, the safe distance is zero, and 15% additional lift stroke will be applied. Mathematically, this is correct. Because the calculation only considers t_{LFL}. If gripper must move straight up at beginning to clear the obstacle, then it is optimum to move as fast as possible, hence the feeding can start earlier. And in order to move up as fast as possible, the best strategy is to add the maximum additional lift stroke, thus the result will be like Figure 6.9 (b).



a: no obstacle at beginning



b: 1 mm obstacle at beginning

Figure 6.9: Speed selection, lift stroke and overlap percentage

However, when considering the top shoe optimization, the above result may not be the optimum. Back to the definition of target value, from Eq. (17):

$$Target\ Value = S_S + S_L + S_{Gz} + MCF + S_{Comp}$$

Where S_{Gz} is the lift stroke. The larger lift stroke, the larger target value. Since larger target value can increase cycle time, increasing lift stroke actually have pros and cons:

Increase lift stroke -> increase overlap -> decrease FOD -> decrease cycle time

Increase lift stroke -> increase target value -> increase cycle time

Therefore, optimization of lift stroke is a complicated task that the net benefit of additional lift stroke must be calculated according to multiple factors (obstacle map, press stroke, system parameters, motion capacity).

Finally, the optimization strategy will be similar to Figure 6.10. As the obstacle position changing from zero to infinity, both additional lift stroke and overlap will increase at the beginning. Then at a certain value overlap reaches 100% and lift stroke starts to decrease. However, not like the previous strategy, with the new strategy, the final additional lift stroke may not be zero. There is a certain value that even the obstacle is at infinity, it is optimum to still have an additional lift stroke. This means, the optimum lift stroke is not decided by initial lift stroke, but a certain value according to multiple factors.

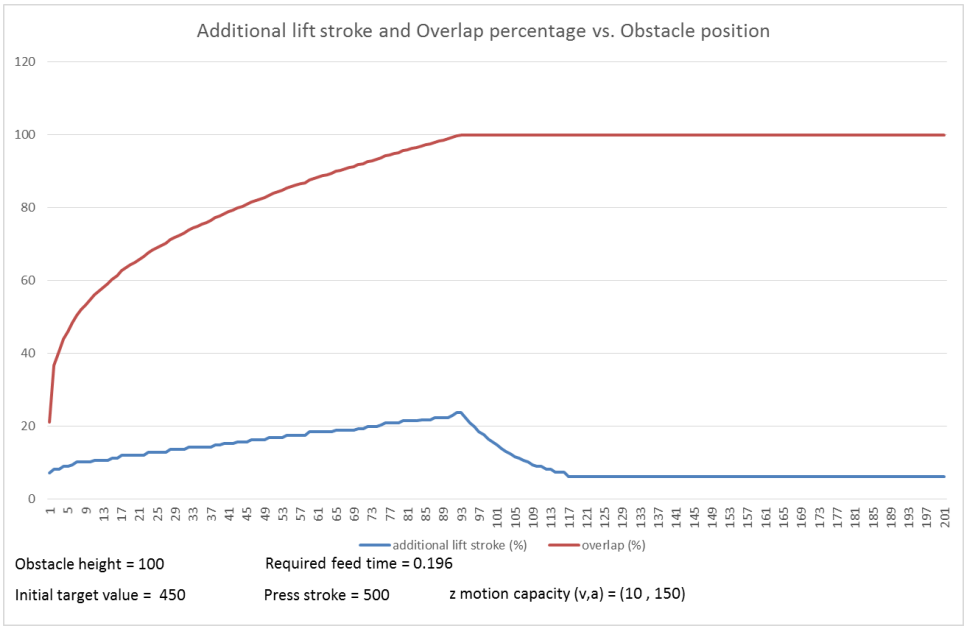


Figure 6.10: New strategy for additional lift stroke and overlap

Figure 6.10 is just an example, for each project with different characteristics, the curve will be different. The optimization strategy can be regarded as an inherent property of particular die system.

The properties of curves in Figure 6.10 are fairly interesting. More discussions about this strategy can be found in Appendix 0.

6.5.5 Workflow of Optimization Level 2

If lift stroke is also to be optimized, the workflow will change.

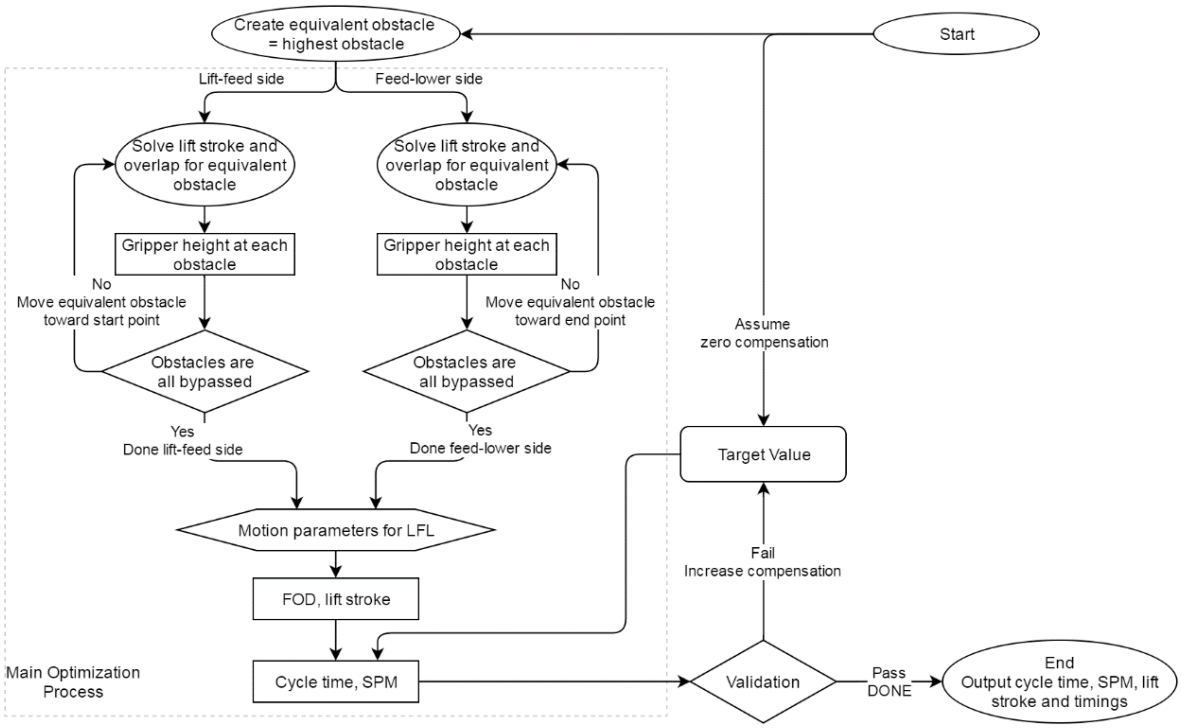


Figure 6.11: Flow chart of optimization level 2

The flow chart for the optimization level 2 in this section is shown in Figure 6.11. The inputs, preprocess and validation module are same as before, but the main optimization process changed. Note: “Validation” process is same as the validation module in level 1 (Figure 6.4).

Firstly, from obstacle map, the highest obstacle will be chosen and a copy of it will be created as the initial equivalent obstacle for both sides (lift & lower). The position of equivalent obstacle will decide the optimization strategy, lift stroke and overlap will be solved according to multiple factors.

Then, the optimization strategy must fulfill the requirement that all obstacles must be bypassed. If such requirement is not fulfilled, the equivalent obstacle will be moved to reduce safe distance. Similar to Figure 6.8, at one certain distance, the equivalent obstacle will result in the optimization strategy that all obstacles are bypassed.

The above process will solve the parameters for LFL, and output FOD and modified lift stroke. Moreover, the modified lift stroke will also change the initial target value. Then, same as the workflow for level 1, the validation process will be conducted.

Finally, the optimization will output not only cycle time, SPM and timings, but also the optimum lift stroke for the transfer system.

6.6 Level 3 – Optimize Overlap, Lift Stroke and Press Stroke

Press stroke is the highest position that top shoe will reach from die close position. In the previous two optimization levels, press stroke is assumed to be fixed, therefore, the optimization is to solve peak velocity and acceleration from press stroke. However, when it is possible to modify press stroke, velocity and acceleration can be pushed to the machine's maximum capacity, and then the related press stroke can be solved.

From Eq. (18) and Eq. (19), it can be found that for given peak velocity or acceleration, the smaller press stroke, the shorter cycle time.

$$t_{cycle,from\ v} = \frac{15 \times Press\ Stroke}{8 \times v_{capa}} \qquad t_{cycle,from\ a} = \sqrt{\frac{10\sqrt{3} \times Press\ Stroke}{3 \times a_{capa}}}$$

Therefore, as Eq. (20) and Eq. (21) showed, according to the relationships between FOD, press stroke, motion capacity and target value, the minimum press stroke can be solved by minimizing target value and FOD.

From velocity: $$FOD = \frac{15 \times Press\ Stroke}{8 \times v_{capa}} \times f(\frac{target\ value}{press\ stroke})$$

From acceleration: $$FOD = \sqrt{\frac{10\sqrt{3} \times Press\ Stroke}{3 \times a_{capa}}} \times f(\frac{target\ value}{press\ stroke})$$

6.6.1 Variable Press Stroke

It is beneficial to modify press stroke, however, in practice, modifying the press stroke is not easy. For traditional mechanical press, the common case is, one press machine has only one fixed press stroke. Although variable press stroke can be achieved for some of these machines, it is not a commonly used function.

Nowadays the hydraulic press and mechanical servo press are developed to have flexible controls of the top shoe motion [29], variable press stroke can be achieved to fit the requirements of specific die sets. However, in practice, manufacturers are still unwilling to modify press stroke unless they are fully convinced, because it is one of the most important parameters of a die system, changes on press stroke will affect many aspects – clearance, cycle time, punching force and even product quality.

This thesis is focused on reducing cycle time and increasing SPM, so in the following sections, discussions will be focused on the optimum press stroke in the interest of these issues.

6.6.2 Workflow of Optimization Level 3

The workflow of optimization level 3 has one major difference from the previous two levels, when the validation process failed, not only the target value compensation will be increased, but also the press stroke will be updated.

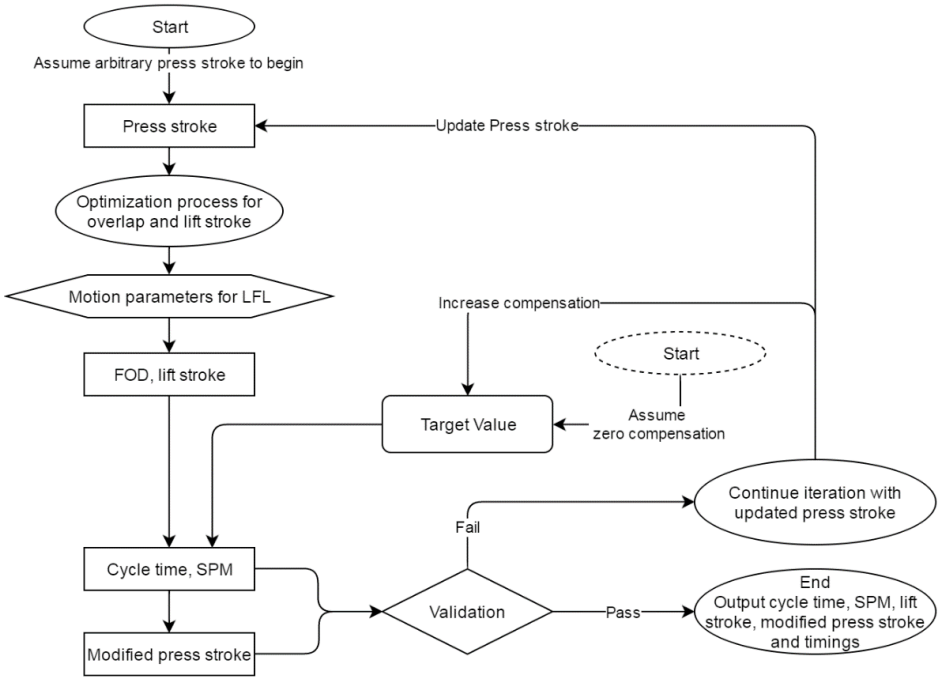


Figure 6.12: Flow chart of optimization level 3

As Figure 6.12 shows, the program start from an initial press stroke to kick off. The initial press stroke can be arbitrary but still need to be a reasonable value, for example, target value plus four times MCF, which should be more than enough but still within a reasonable range of calculation.

With the press stroke, the optimization for overlap and lift stroke can be done following the steps in optimization level 2. However, at the end, from FOD, cycle time and target value, a modified press stroke can be calculated, which may or may not be same as the input press stroke. Use the new press stroke to conduct validation process. If validation fails, increase compensation just like previous levels, plus, the press stroke should be renewed as well. Because the modified press stroke is, to

some degree, closer to the optimum value. Therefore, the whole loop will be done again using the modified press stroke.

As Figure 6.13 shows, when target value compensation increases, the outcome press stroke will also increase, the positive correlation (close to but not exactly linear) indicates that the smaller target value, the smaller press stroke, hence the smaller cycle time. This phenomenon is qualitatively identical to the previous statements at the end of 6.2.4, but mathematically fuzzier, because after introducing lift stroke modification, the effect of target value modification becomes complex. This is also one of the reasons that the process should be redone when target value changes.

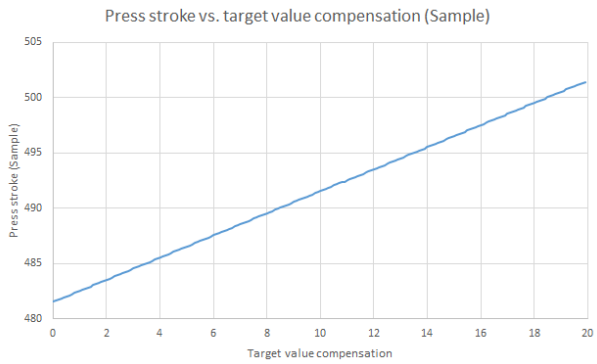


Figure 6.13: Press stroke vs. target value compensation

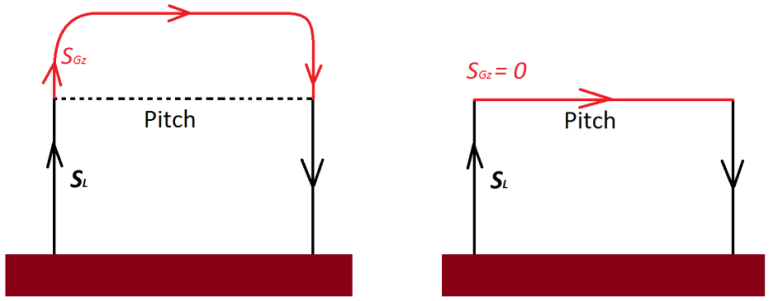
With the increment of target value, press stroke will increase until the validation is passed. Then, a set of values, including cycle time, SPM, lift stroke and press stroke, will be output as the result. The process ensures the minimum target value and press stroke that can pass the validation, thus ensures the minimum cycle time.

6.7 Expansion to Progressive Die

The previous optimization algorithms are based on transfer die. Transfer system in transfer die is gripper, which have x, y and z-axis motion. Progressive die can be considered as a simple case of transfer die. The lifter will lift the part (strip) to transfer position when die opens, which is same as transfer die. However, after that, part will directly be fed as a strip, there is no gripper to pick the part. So in transfer die, part will be lifted twice (by lifter and gripper), while in progressive die, part will only be lifted once (by lifter).

Essentially, because in progressive die, all parts are on one continuous strip, the lift height of each stage must be same. Plus, the lifters in progressive die are usually rails in order to guide the strip, so from the functional point of view they are more like grippers rather than

lifters in transfer die. Therefore, it is also safe to say: in progressive die, part will be lifted once, by gripper which has zero clamp stroke and zero lift stroke.



a: Transfer Die b: Progressive Die

Figure 6.14: Expansion to Progressive Die

As Figure 6.14 shows, in both transfer die and progressive die, part will be firstly lifted by lifter, then feed forward. The difference is, in transfer die, the feeding motion profile is contains another lifting distance S_{Gz}. If S_{Gz}=0, motion profile will be same.

However, the optimization introduced in this thesis is to optimize motion profile and timings of the transfer system, then calculate maximum top shoe speed or press stroke. If S_{Gz}=0, the motion profile is simply a straight line and cannot be optimized. From another perspective, progressive die has no overlap and lift stroke. Note: the sharp corner in Figure 6.14 (b) is necessary, because strip cannot be fed until lifter and stripper separate, which is when lifter fully extend.

Therefore, to expand the above algorithms to progressive die, the process of solving optimum overlap and lift stroke can be skipped because lift stroke = 0. Moreover, clamp stroke = 0. Then just solve the optimum timings. Only the timings for x-axis advance motion exist (and need to be solved) in progressive die, because:

1. No lift stroke and clamp stroke, so no y-axis and z-axis motions and timings.

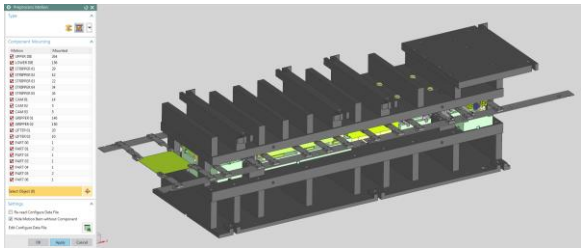
2. No x-axis return motion, because strip will just be fed forward on the rail.

Finally, enter the validation process to solve the optimum top shoe speed or press stroke by varying target value, so optimization for progressive die can be done using the same algorithms.

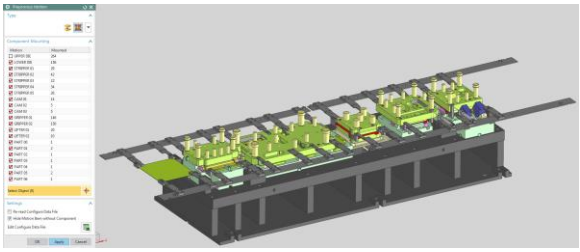
7 Case Study

One case study is chosen to validate the algorithms proposed in this thesis. The case study project is provided by LTS, with the part/assembly files and parameters before optimization.

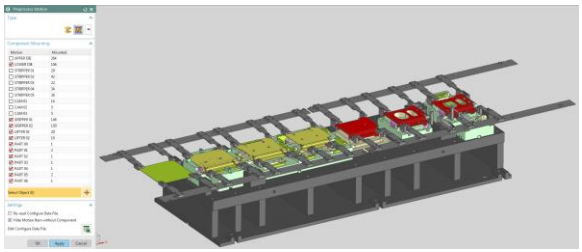
7.1 Overview



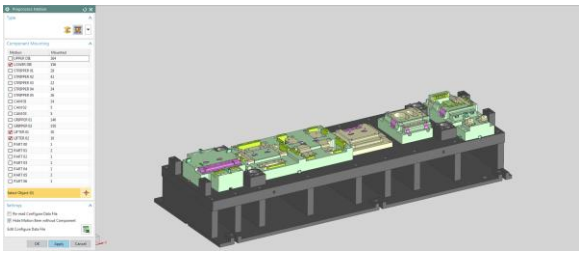
a: overview



b: top shoe hided



c: strippers and cams hided



d: grippers and parts hided

Figure 7.1: Overview of Case Study

The case study is a transfer die project with 6 stages, final product is a seat panel. From Figure 7.1 (a) to (d), components are hidden layer by layer to show the overview of the project. Figure 7.2 shows the final product, which has several holes and bending features.

Figure 7.2: Case study final product

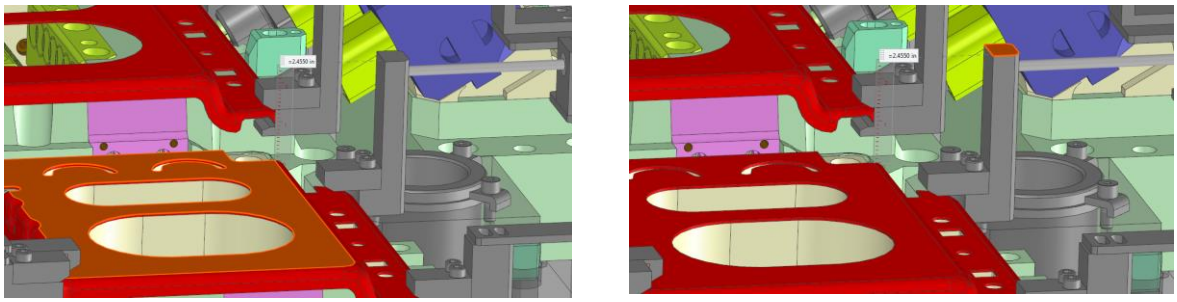
The whole die assembly contains over 900 parts, these parts are defined as 21 die components, include: 5 strippers, 2 lifters, 3 cams, 2 grippers, 7 parts (1 blank + 5 intermediate product + 1 final product), plus top shoe and lower shoe.

7.2 Parameters

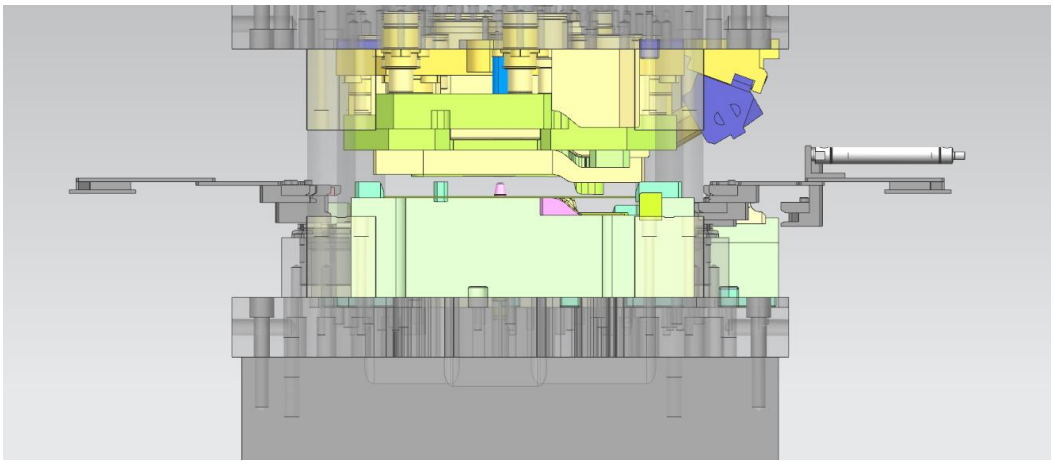
Unit of calculations is mm (initially inch but all converted to metric for the algorithms).

Initial SPM is 14. Motion capacity for gripper x and y motion is 1 m/s for velocity, and 4 m/s^2 for acceleration. For gripper z motion, the velocity is limited to 0.4 m/s for slower lift up and lower down. Top shoe motion capacity is 1 m/s and 2 m/s^2.

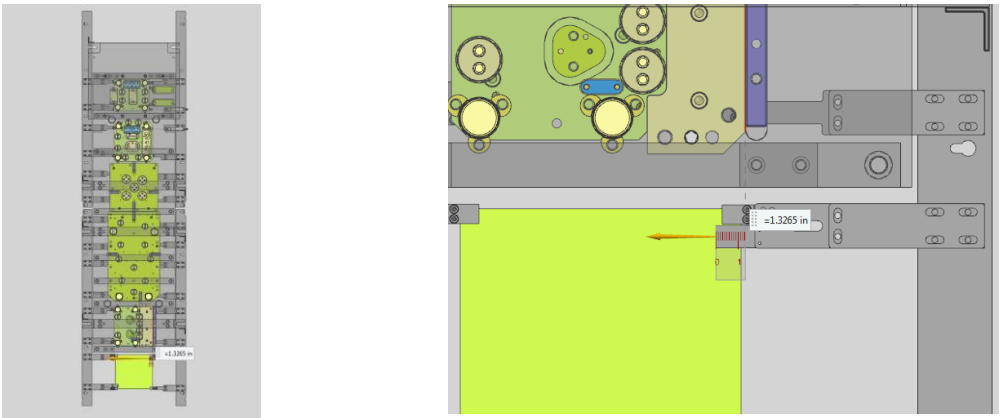
From the travel distances of strippers and lifters, the critical lifter-stripper pair is at stage 4, where the lift height is 47.63 mm, stripper travel is 34.93 mm.



a: Minimum clearance for clamping



b: Minimum clearance for feeding



c: clamping danger zone

Figure 7.3: Obtain MCC and MCF manually

Then, open the die set and manually analyze the geometry, MCF and MCC can be obtained. As Figure 7.3 shows, MCC is obtained mainly by measuring the distance between the top face of part and the top face of the gripper, MCF is obtained by viewing from the front and find the clearance when the part geometry is fully separated from top shoe and stripper.

Danger zone for clamping is obtained by measuring how “deep” the grippers will go into the die to pick the part.

Figure 7.3 shows how the MCC, MCF and the clamping danger zone is obtained. It is given that MCC is 62.36 mm, MCF is 70 mm, and danger zone is 35 mm.

It should be noted that the above values are obtained manually, which means there is still room to improve, not only the value, but also the process. This topic will be further discussed in Chapter 8.

7.3 Obstacle Mapping

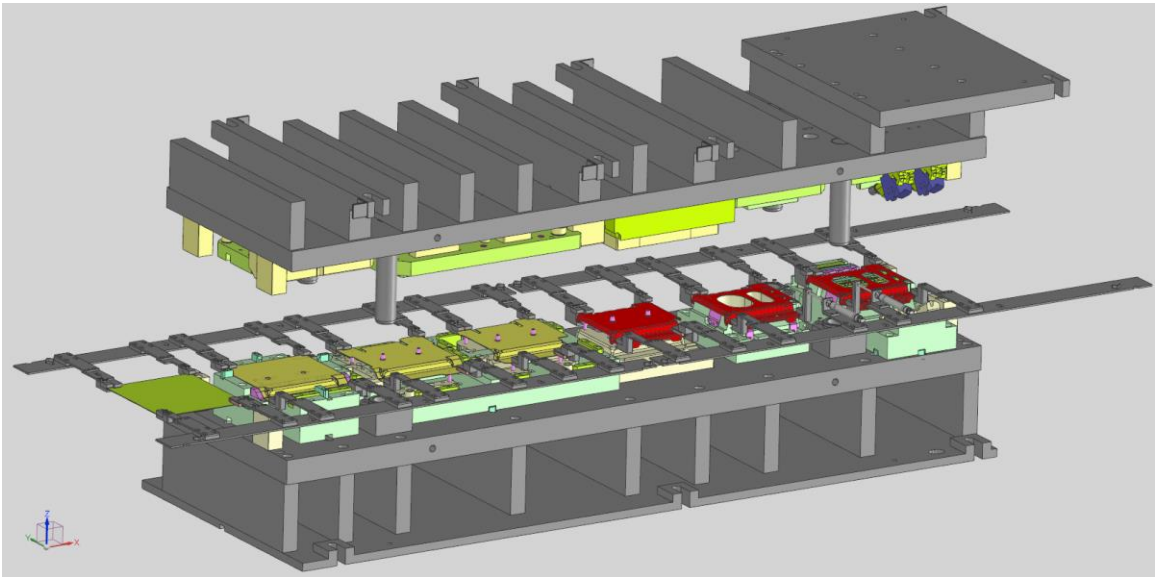
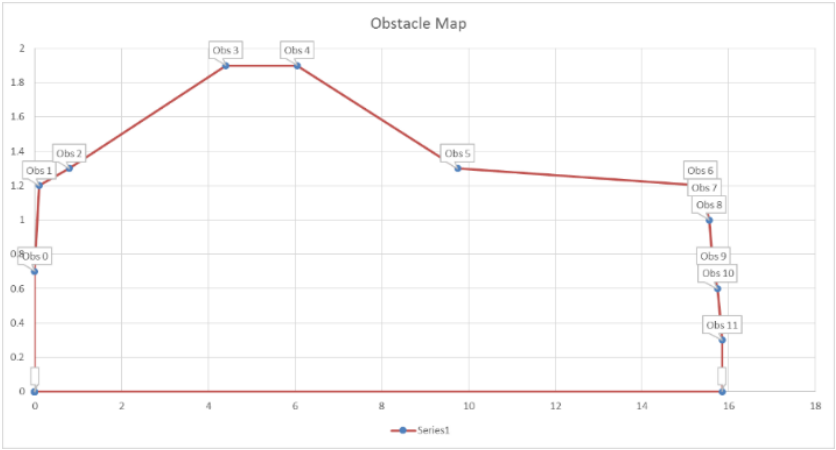


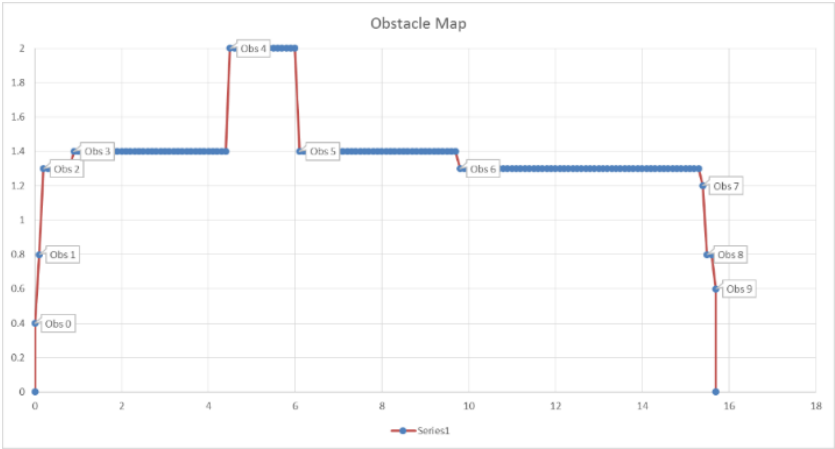
Figure 7.4: Initialization for Obstacle Mapping

After initialization (Figure 7.4), the whole assembly is opened and ready for obstacle mapping. Both zig-zag and column-scan mapping strategy are tried to generate obstacle maps for the case study. The obstacle mapping process in this case study is tested in NX 10 software environment. Hardware configuration is Intel(R) Xeon(R) E5-1620 v3 CPU, 32 GB RAM, NVIDIA Quadro K2200 GPU. Moving step is 0.1 inch or 2.54 mm.

With the above configuration, the zig-zag mapping took around 40 minutes, while the segmented column-scan mapping took around 180 minutes to conduct the forward obstacle mapping. Result forward obstacle maps are shown in Figure 7.5.



a: result from zig-zag (unit in inch)



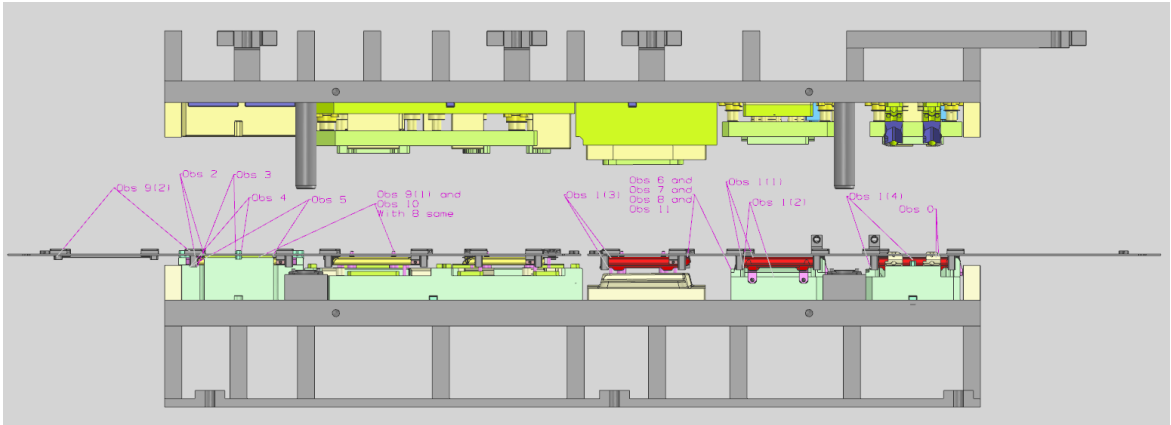
b: result from column-scan (unit in inch)

Figure 7.5: Forward Obstacle Map of Case Study

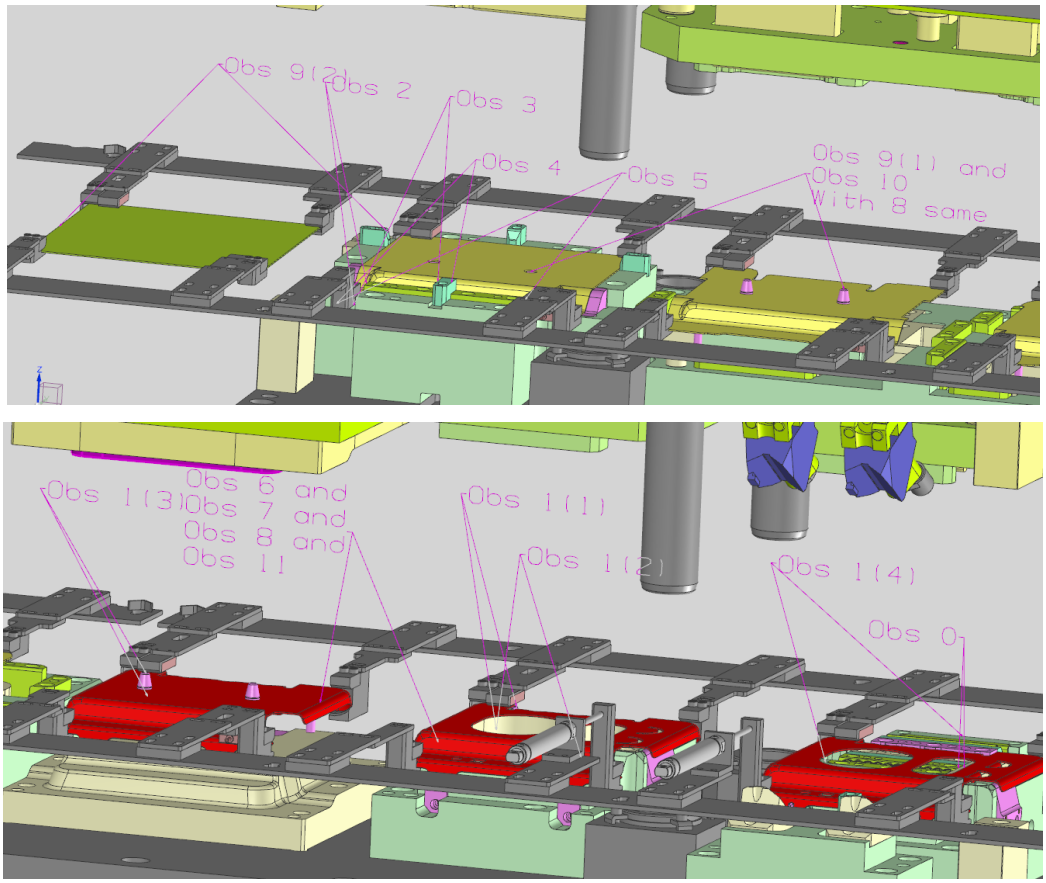
As previously introduced, obstacle map from zig-zag mapping will only find the critical obstacle pixels, while column-scan will find the obstacle at each column. Compare Figure 7.5 (a) and (b), it can be found that the critical obstacles appear to be similar for both strategies. Zig-zag mapping will ignore some obstacles. It can be found that the ignored obstacles are those who have the same or lower height comparing to a previously registered obstacle. Column-scan mapping will faithfully record all these pixels. Hence the shape of obstacle map is different – inclined lines in zig-zag represent the connection of corner points in column-scan.

For this case study, as Figure 7.5 shows, zig-zag strategy is good enough since it does not miss critical obstacles.

Figure 7.6 shows the actual locations of obstacles. It can be found that obstacles locate at different stages and between different components. Some obstacles contains different collision pairs (e.g. obstacle 1), some has only one collision pair (e.g. obstacle 0). Plus, for some component pairs, they generate multiple obstacles (e.g. obstacle 6, 7, 8, 11) at different locations. All the information can be helpful for designers.



a: overview



b: zoom in

Figure 7.6: Locations of obstacles

Similar to forward map, backward map can be obtained by moving the gripper at x-y plane, the result will be two obstacles at (0.87, 4.6) and (15.49, 4.6).

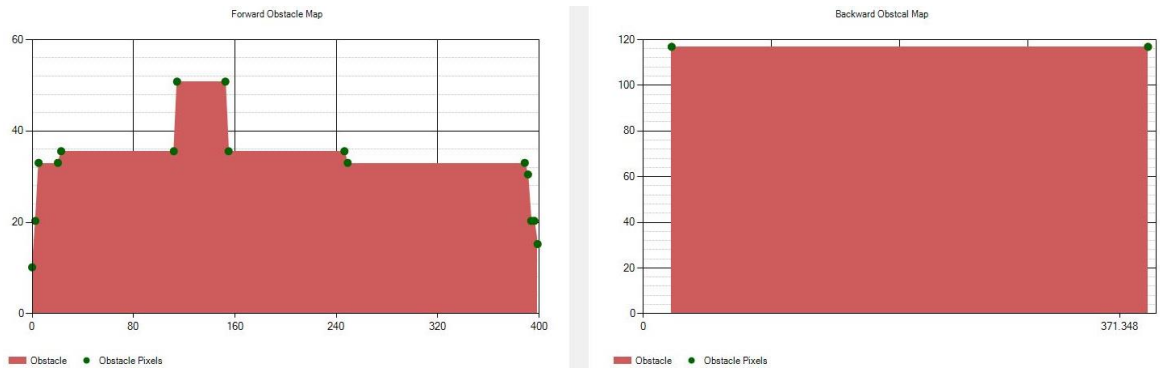


Figure 7.7: Obstacle Map of Case Study

Figure 7.7 shows both forward and backward obstacle map used in the later optimizations (unit converted to metric).

7.4 Optimizations

In order to test the algorithms, four optimization strategy will be tried. Other than the optimization level 1~3, one more strategy (say level 0) will be conducted as follows:

Similar to optimization level 1, level 0 is also optimization for overlap only. The difference is, for level 1, the optimization will use the motion capacity, which is the highest velocity or acceleration that the transfer system can handle. For level 0, the velocity and acceleration will not excess the current value.

Consider the initial system parameters, from these parameters the current maximum velocity and acceleration can be calculated, and optimization level 0 will just use these values as motion capacities, so the total time on any single axis will be same as, or even longer than before.

The above strategy will show that even the duration for any single axis is the same, cycle time still can be reduced by applying overlap alone.

7.4.1 Level 0

Initial SPM is 14, so initial cycle time is 60/14=4.286s. The duration for x, y and z-axis advance and return motion can be calculated. Hence the maximum velocity and acceleration can be calculated using equations in Table 3.1. Since the initial timings result in different peak v and a, the larger one will be used because such value has been already “proved” to be feasible.

Axis	Travel distance (mm)	Duration (s)	Peak. v (mm/s)	Peak. a (mm/s^2)
x	400	0.83 (feed) 1.67 (back)	903	3325
y	140	0.95 (open) 0.6 (close)	438	2245
z	70	0.36 (lift) 0.36 (lower)	367	3168

Table 7.1: Initial peak velocity and acceleration

The result of optimization is shown by three items: data sheet, motion profile chart and motion curve chart.

Data sheet contains information about the outcome parameters, such as cycle time, SPM, lift stroke, press stroke, overlap percentage, top shoe speed, and optimized timings. According to different optimization option, some value in data sheet will be same as input, for example, in optimization level 0, 1 and 2, press stroke is not changed.

Motion profile chart shows the motion profile in LFL and OBC. It can clearly show how the gripper motion will bypass the obstacles.

Motion curve chart shows the motion curve for top shoe, stripper, lifter and gripper z-axis. It also contains the clearance chart to show how the clearance requirements are fulfilled.

The following is the optimization result of case study with optimization level 0.

First of all, it can be found that SPM is improved from 14 to 22.9. The huge improvement is due to the large overlap in LFL and OBC. The four overlap are all excess 50%, which can save a lot of time in part transfer and gripper return. The durations shown at the bottom of data sheet also indicates that the speed and acceleration is the same as or lower than initial values.

lift stroke: 70

lift-feed overlap percentage: 71.3000000000016
feed-lower overlap percentage: 82.400000000001

open-back overlap percentage: 67.9
back-close overlap percentage: 54.3

press stroke: 350
cycle time: 2.6190784397061
SPM: 22.9088213206524
minimum clearance when feeding: 189.303583770529
yValueAtSCVt_lift: 35.0476222831687
yValueAtSCVt_lower: 35.0476222831687

top shoe maxv: 0.50113046638927
top shoe maxa: 1.17833939463148

Optimized Timings		Default Timings	
X_Advance	X_Return	X_A_Def	X_R_Def
305	95	330	110
60	254	40	250
Y_Advance	Y_Return	Y_A_Def	Y_R_Def
69	209	70	250
151	291	150	300
Z_Advance	Z_Return	Z_A_Def	Z_R_Def
291	20	300	40
340	69	330	70

	Optimized Durations	Default Durations
x_Feed:	0.84	0.83
x_Back:	1.16	1.67
y_Open:	0.6	0.95
y_Close:	0.6	0.6
z_Lift:	0.36	0.36
z_Lower:	0.36	0.36

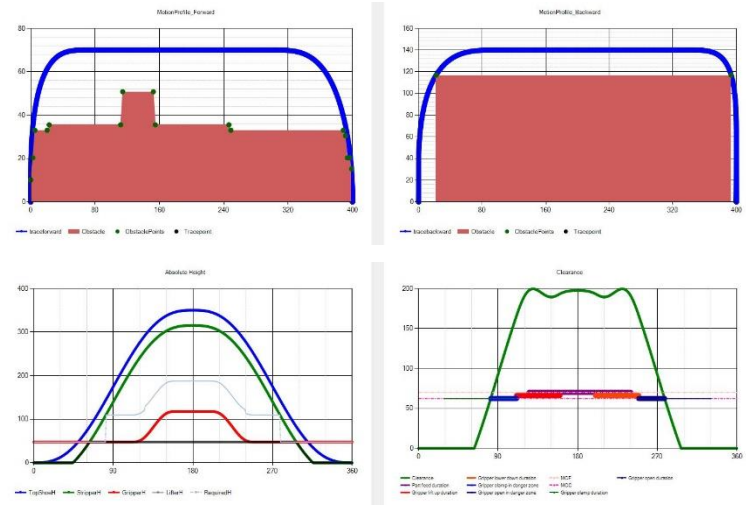


Figure 7.8: Case study level 0 optimization result

7.4.2 Level 1~3

Optimization level 1~3 are already introduced in previous contents, the result will be given directly as follows.

lift stroke: 70

lift-feed overlap percentage: 71.3000000000016
feed-lower overlap percentage: 82.200000000001

open-back overlap percentage: 76.7
back-close overlap percentage: 60

press stroke: 350
cycle time: 2.26263137085708
SPM: 26.5177972748041
minimum clearance when feeding: 181.669099481143
yValueAtSCVt_lift: 35.0231215720681
yValueAtSCVt_lower: 35.0231215720681

top shoe maxv: 0.580076815386339
top shoe maxa: 1.57884610436082

Optimized Timings		Default Timings	
X_Advance	X_Return	X_A_Def	X_R_Def
302	89	330	110
63	259	40	250
Y_Advance	Y_Return	Y_A_Def	Y_R_Def
73	216	70	250
144	287	150	300
Z_Advance	Z_Return	Z_A_Def	Z_R_Def
287	20	300	40
340	73	330	70

	Optimized Durations	Default Durations
x_Feed:	0.76	0.83
x_Back:	1.07	1.67
y_Open:	0.45	0.95
y_Close:	0.45	0.6
z_Lift:	0.33	0.36
z_Lower:	0.33	0.36

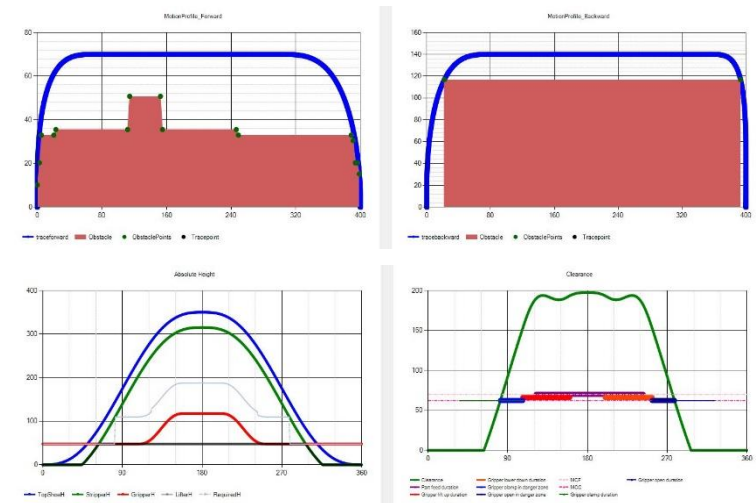


Figure 7.9: Case study level 1 optimization result

Note: SPM = 26.52, x, y and z-axis all speed up.

lift stroke: 53.4416

lift-feed overlap percentage: 68.0000000000004
feed-lower overlap percentage: 78.9850438974725

open-back overlap percentage: 76.6
back-close overlap percentage: 59.9

press stroke: 350
cycle time: 2.25483629860718
SPM: 26.6094705132529
minimum clearance when feeding: 181.85544678367
yValueAtSCVt_lift: 35.2907565086021
yValueAtSCVt_lower: 35.2907565086021

top shoe maxv: 0.582082167477406
top shoe maxa: 1.58978125985122

Optimized Timings		Default Timings	
X_Advance	X_Return	X_A_Def	X_R_Def
302	89	330	110
63	259	40	250
Y_Advance	Y_Return	Y_A_Def	Y_R_Def
72	216	70	250
144	288	150	300
Z_Advance	Z_Return	Z_A_Def	Z_R_Def
288	28	300	40
332	72	330	70

	Optimized Durations	Default Durations
x_Feed:	0.76	0.83
x_Back:	1.06	1.67
y_Open:	0.45	0.95
y_Close:	0.45	0.6
z_Lift:	0.28	0.36
z_Lower:	0.28	0.36

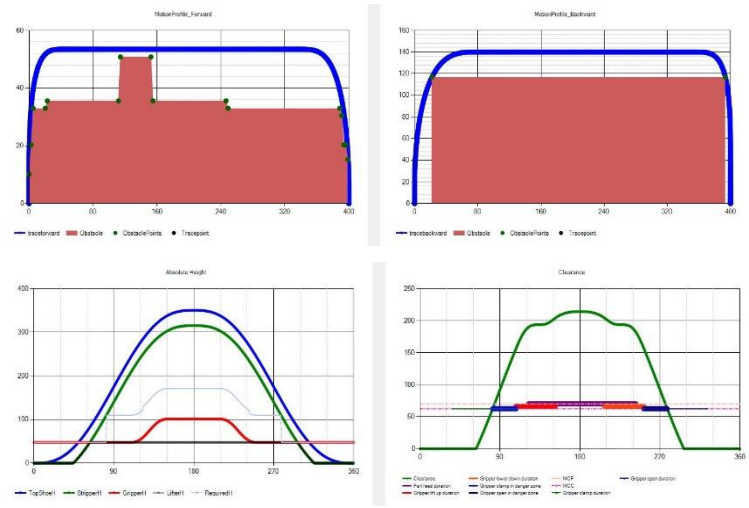


Figure 7.10: Case study level 2 optimization result

Note: SPM = 26.61, lift stroke = 53.44, x, y-axis same as level 2, but z-axis further speed up.

lift stroke: 54.61

lift-feed overlap percentage: 68.3000000000004
feed-lower overlap percentage: 80.9562013772952

open-back overlap percentage: 69.7
back-close overlap percentage: 55.5

press stroke: 397.280654999994
cycle time: 2.14363228187615
SPM: 27.9898751792853
minimum clearance when feeding: 204.393189441724
yValueAtSCVt_lift: 35.7183422422474
yValueAtSCVt_lower: 35.7183422422474

top shoe maxv: 0.999676350868572
top shoe maxa: 1.99662362188885

Optimized Timings		Default Timings	
X_Advance	X_Return	X_A_Def	X_R_Def
299	99	330	110
67	251	40	250
Y_Advance	Y_Return	Y_A_Def	Y_R_Def
76	209	70	250
151	284	150	300
Z_Advance	Z_Return	Z_A_Def	Z_R_Def
284	29	300	40
331	76	330	70

	Optimized Durations	Default Durations
x_Feed:	0.76	0.83
x_Back:	0.91	1.67
y_Open:	0.45	0.95
y_Close:	0.45	0.6
z_Lift:	0.28	0.36
z_Lower:	0.28	0.36

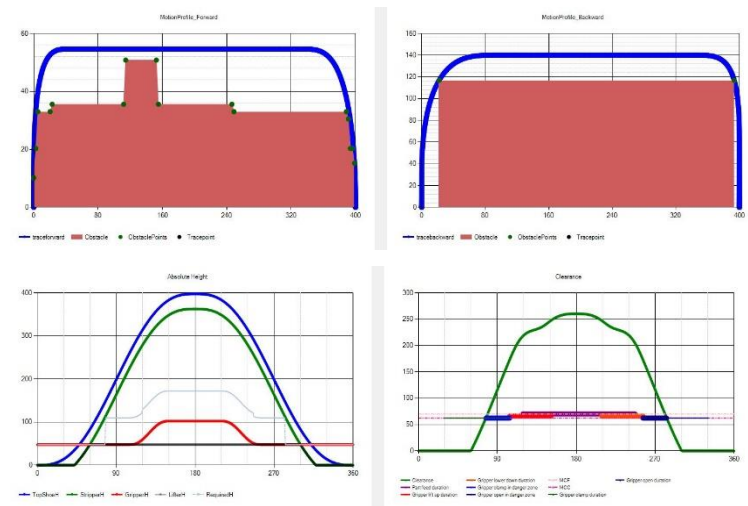


Figure 7.11: Case study level 3 optimization result

Note: SPM = 27.99, lift stroke = 54.61, press stroke =397.28.

7.5 Result Discussion

SPM

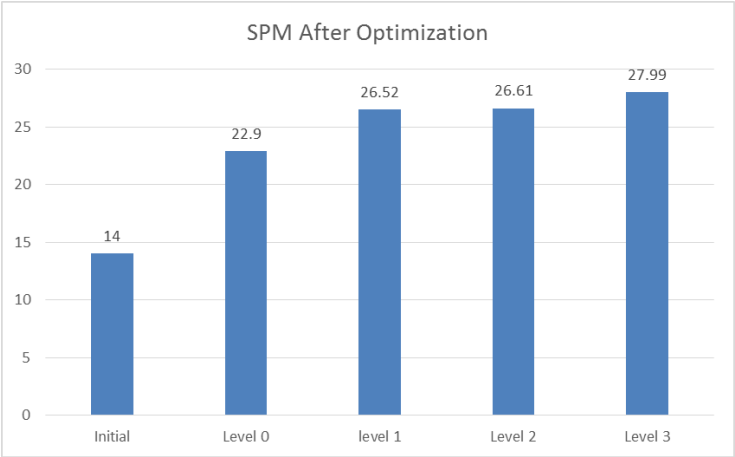


Figure 7.12: Result SPMs of each optimization level

Result SPMs are shown in a bar chart in Figure 7.12. It can be found that the outcome SPM increases when the optimization level up. The largest improvement appears between initial SPM and optimization level 0, which show large room of optimization of the initial project. However, in practice, the improvement may not be as big as Figure 7.12 shows, because in this case study, the initial settings have zero overlap. But in reality, manufacturers may notice the potential of applying overlap during the producing, and apply some overlap based on their experience. The actual SPM without proposed optimization algorithms could be set around 20. Yet, with the proposed algorithms, SPM can be further improved.

With more freedom of changing parameters, the optimization level can increase, and result SPM will be higher.

Lift Stroke and Press Stroke

In level 0 and 1, lift stroke is fixed as 70 mm, while the highest obstacle is only 50.8 mm. So in level 2 and 3, the modified lift stroke is reduced to 53~55 mm to reduce lift duration. Moreover, in level 3, press stroke is modified from 350 mm to 397 mm. Although press stroke is increased, the cycle time can be reduced, because the extra clearance created from the extra press stroke can ensure that the top shoe run at its maximum velocity and acceleration. This will also affect the operation cost, since faster top shoe motion will consume more energy, and the net profit of such modification varies due to a lot of factors, which should be considered by manufacturers. But this is out of the scope of this research.

Consider Feasible Values

In practice, the modification of system parameters is not totally free even when it is allowed.

```
lift stroke: 55

lift-feed overlap percentage: 68.4000000000018
feed-lower overlap percentage: 81.1000000000011

open-back overlap percentage: 71
back-close overlap percentage: 56.3

press stroke: 400
cycle time: 2.16400408397111
SPM: 27.7263802062219
minimum clearance when feeding: 209.970645192544
yValueAtSCVt_lift: 39.5791791038454
yValueAtSCVt_lower: 39.5791791038454

top shoe maxv: 0.693159505155549
top shoe maxa: 1.97261896060018

      Optimized Timings                Default Timings
X_Advance        X_Return |  X_A_Def        X_R_Def
300              97       |  330            110
66               252      |  40             250
                          |
Y_Advance        Y_Return |  Y_A_Def        Y_R_Def
75               210      |  70             250
150              285      |  150            300
                          |
Z_Advance        Z_Return |  Z_A_Def        Z_R_Def
285              28       |  300            40
332              75       |  330            70

                 Optimized Durations          Default Durations
x_Feed:          0.76                         0.83
x_Back:          0.93                         1.67
y_Open:          0.45                         0.95
y_Close:         0.45                         0.6
z_Lift:          0.28                         0.36
z_Lower:         0.28                         0.36
```

Figure 7.13: Level 1 with feasible optimum parameters

For example, the press stroke may be allowed to be modified, but the value cannot be set to 397.28 mm, it probably has a restriction that press stroke can only be integer multiples of 50 mm, so the nearest value is 400 mm. Similarly, lift stroke may not be able to set to 54.61 mm, but 55 mm is a reasonable value.

Optimization level 3 will output the theoretical optimum settings for the die project, but the values may not be feasible. By rounding the lift stroke and press stroke to feasible values, and run optimization level 1 to solve best timings for these values, the feasible result for real case can be obtained.

It can be found in Figure 7.13 that the SPM for this case will be 27.72. Lower than theoretical optimum value (27.99) but still highly optimized.

Further Improvements

It is introduced in Chapter 6 that the workflow contains a “validation” process. The clearance must meet requirements of MCC and MCF. In case study, MCC has become the boundary condition. From clearance charts, it can be found that clearance in the middle of the chart (for MCF) is way more than enough, while at the side of the chart, the bold lines (MCC and danger zone) is just on the edge of clearance curve. From Figure 7.3, the reason of such phenomenon can be found: part contains bending features, but overall it is quite flat, so MCF is not large, however, gripper in transfer system has a weird geometry that is even thicker than the part, hence result in large MCC.

The grippers in this case study may come from a general transfer system, not specialized for this part. It is also possible that the design of grippers has considered other factors that are not shown in the assembly. Anyway, the current gripper design is not optimal for part transfer efficiency and system productivity. Changing the gripper design and reduce MCC can be suggested to further improve SPM. If MCC can be reduced from 62.36 mm to 30 mm, with 55 mm lift stroke and 400 mm press stroke, SPM can be further improved to 29.4.

8 Conclusions and Future Works

This thesis is devoted to transfer system parameters optimization in transfer die according to the geometries of die components. The result of optimization can provide an improved productivity (SPM) while avoiding collision during part transfer.

In current industry, especially sheet metal forming for vehicle components, transfer die is widely used due to its highly automated process and stable product quality. The productivity of transfer die highly depends on transfer system. However, due to difficulties in accurately analyzing geometries and motions of the die system, the decision of transfer system settings is currently based on experience. In this research, with DYNMIK and Siemens NX software, the whole die assembly can be presented virtually, motion simulation can be conducted, and potential collisions can be detected. Hence, information of die geometry and its interaction with transfer system can be extracted to be the basis of an accurate transfer system optimization.

8.1 Contributions

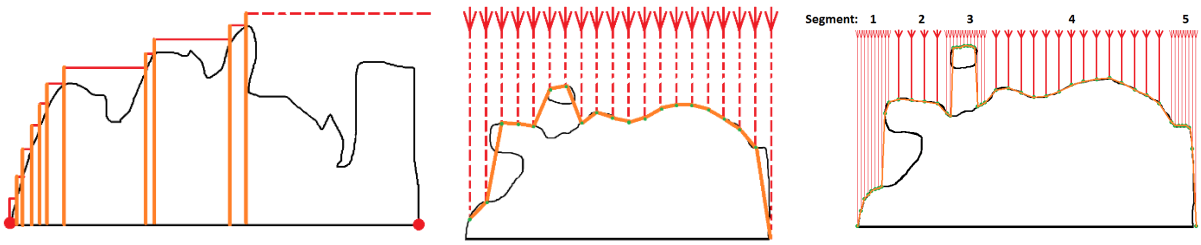
This thesis proposed algorithms for transfer die designer and manufacturers to conduct geometry analysis and motion analysis in order to optimize the transfer system. The optimization algorithms proposed in this thesis contain two steps – “Obstacle Mapping” and “Transfer System Optimization According to Obstacle Map”.

Obstacle Mapping

“Obstacle Map” is the collection of potential collision during part transfer. “Obstacle Mapping” is the process of creating Obstacle Map.

It is conceivable that different die projects should have different optimum transfer system settings. These settings should regard to the geometry of the die components. In transfer die operation, part will be transferred from current stage to next stage during die open, and the motion profile must ensure that collision must be avoided during part transfer. To achieve this, the potential collisions during part transfer must be detected and recorded.

In this thesis, Siemens NX is used as the CAD platform, with a customized kinematic model from DYNMIK, the obstacle mapping program is developed, parts can be moved virtually and the collision check result will show the potential collisions.



a: zig-zag mapping b: column-scan mapping c: segmented column-scan mapping

Figure 8.1: Automatic Mapping Strategies

Multiple automatic mapping strategies are proposed, each has their own pros and cons. Zig-zag mapping is quick, and its result can be directly used in optimization, but for complex die geometry, its reliability is not high. Column-scan mapping has accurate result, but the mapping efficiency is low. By segmenting the mapping task, the drawbacks of column-scan can be overcome, and flexible accuracy can be achieved, but it requires multiple computers or a powerful computer that can run multiple NX sessions.

Obstacle map is the inherent property of a die assembly. No matter what will be input to transfer system, the outcome motion profile will need to bypass all the obstacles. Therefore, the obstacle map can be the basis of, not only the proposed optimization algorithms in this thesis, but also other optimization algorithms in future works.

Transfer System Optimization According to Obstacle Map

It is clarified that 345 polynomial curve is commonly used in transfer die system as the motion curve of components. With the properties of 345 polynomial curve, multiple optimization algorithms are proposed in this thesis based on obstacle map.

The optimization will result in suggested values to input to transfer system, however, in practice, the modification of transfer system settings is not always feasible. Hence, according to different case, optimization proposed in this thesis is divided into three levels.

In level 1, only the timings of each axis motion can be modified. The optimization algorithm will only output the overlap between axis, thus can shorten transfer duration and finally result in a shorter cycle time.

In level 2, in addition, lift stroke can also be modified. Longer lift stroke will result in longer lift time, but it will also allow larger overlap. In this level net benefit of changing lift stroke is assessed, and the optimum lift stroke is output along with overlap and timings.

In level 3, not only overlap and lift stroke, but also press stroke can be modified. By pushing the top shoe motion to its highest velocity and acceleration, the clearance during die open will be decided by press stroke. Optimization level 3 will output the minimum press stroke that the top shoe can run at maximum velocity and acceleration, while still can create enough clearance for part transfer, along with the corresponding lift stroke and timings.

Moreover, optimization level 3 also shows the capability of expanding the proposed algorithms to progressive die, which can be regarded as a simple case of transfer die.

One case study has shown that the proposed algorithms work well as expected. SPM can be improved even using the initial peak velocity and acceleration (level 0). And with level up, more parameters are optimized, the outcome SPM can be further improved.

8.2 Future Works

The current researches in the aspect of die industry, especially transfer die industry, is very limited and scattered. Only a few research is about the manufacturing stage. However, this thesis has shown that transfer die industry still has a large potential to improve. Designers and manufacturers are keen to apply more advanced tools to help them analyze and optimize their die system.

This thesis is focused on optimizing transfer system in transfer die in order to improve SPM. The proposed algorithms have shown the direction of research in transfer system optimization aspect. However, there are still several topics left open, some steps of the optimization are still done manually, and some interesting properties have been shown during the optimization but not fully studied. The following topics can be the focus of future works, which can lead to improvements of the algorithms and studies on the properties of die assemblies:

Other motion curves

In chapter 3, 345 polynomial curve is clarified to be the common motion curve used in die industry. However, it is also possible that other motion curves are used, for example, cycloidal curve also have good SVAJ properties. Dwelling may also exist in some advanced press machines.

In later contents, it can be found that the optimization strategy will be affected by motion curve properties, but the basic ideas (overlap, FOD, MCC and MCF) are not linked to

motion curve. Whatever the curve equation is, optimization can follow the similar idea with strategies regarding to properties of the chosen curve. In future works, the properties of other motion curves should be studied, and added as other options in the optimization strategy.

Complex motions

In more advanced production line, the motions during part transfer can be more complex. For example, self-driven lifter exists in some die systems, the timing of which is not decided by stripper, but its own predefined timings.

Another possible case is part rotation. Grippers will rotate the part along an arbitrary axis during transfer. If this kind of motion exists, the possible collisions will be difficult to detect, because the angles and timings of rotation must be considered.

Therefore, obstacle mapping, and motion optimization for these complex motions can be further studied.

Progressive die

In 6.7, it is clarified that the proposed algorithm can be expanded to progressive die, because progressive die can be considered as a simple case of transfer die. However, it is not guaranteed that the proposed algorithm will work without any customization. Some validation works, and possibly, customization works should be done on progressive die.

Mathematical Properties

In this thesis, some problems are solved by trials. For example, in 6.6, press stroke is solved from target value compensation, their relationship is close to, but not exactly linear. This is found during the research, but the mathematical expression of such relationship is not found yet. Another example is the optimization strategy curve in 6.5.4, shown in Figure 6.10, the shape of the curve is solved by traversing, because the mathematical solution was not found yet. In future works, topics can be proposed to find the mathematical relationships between the die geometry/parameter and optimization strategies.

Advanced MCC and MCF

In 7.2, MCC and MCF of the case study are obtained manually. Future works can be focused on obtaining MCC and MCF automatically. To achieve this, the program must be able to judge the area, in which the top/lower shoe and part/gripper will collide during

clamp/transfer. So not only parts in an assembly file, but also features in each part file should be accessed in the analyzation.

Moreover, as Figure 4.3 and case study shows, the danger zone and MCC in proposed algorithm is can be presented as a single pixel. However, in reality, the danger increases when gripper getting close to part, so the better solution is to make MCC a variable related to y-axis position.

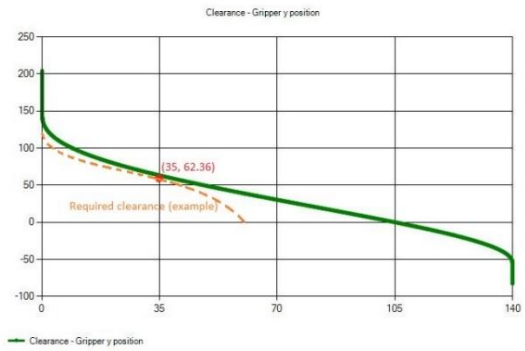


Figure 8.2: Dynamic MCC

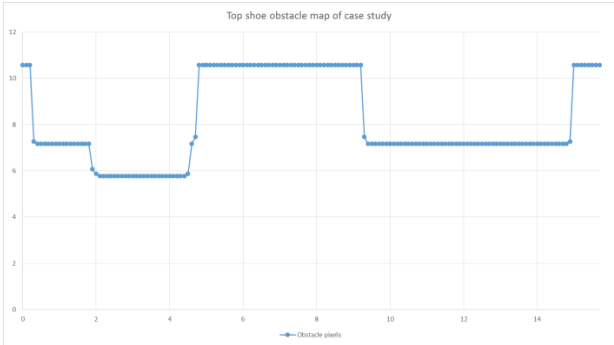


Figure 8.3: Top shoe obstacle map

For example, as Figure 8.2 shows, the vertical axis is the clearance between stripper and gripper, horizontal axis is gripper y-axis position. Green curve is the result of level 1 optimization of case study. Currently, the optimization just ensures that when y-axis position is lower than danger zone (35), clearance must be higher than MCC (62.36). In future works, dynamic MCC may be developed, for example, like the orange dashed curve in Figure 8.2, and the optimization should ensure that green cuthe orange dashed curver than orange dashed curve.

Similar idea can be applied to MCF as well. In Figure 7.3 (b), it shows that the current method in obtaining MCF is simply to consider top shoe geometry as a block. However, potential collision with top shoe can also be mapped. As Figure 8.3 shows, the top shoe obstacle map can be used to determine the actual MCF, and even a dynamic MCF regards to the gripper x-axis position.

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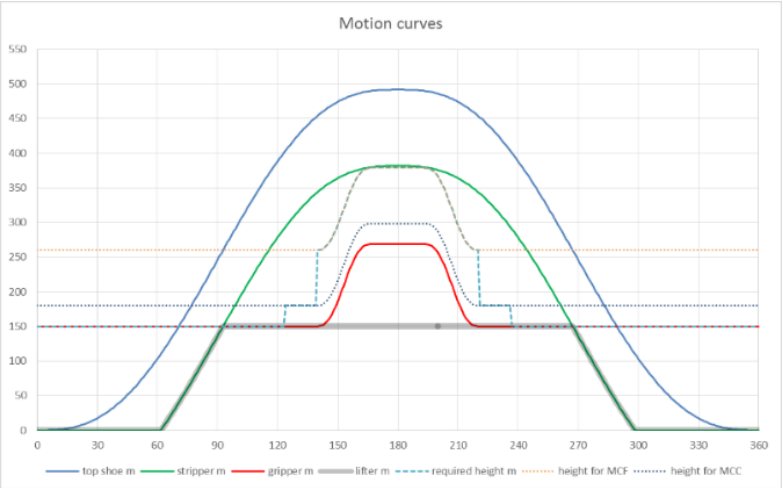
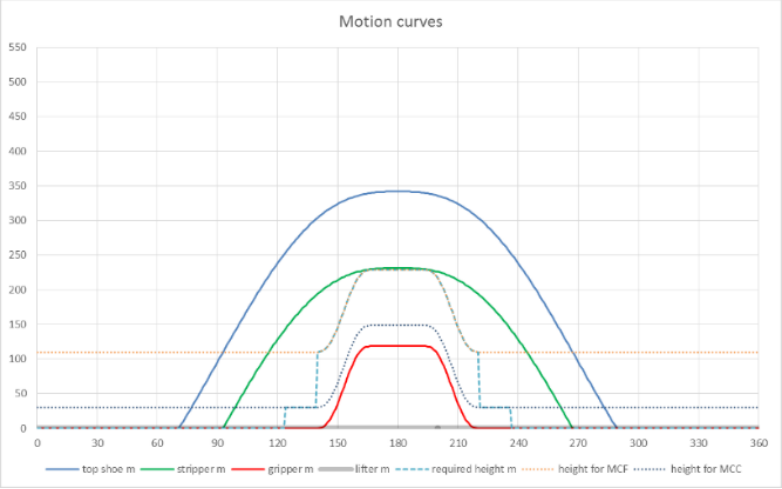
Appendices

A. Transfer Between Motion Curve and Clearance Curve

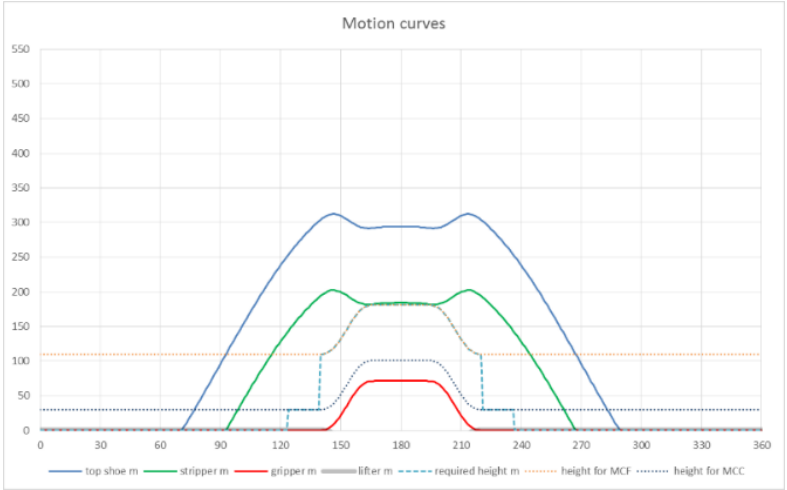
Figure 0.1 (a)~(e) shows how the motion curve is transferred to clearance curve, which is simply subtract the height of gripper from height of stripper. Plus, MCC and MCF applied in clearance curve then can be transferred back to motion curve chart.



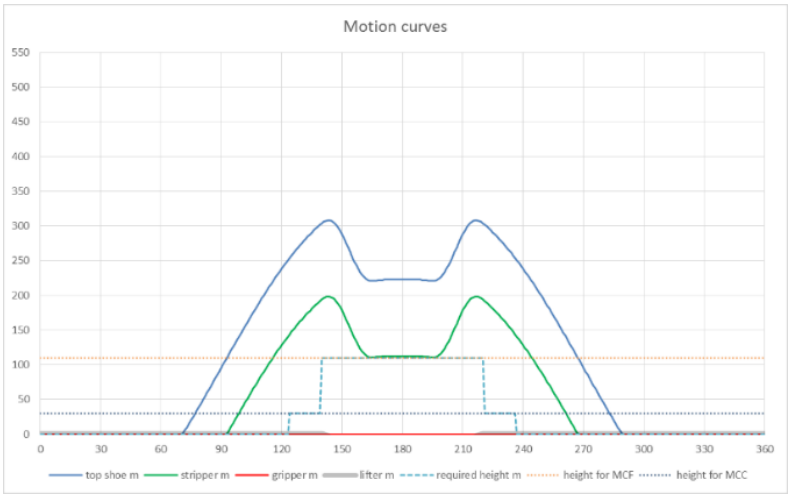
a: motion curve



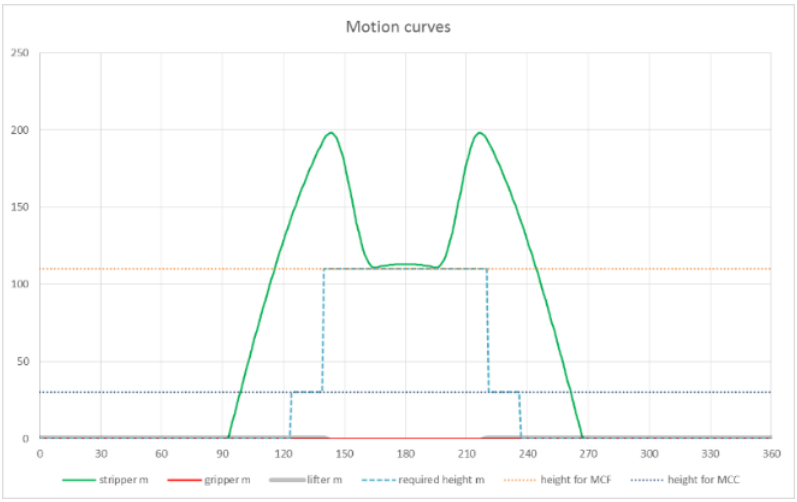
b: set pick up height as zero



c: minus 40% of gripper (z)



d: minus 100% of gripper (z)



e: show stripper only and modify scale

Figure 0.1: Transfer between motion curve and clearance curve

B. Additional Lift Stroke for a Simple Block

This section is an additional of “6.5.2 Additional lift stroke – consider simple block obstacle”. In this section, the reason that optimum additional lift stroke is 15% will be discussed.

The followings are known or assumed:

1. The gripper motion curve is a 345 polynomial curve.

2. $maxv = \frac{15h}{8t}$; $= \frac{10\sqrt{3}h}{3t^2}$;

Consider the following movement, the brown block is inviolable, S2 is the minimum travel distance on z-axis, S1 is the transfer pitch. Gripper needs to move S2 to clear its way for feeding forward. If gripper move S2 then stop at the corner, and start again on x axis for S1, the total travel distance is minimized, however, minimum travel distance does not mean minimum time.

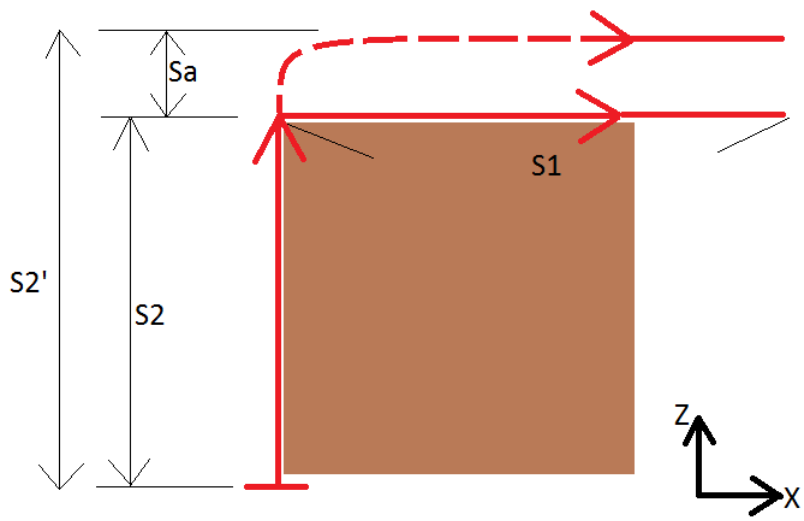


Figure 6.6: Additional Lift Stroke

If gripper moves an additional distance (Sa) on z-axis and make the trace a round corner, it can start its x-axis motion right after passing the sharp corner, so its travel time on x-axis is not changed, but it can have a higher average speed on its previous S2 segment. Therefore, travel time on S2 segment is reduced, and total time is reduced.

Sa must have an optimum value to minimize total time. The following sections will introduce how this value is obtained.

Experimental method:

Simply testing Sa from 0 to S2 and calculate how much time it saved can give an experimental result of optimum Sa value. Firstly, only consider the maximum velocity, for 345 polynomial curve, if the maximum velocity and travel distance are given, travel time can be directly calculated. Plus, by solving the 345 polynomial function, the time when gripper reach S2 can be calculated as well.

Let's assume S1=500 mm, time for x-axis motion is t1=200s, S2=10 mm, so t2=4s because S1/t1=S2/t2 (for velocity). Therefore, if no Sa is applied, the total time is t1+t2=204 s.

Now apply an additional travel on z-axis, say Sa= 0.2*S2=2 mm, so S2'=12 mm. t2'=4.8 s. However, gripper does not need to run full 4.8 s before it can start to move on x axis, actually, by solving 3-4-5 polynomial function, $y = 12 \times (10\left(\frac{t}{4.8}\right)^3 - 15(\frac{t}{4.8})^4 + 6(\frac{t}{4.8})^5)$, gripper will reach 10 mm at 3.347 s. That means, from 3.347 s, the gripper can start its x axis movement, and x axis movement takes 200 s, so the total time is 203.347 s.

By applying different Sa/S2 from 0 to 1, the calculated total time shows a curve as follows.

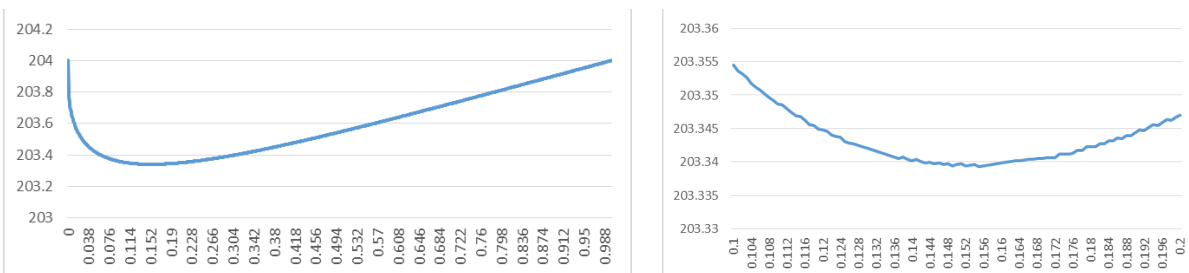


Figure 0.2: Optimum additional lift stroke, consider velocity

The lowest point is at around 0.15, which mean Sa=0.15*S2=1.5 mm is the optimum value.

By testing other S1, t1 and S2 values, it can be found that the shape of the above curve are exactly the same, lowest point always locate at 0.15. This indicates that the ratio 0.15 is an inherent property of the 3-4-5 polynomial curve!

Mathematical method:

Since the optimum ratio of Sa/S2=0.15 is an inherent property of 345 polynomial curve, it should be able to be obtained by mathematical analysis.

$$y = Distance \times (10\left(\frac{t}{required\ time}\right)^3 - 15(\frac{t}{required\ time})^4 + 6(\frac{t}{required\ time})^5)$$

The above equation is the general equation used for 345 polynomial motion curve. Required time here means the time for one linear motion (e.g. t1, t2 or t2').

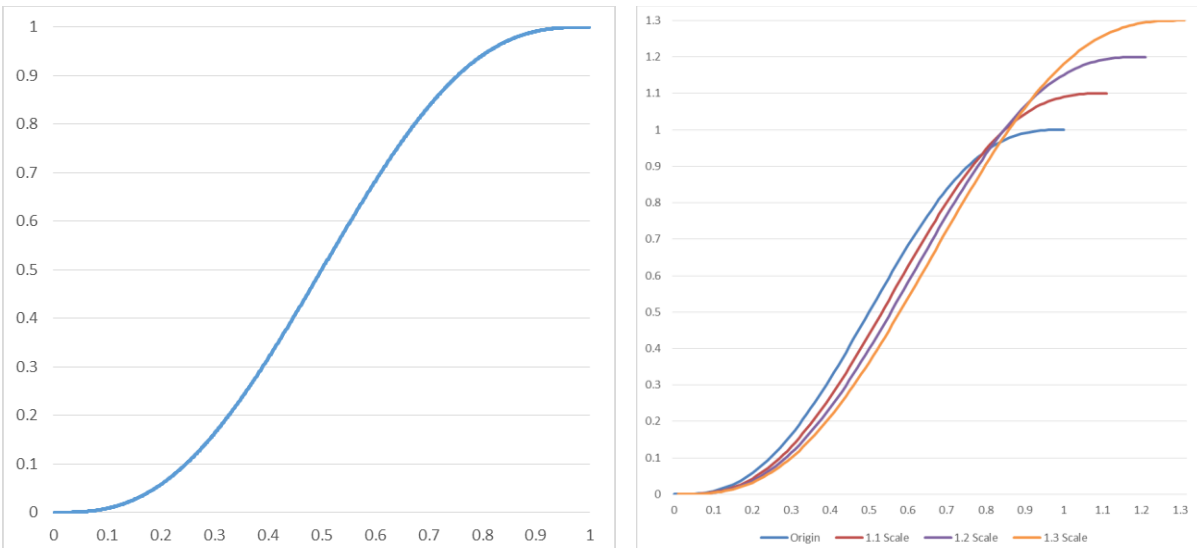


Figure 0.3: drag 345 polynomial curve

As above picture shows when both distance and total time is set as one. When applying different distance and total time, the shape of the curve does not change, only the scales on chart are modified. If plot the extended curve with original one, it can be found that although travel distance increased, the timing when the curve reaches "1" are actually earlier. This is why an additional travel distance can benefit total time, the earlier curve reaches "1", the earlier it can start to move on the other axis, so the more time it saves.

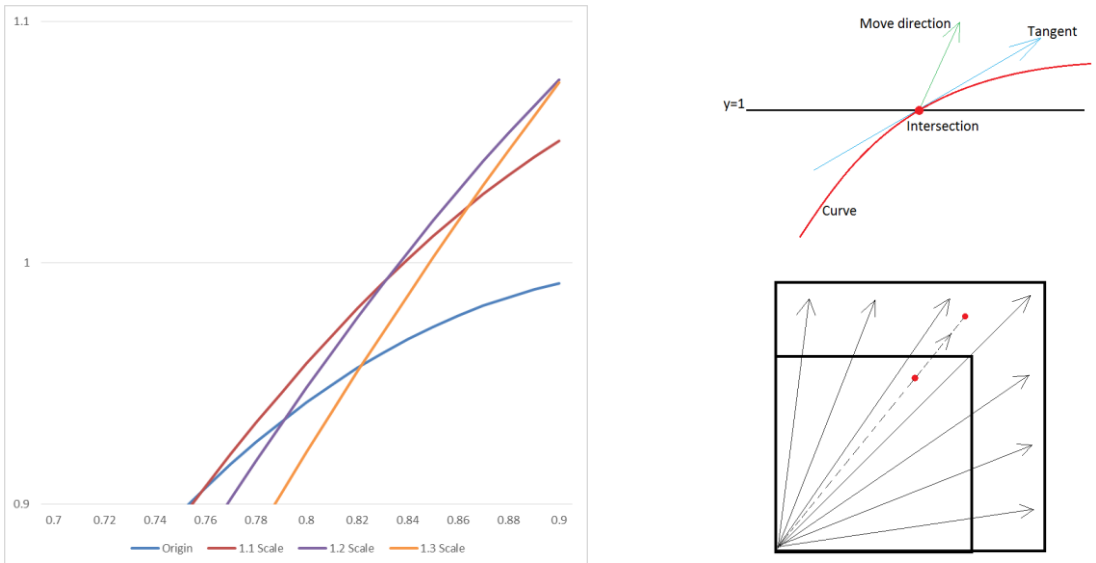


Figure 0.4: Solve optimum additional lift stroke mathematically

Zooming in to the critical area, it can be found that the intersection point of y=1 and curve of 1.1 scale is around 0.84, when scale increase to 1.2, the intersection point moved slightly to left, then at 1.3 scale, the intersection point move to right. The movement of intersection point is the key of this problem, it is required to find a scale that makes the point move to its left most.

Imaging dragging the top right of curve while fixing the bottom left corner, due to the convex shape of the curve near the end of it, the intersection point will firstly go left, then right. Hence total time will decrease and then increase just like what it shows in experimental results.

Consider a moving curve intersects with y=1, the movement of intersection is decided by two factors. One is, for an infinitesimal movement, the actual moving direction of the intersection point on the curve. The other factor is the tangent direction of the intersection point on the curve. As the example in Figure 0.4 shows, the slope of move direction is larger than the tangent, then intersection point will move leftward. Intersection point keeps moving left until move direction equals tangent.

Slope of tangent can be easily obtained from polynomial equation, which is $(30x^2 - 60x^3 + 30x^4)$. Moving direction is related to the point's original position on the picture. So the moving direction is $(x, 10x^3 - 15x^4 + 6x^5)$, translate to slope, result in $(10x^2 - 15x^3 + 6x^4)$. Let them equal and solve x, it will result in $x = \frac{45-\sqrt{105}}{48} \approx 0.724$. Then y=0.867.

Therefore, point (0.724, 0.867) on polynomial curve is the intersection point after the curve is extended. When intersection happens, this point will locate on y=1, and its moving direction and tangent have the same slope, thus the intersection point will be at its leftmost position. The extension scale is 1/0.867=1.1534. So the optimum scale is 1.1534, which means, from velocity point of view, 15% additional lift stroke is the optimum.

Consider acceleration:

Methods are similar, but mathematically solving will be $\frac{10x^3-15x^4+6x^5}{\sqrt{x}} = 30x^2 - 60x^3 + 30x^4$, simplified equation is a 5-order one so it is difficult to solve directly. However, experimental method still works well.

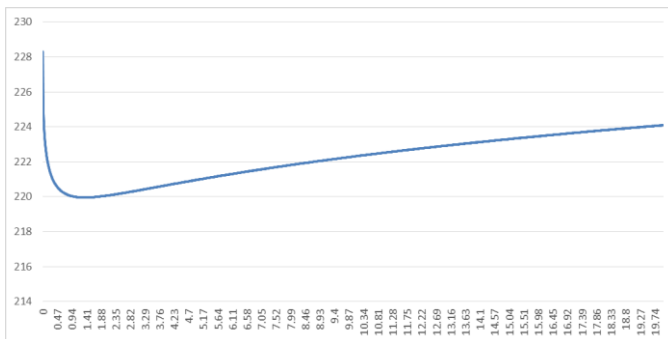


Figure 0.5: Optimum additional lift stroke, consider acceleration

The curve becomes sharper and the lowest point locate at around 1.35, which means the optimum travel distance is 235% of the original one. This is mathematically true, but may not be applicable because it is indeed too large, plus, the restriction of velocity is also a limit. However, it can be found that the curve decreases sharply at the beginning. Although it reaches the lowest at 1.35, at 0.15, it drops from 228 to 222, from 0.15 to 1.35, it drops from 222 to 220, so it completes 75% of total drop at the beginning 11% of drop range. This indicates that 0.15 is already an acceptable value for optimization, it is optimum for calculation regard to velocity, and it is good enough for calculation regard to acceleration.

Conclusion:

An additional travel distance Sa=115%*S2 is optimum for grippers z axis motion. This will result in: 27.4% overlap time and 16.5% saved time on z axis against the previous movement.

C. Properties of Optimization Strategy Curves

This section is an addition to “6.5.4 Additional lift stroke – consider effect on top shoe”. With given press stroke, the highest peak velocity and acceleration of top shoe can achieve highest SPM.

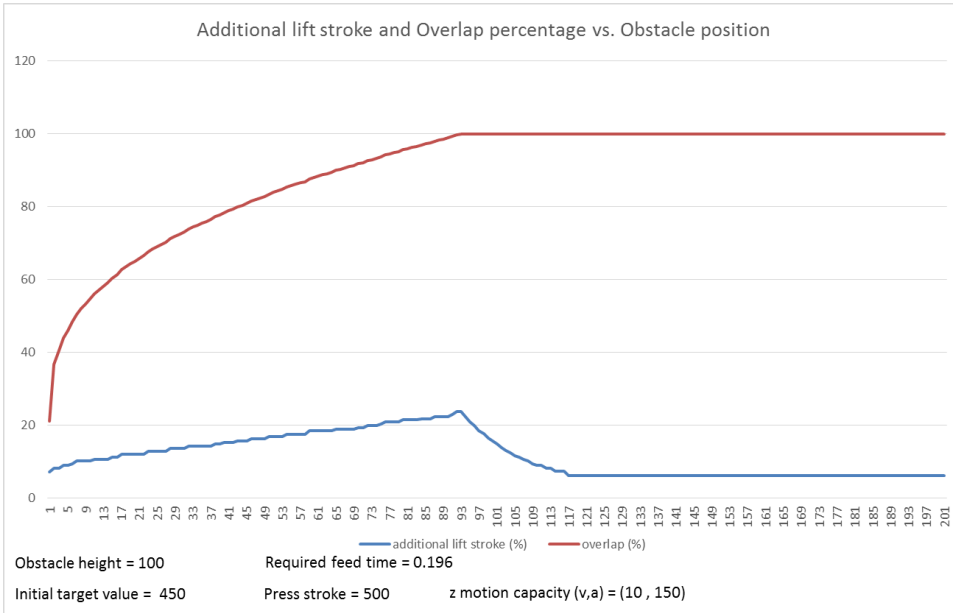


Figure 6.10: New strategy for additional lift stroke and overlap

Figure 6.10 shows the strategy of overlap and lift stroke optimization. The above figure is the strategy curves for an example with parameters shown in the figure: obstacle height, feed time, initial target value, press stroke and motion capacity.

In this section, these parameters will be modified, following figures will show qualitatively how these parameters affect the curve. Due to the impossibility of solving 5-order polynomial equation, and other mathematical complexities, no quantitative analysis will be conducted. But qualitative analysis will be done for each parameter, in order to help understanding the relationship between project parameters and optimum modification strategy.

Note:

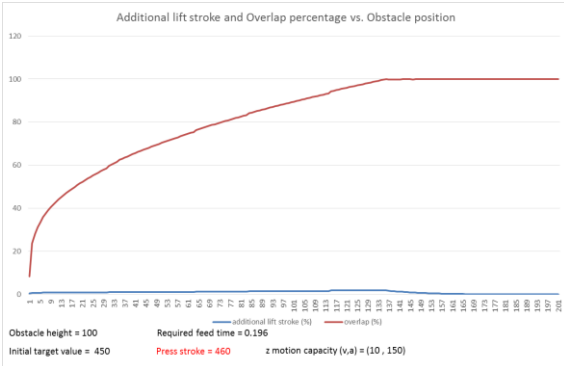
- One concept may need to be recalled is “Initial target value”, this is the minimum top shoe height that part can feed. It equals “Lift Height + Stripper Travel + Minimum Clearance for Feeding + Initial Lift Stroke”.

$$Initial\ Target\ Value = S_S + S_L + S_{Gz} + MCF \quad \textbf{(12)}$$

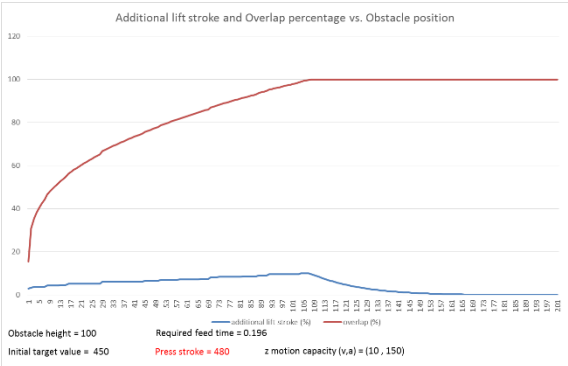
When lift stroke is modified, this value will also be modified.

- In following contents, the curve of additional lift stroke for different obstacle position will be called “strategy curve” since it shows the optimization strategy for different situations.

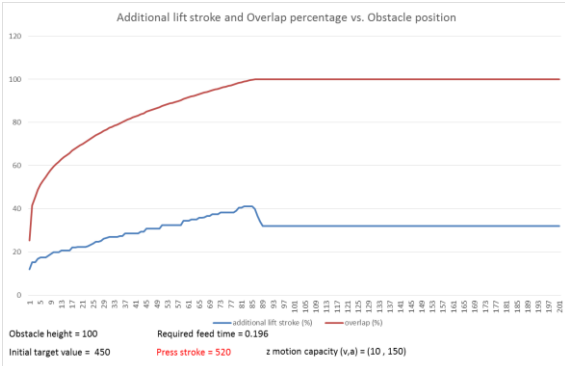
1. Press stroke



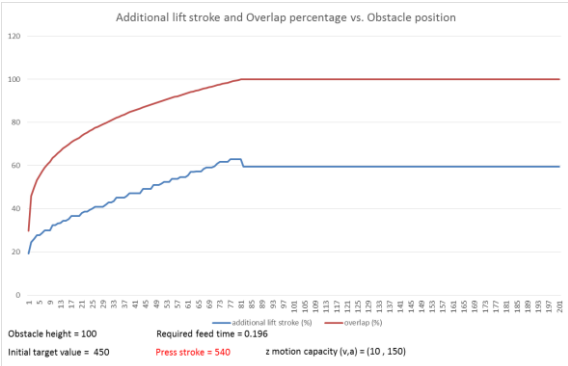
Press stroke = 460



Press stroke = 480



Press stroke = 520

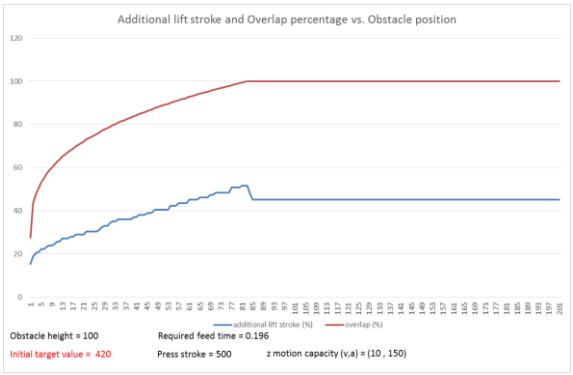


Press stroke = 540

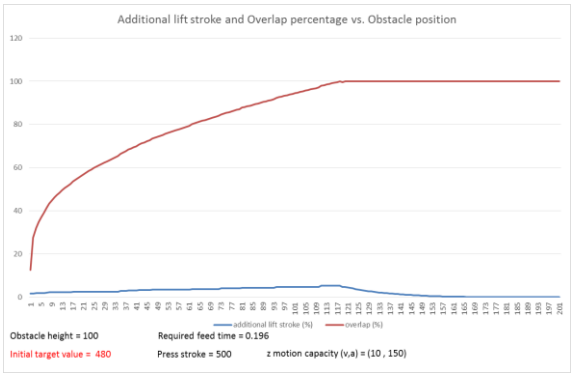
Figure 0.6: Additional lift stroke for different press stroke

It is shown in Figure 0.6 that press stroke will significantly affect the additional lift stroke. The whole strategy curve is “lifted” when press stroke increases. Plus, the final value (when the obstacle is at infinite) will also increase with press stroke. The reason is, when press stroke increases, there will be more space for the gripper. So gripper can apply larger lift stroke in order to obtain larger overlap time, then lead to shorter FOD and finally result in a shorter cycle time.

2. Initial target value



Initial target value = 420

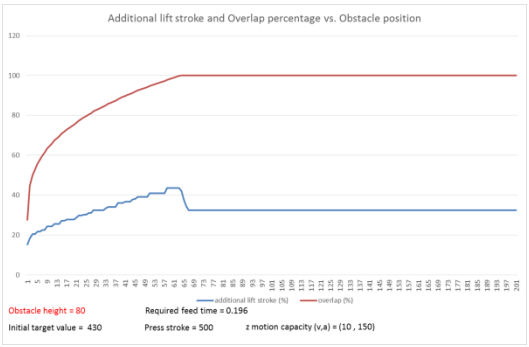


Initial target value = 480

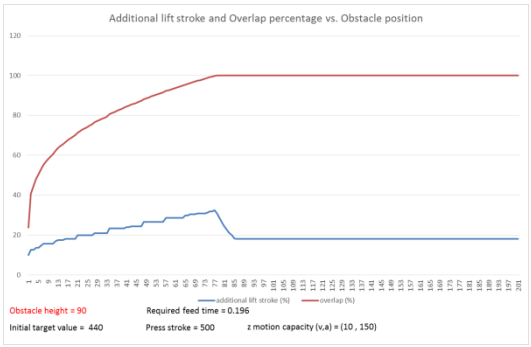
Figure 0.7: Additional lift stroke for different initial target value

Increasing initial target value is similar to decreasing press stroke. The space for gripper will be affected. Actually, it was found that for same "press stroke – initial target value", the shape of strategy curve will be very similar (but not exactly same). Analysis of its effect is similar to that in "press stroke" part.

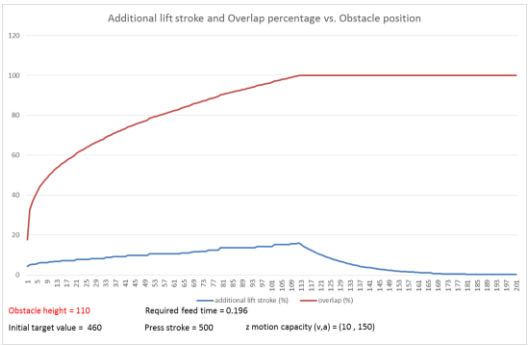
<u>Obstacle height</u>



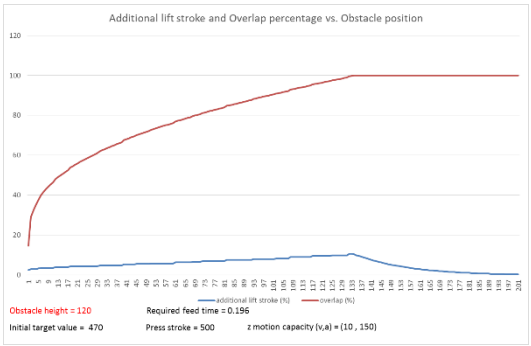
Obstacle height = 80



Obstacle height = 90



Obstacle height = 110



Obstacle height = 120

Figure 0.8: Additional lift stroke for different obstacle height

It should be noted that “Initial target value = Lift Height + Stripper Travel + Minimum Clearance for Feeding + Initial Lift Stroke”. When obstacle height increases, initial lift stroke will also increase and then affect the initial target value as well.

For larger obstacle height, strategy curve will take more distance to reach the peak value. Meanwhile, the final value of strategy curve will decrease. This is because when increasing obstacle height, the scale in x and z axis increase simultaneously.

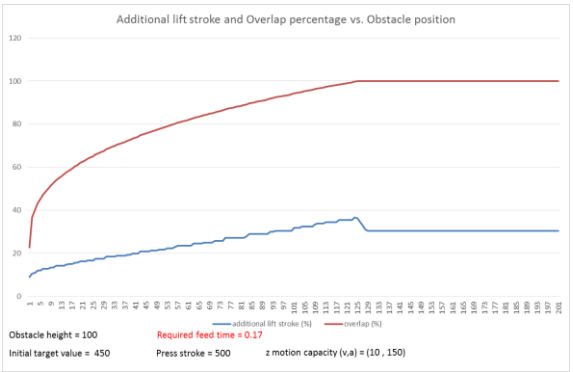
For example, previously it took 1 second for z-axis motion to reach the obstacle height, then an additional lift stroke (%) is applied, make it 10% more time needed, part can start feeding 1s x 10% = 0.1s earlier. During this time, it can feed, say 50 mm.

Now, if the obstacle height is higher than before, and it takes 2 second to reach the height, if the same additional lift stroke (%) is applied, make it 10% more time needed, part can start feeding 2s x 10% = 0.2s earlier. During this time, it can feed more than 50 mm (maybe around 100 mm), which is too much. So the solution should be fewer additional lift stroke (%) in order to keep part fed at 50 mm.

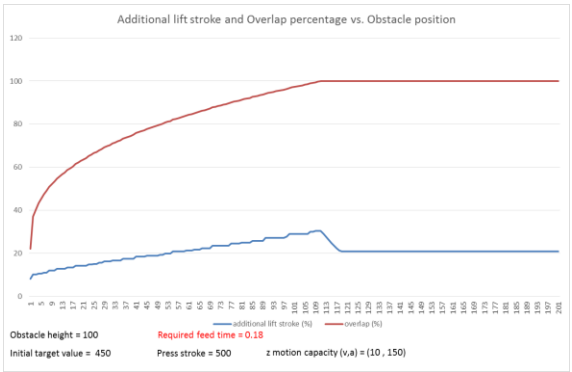
Therefore, when obstacle height increases, all the points in strategy curve should be extended.

For the final value, it is again related to space. For higher obstacle, the initial target value will increase, which suppresses space between gripper and stripper, so the final value will be lower.

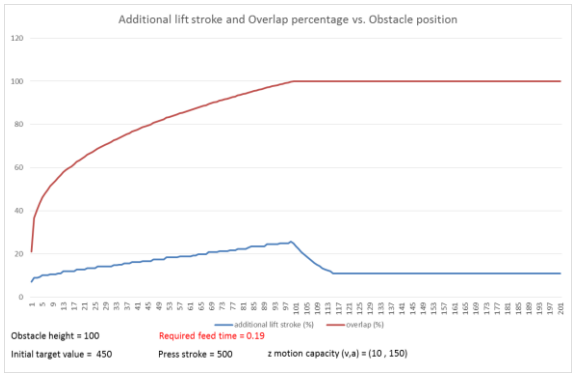
<u>Required feed time</u>



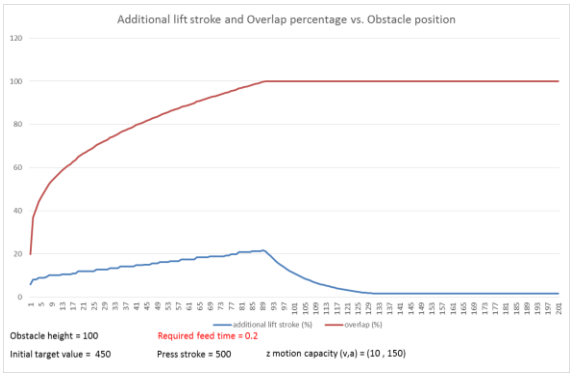
Feed time = 0.17



Feed time = 0.18



Feed time = 0.19



Feed time = 0.20

Figure 0.9: Additional lift stroke for different feed time

Feed time is calculated from transfer pitch, maximum velocity and maximum acceleration. But in the calculation, these three parameters are just used once to generate feed time, so they are simplified to one parameter.

Similar to the term “obstacle height”, changes in feed time will change the scale of x and z axis. But the behavior will be different. Use the same example in the last section:

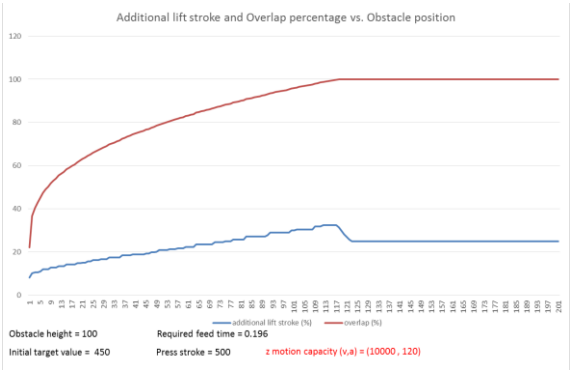
Previously it took 1 second for z-axis motion to reach the obstacle height, then an additional lift stroke (%) is applied, make it 10% more time needed, part can start feeding 1s x 10% = 0.1s earlier. During this time, it can feed, say 50 mm.

Now, it still take 1 second to reach the height, if the same additional lift stroke (%) is applied, make it 10% more time needed, part can start feeding 1s x 10% = 0.1s earlier. However, because it will take more time to feed, which means the speed is lower, during this time, it feed less than 50 mm. So the solution should be larger additional lift stroke (%) in order to keep part fed at 50 mm.

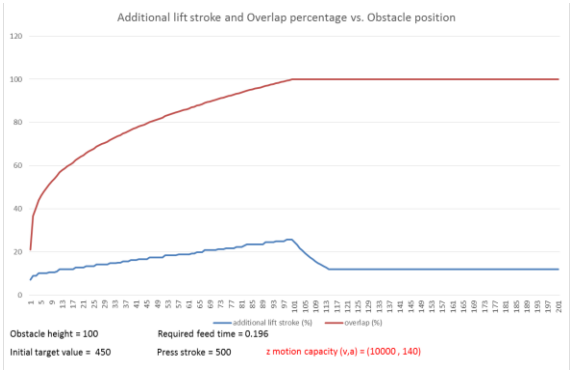
Therefore, when feed time increases, all the points in strategy curve should be compressed.

For the final value, when feed time increases, top shoe needs to be at high position for a longer time. It should rather run slower, or have more space. When obstacle position is far away, it is shown that “more space” benefits more, and additional lift stroke should decrease.

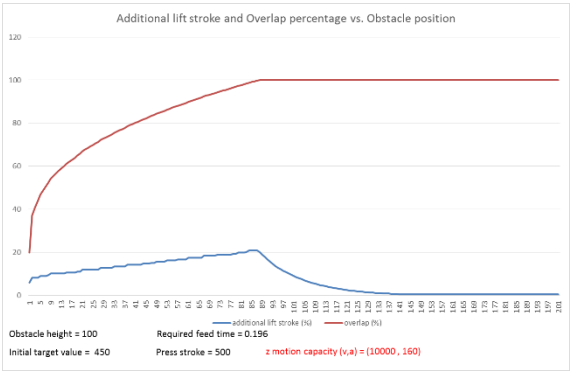
Z axis motion capacity



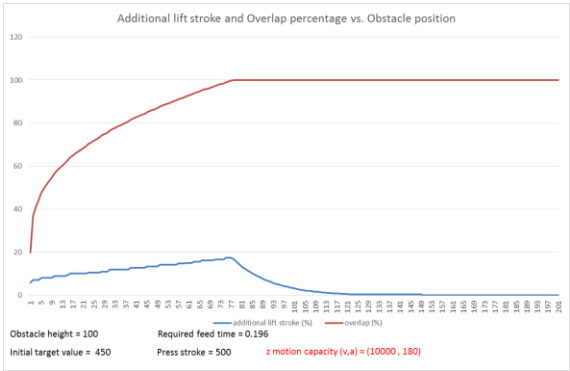
Maximum acceleration = 120



Maximum acceleration = 140



Maximum acceleration = 160



Maximum acceleration = 180

Figure 0.10: Additional lift stroke for different z axis acceleration capacity

It should be noted that motion capacity is decided by both velocity and acceleration. In the calculation, both parameter will work but only one will be the boundary condition. Here, for easier analysis, the velocity capacity is assigned a high value, which will not make it the boundary condition, hence acceleration can represent the whole concept of motion capacity.

Basically, increasing z axis motion capacity is similar to decreasing x axis motion capacity. This is very straightforward, just like running the whole system at higher speed. And since decreasing x axis motion capacity is identical to increasing feed time, the trends for strategy curve in Figure 0.9 and Figure 0.10 are same. The analysis will also be similar.

To summarize, the strategy curve's characteristic is affected by several parameters. It may not be possible to generate a mathematical expression for its behavior. However, all the parameters are constants for a given project, this indicates the possibility to see its characteristic as a property of the particular project. More investigations can be done as future works.