Frequency Domain Quantification Of Manufacturing Process Resolution

by

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Abstract

Manufacturing processes are input/output systems subject to disturbances and uncertainties. Hence, process control is a necessary compensation. However, control tools cannot be chosen arbitrarily, but are limited by several process characteristics. Primary among these, process resolution determines the degree to which changes in process inputs produce changes in process states and in process outputs. In turn, process resolution dictates the applicability of specific control tools. Two other limitations are feedback time and process state measurability.

This thesis provides a means of quantifying process resolution and thereby gives a metric of process controllability. Using Fourier Transforms, parameterized process-inputs and process-outputs are expressed as input frequencies and output frequencies. The process itself is represented as a transfer function, and process resolution is defined as the transfer function bandwidth.

The use of Fourier Transforms is a generalization of digital signal processing techniques. These have been used previously in manufacturing to describe the shape of sheet-metal-stamping parts and tools.

Reviews of control problems in injection molding, sheet metal forming, and composite processing are included as background and examples.

Department of Mechanical Engineering Advisor: David E. Hardt
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In the School of Engineering, several professors have repeatedly gone to great lengths to provide advice and assistance. Professor Woodie Flowers' Product Design course was addictive, and his enthusiasm, contagious. Both Professor David Gossard and Professor Warren Seering have been exceedingly generous in providing direction, and

without their efforts I could not have secured an invitation to spend a year at the University of Tokyo.

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Steve Spear
Cambridge, Massachusetts
February 1993

Preface

This thesis describes manufacturing processes as input/output dynamic systems that require closed loop control due to disturbances and uncertainties. Using frequency domain techniques, processes are described as temporal and spatial filters, and bandwidth is used to quantify the responsiveness of outputs to changes in inputs. In turn, this is a way to quantify process capabilities such as accuracy, controllability and flexibility.

This project is the result of a challenge posed to several graduate students in the summer of 1991 by Professor David Hardt, director of the Massachusetts Institute of Technology's Laboratory for Manufacturing and Productivity. Our charge was to employ the terminology and tools of system dynamics and closed loop feedback analysis and control. We were to avoid the temptation to group processes only by the material being altered (i.e. sheet metal or plastics) or by the physical consequences of the processes (i.e. material addition, material removal, plastic deformation, solidification). Rather, we were to develop a control-based taxonomy that not only allowed for categorization, but also anticipation and diagnosis of, and prescription for problems associated with control and quality.

This thesis builds upon specific prior research conducted in the MIT Laboratory for Manufacturing and Productivity. This includes general manufacturing process control and sheet metal forming process control. The general manufacturing process control work includes papers which outline the constraints and limitations imposed by process characteristics [Hardt, Manufacturing Processes and Process Control (draft), 1991; Real-Time Process Control: Limits To Progress, December 1990].

The sheet metal process control research employs Fourier Transforms to move between space domain and frequency domain descriptions of part and tool geometry, much as Fourier Transforms are used to move between time domain and frequency domain characterizations for signal processing [Webb and Hardt, 1989; Hardt, et al, 1991]. In a generalized form, n-dimensional frequency domain analysis can quantify notions such as process resolution, process accuracy, and process flexibility.

Recent research in composite material processing was especially important in developing this thesis's taxonomy. Particularly because the phrase "composite processing" encompasses several distinct activities, a review of composites related research provided an effective way to validate some parts and refute other parts of the model as it developed. Consequently, an overview of this literature is given, and the research is evaluated for its potential to improve process capabilities such as quality, flexibility, and rate from the perspective of the control model.

In sum, this thesis is part of the attempt to develop a control-system description of manufacturing processes that is general enough to apply to a broad range of processes while being rigorous enough to yield valuable insights into the capabilities of specific manufacturing techniques. The result is a frequency domain characterization of processes as filters with temporal and spatial dynamics.

The most important contribution of this thesis is the generalization of frequency domain signal processing methods. They are used to create an n-dimensional frequency domain representation of manufacturing processes as input/output dynamic systems subject to closed loop control.

Also of value, the extensive literature review and cross-process study, which supports this work, affords the reader the opportunity to compare processes for similarities and differences based on the control problems they represent rather than on the basis of the material they manipulate or the fashion in which this manipulation is carried out.

Chapter 1: Introduction

Control techniques are used to improve the quality, increase the rate, and enhance the flexibility of manufacturing processes. Closed-loop control is employed in some form because manufacturing processes are not strictly deterministic. It is not always possible to analytically or empirically forecast process behavior. Even those processes that can be described with great deterministic accuracy are subject to a wide variety of disturbances and uncertainties which demand compensation.

While feedback control methods are an essential aspect of manufacturing systems, control tools cannot be chosen arbitrarily. It is the premise of this thesis that, in fact, control must be chosen on the basis of very real physical constraints imposed by each specific process. By developing and employing a control taxonomy, manufacturing processes can be described by their location along the continua of feedback time, dynamic state measurability, and process resolution. The combination of locations that describe each process signifies the control tools that can be employed effectively.

Process resolution is a limit on process control because the manner in which machines and materials interact determines the level to which material conditions and outputs can be controlled by altering inputs. In image processing terminology, this notion of process resolution is qualitatively comparable to the spatial idea of pixel density, and temporally, it is akin to the image refresh rate. Processes with higher spatial resolution can better impart spatial detail. Processes with higher temporal resolution can change these details at faster rates.

By using Fourier Transforms to relate inputs and outputs (i.e. forces, velocities, currents, dimensions, and densities) as input frequencies and output frequencies, processes are seen to be analogous to frequency domain filters, and process resolution can be quantified as filter bandwidth. In turn, this is a way to quantify process performance limits.

Thesis Organization

In Chapter 2, manufacturing processes are described as input/output dynamic systems, subject to disturbances and uncertainties. These disturbances and uncertainties require the application of control tools.

Therefore, Chapter 2 outlines the types of inputs, outputs and other components which comprise manufacturing systems, and then delineates sources of variation and various types of process control.

Chapter 2 concludes by suggesting that rapid forms of control are preferable to slower forms of feedback. However, feedback control systems cannot be applied arbitrarily because they are constrained by temporal, measurement and resolution concerns.

Chapter 3 further develops the idea of process resolution as a limit to control. Examples of process control problems in injection molding and sheet metal forming are related as qualitative illustrations. Chapter 3 concludes by describing the use of Fourier Transforms to represent part and tool shape during sheet metal forming.

Chapter 4 illustrates how physical shapes or time-domain signals can be approximated as the sum of sinusoids. This is done to explain the ideas of spatial and temporal frequency content.

Chapter 5 employs a heat transfer example to demonstrate how process inputs and outputs can be re-expressed as input and output frequencies. It suggests process resolution is determined by machine properties and not by material properties.

This frequency domain description of process resolution in Chapters 3, 4, and 5 is offered as an improvement over using the terms 'serial' and 'parallel' to qualify the manipulability and controllability of processes. This generalization of signal processing techniques to quantify process resolution is the original contribution of this thesis.

Chapter 6 contains conclusions and suggestions for additional research.

Several appendices deal with composite processing, providing a review in light of the control taxonomy. One appendix focuses exclusively on cure control and issues surrounding curing, such as sensing, modeling, and actuation. Another appendix looks at other composite issues like forming and resin flow during resin transfer molding.

For the benefit of the reader, this thesis contains both a reference section and a bibliography. The references are organized alphabetically and correspond to the citations in the text. The bibliography is organized by topic, and it includes works that are directly cited and also works that were used for background only.

Chapter 2: A Control Taxonomy Of Manufacturing Processes

Overview

In this chapter, a control systems description of manufacturing processes will be given. It provides the context for the frequency domain characterization of manufacturing processes in the Chapter 3.

The model will be developed by:

- Defining inputs, outputs and interactions of manufacturing systems,
- Describing the need for process control,
- Presenting constraints on controlling processes.

These constraints will be of three forms.

- Feedback speed influences the applicability of control tools.
- The measurability of process conditions determines the controllability of process conditions.
- Process resolution, the degree to which outputs change in response to changes in inputs, determines which control tools are usable.

The third item, process resolution, will be developed in several ways.

- It will be illustrated by examples from sheet-metal forming and injection molding.

- In Chapters 3 and 4, process resolution will be quantified in terms of frequency content. This will be a generalization of techniques used in digital signal processing which have been applied previously in the LMP's work on sheet metal forming process control.

- In Chapter 5, Fourier Transforms will be used to re-express the inputs and outputs of a two dimensional heat transfer simulation. The process is then described as a filter, which, the more it filters high frequencies from the input spectrum, the less controllable are its outputs.

The Control Perspective[1]

A Process Model

Manufacturing processes can be represented as input/output relationships, characterized by interactions between machines and materials. These interactions are in response to inputs, and as a result of these interactions, outputs are generated. Inputs are the machine settings that have a clear and deterministic causal effect on the output. Outputs are the material and geometric properties of the manufactured part.

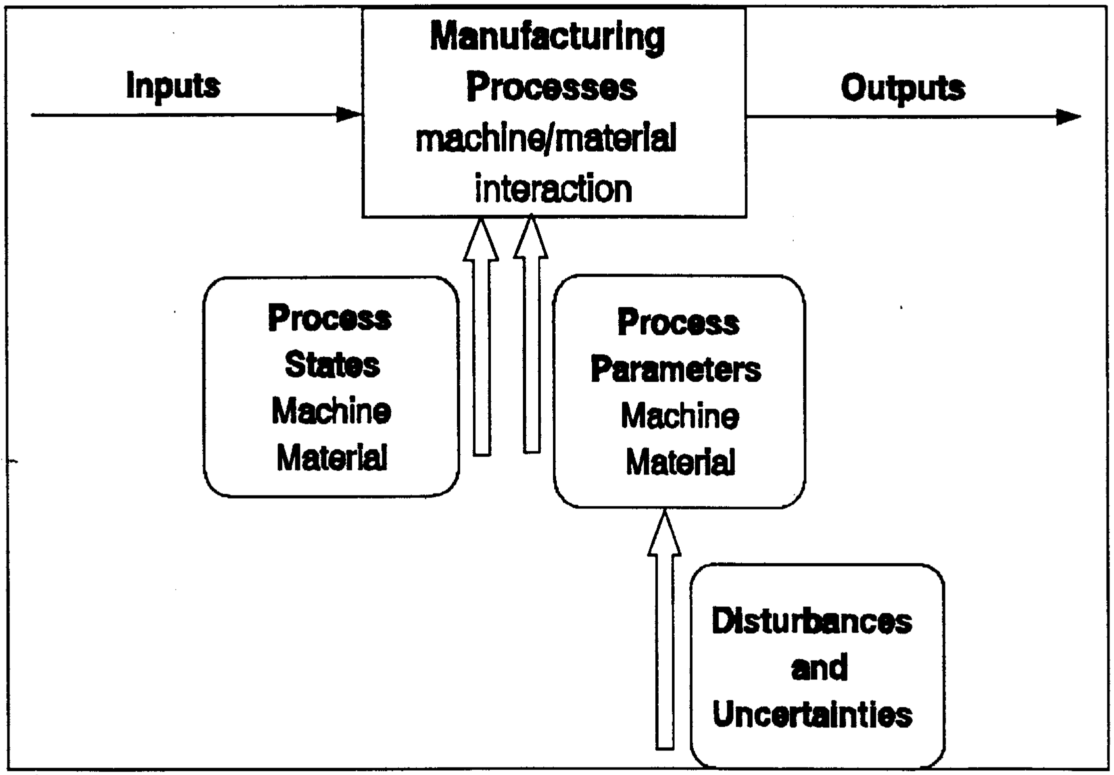

Figure 1

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[1] This control perspective was presented in papers by Professor Hardt [Hardt 1991, Hardt 1990] and later modified in conversations with Professor Hardt and graduate student Andrew Parris [Parris 1993].

It is presented as the context for the original work of this thesis, which is in Chapters 3, 4, and 5.

Inputs[2]

- Accessible and manipulatable with a characteristic time less than part fabrication time ($T_{CHAR} < T_P$).
- Determinable: inputs are not subject to disturbance and uncertainty. σ(input) = 0.
- Equal to or greater in number than the number of controllable outputs.

Outputs of Manufacturing Processes[3]

Discrete part manufacturing has two important outputs. The first of these -- **Material Properties** -- includes mechanical properties such as elasticity and yield strength, thermal characteristics such as conductivity, electrical characteristics such as resistivity, and chemical characteristics such as resistance.

However, discrete part manufacture is distinguished from other "material processes" by an additional set of outputs. These -- which will be described as **Geometric Properties** -- are the macroscopic characteristics of the part, including size and shape.

Ultimately, the goal of controlling a manufacturing process is controlling its Geometric Property and Material Property

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[2] Same as footnote 1.

[3] Same as footnote 1.

Outputs, since these are the values or conditions that define final part quality and performance. This differs from controlling other dynamic states, such as machine trajectory, pressure, or temperature, which are only intermediate process conditions. As a result, in what follows, a clear differentiation will be made between the Geometric Property and Material Property Outputs and intermediate dynamic states such as trajectory, pressure, and temperature.

The Components Of A Manufacturing Process

All manufacturing processes involve:

- **Machines** - the sole means of manipulating material and the source of external power to the manufacturing process.
- **Materials** - the substance from which products are made.
- **Interactions between machines and materials** - Measured by the boundary conditions between machine and materials. Interactions result in the transformation of initial machine and material conditions into final machine and material conditions.

It is only through these interactions that the material can be transformed by the machine and hence by the operator, since the interaction marks the power flow between the machine and the material.

There is a difference between machine and material qualities that are time-invariant and those that are time-variant.

Those characteristics that are time-invariant are called **parameters**. Those that are time-variant are **dynamic states**, and typically correspond to energy states such as force, velocity, physical orientation, pressure, temperature and heat flow.

A summary with examples:

- **Machine Parameters:** time-invariant intrinsic machine properties: Machine geometry, mechanical properties, dynamics (generalized capacitances, resistances, inertances), thermal properties, etc.
- **Machine Dynamic States:** state variables such as speeds, positions, temperatures, pressures, etc.

- **Material Parameters:** time-invariant intrinsic material properties: viscosity, modulus, specific heat, strength, and chemical affinity.
- **Material Dynamic States:** state variables such as temperature, surface geometry, rate of reaction, and orientation.

It is through the interaction between machines and materials that initial machine and material dynamic states become final machine and material dynamic states. These final states include the two outputs of real concern:

- Geometric properties of the part.
- Material properties of the part.

Within the context of the terms **Parameters** and **Dynamic States**, and **Machines**, **Materials**, and **Interactions**, **Outputs are Material States at t_{FINAL}**.

Algebraically, this input/output relationship is:

$$\beta_t = \Phi(\alpha + \varepsilon(\alpha),\ \beta_{t-1},\ \varpi_t) \tag{1}$$

where β_t ($\beta_{MACHINE}$ and $\beta_{MATERIAL}$) is the process-state vector at time 't', α is the process-parameter vector (including machine and material parameters; $\alpha_{MATERIAL}$ and $\alpha_{MACHINE}$), $\varepsilon(\alpha)$ is disturbances to, variations in, and uncertainties about process parameters, and ϖ_t is the input vector at the start of $time_t$. Outputs are the material-states at $t = t_{FINAL}$ ($\beta_{MATERIAL}(t_{FINAL})$).

This model, as shown in equation 1, assumes that the process is 'state determined' since only knowledge of the previous state, β_{t-1}, the inputs ϖ, and the current parameters is necessary to predict the next state, β_t.

The Need For Process Control

Sources Of Variation

As stated earlier, in imposing a control theory framework on manufacturing processes, the concern is with **inputs**, **outputs**, and the relationships that turn the former into the latter. Of course, were these relationships strictly deterministic, were the particular combination of inputs that would produce a particular set of outputs were precisely known, closed loop control would not be needed.

However, manufacturing is decidedly non-deterministic because of disturbances and uncertainties. Incoming materials vary, environmental conditions change, 'identical' machines may have different 'personalities', and even the same machine may exhibit fluctuations over time. And of course, the fundamental process physics may be poorly understood. For instance, hardness or yield strength of steel may vary from batch to batch, humidity and ambient temperature may change from day to day, and machines may behave differently under the guidance of different operators.

Referring to the algebraic description of manufacturing,

$$\beta_t = \Phi(\alpha + \varepsilon(\alpha),\ \beta_{t-1},\ \mho_t) \qquad (2)$$

- Disturbances are variations in parameters, $\varepsilon(\alpha)$;
- Uncertainty about Φ is akin to empirical uncertainty about the process,

- Uncertainty about β_t is a process monitoring problem resulting in uncertainty about machine and material conditions.

As a consequence of the uncertainties and disturbances inherent in manufacturing processes, feedback control is always employed in some fashion.

To restate and defend this statement for those who skeptically read the word "always": In a case of extremely slow feedback, a producer may make a product, pack it, sell it, and ship it without any effort at inspection or quality control. Ultimately though, products that fail to meet consumer performance objectives will be subject to return, recall or non-existent future sales.

While corporate failure is the extreme case of feedback control, it is an example of an extremely slow feedback system on a continuum of fast response to slow response. Anchoring the fast end of this continuum is Real Time Output Control with Iterative Control, Statistical Process Control, and other methods lying in between.[4]

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[4] **Iterative Control:** Measurements taken during and after the formation of Part_t are used to change inputs for the formation of Part_{t+i}.

Statistical Process Control: Process states are monitored and improved until it is determined that variations are caused purely by non-random events.

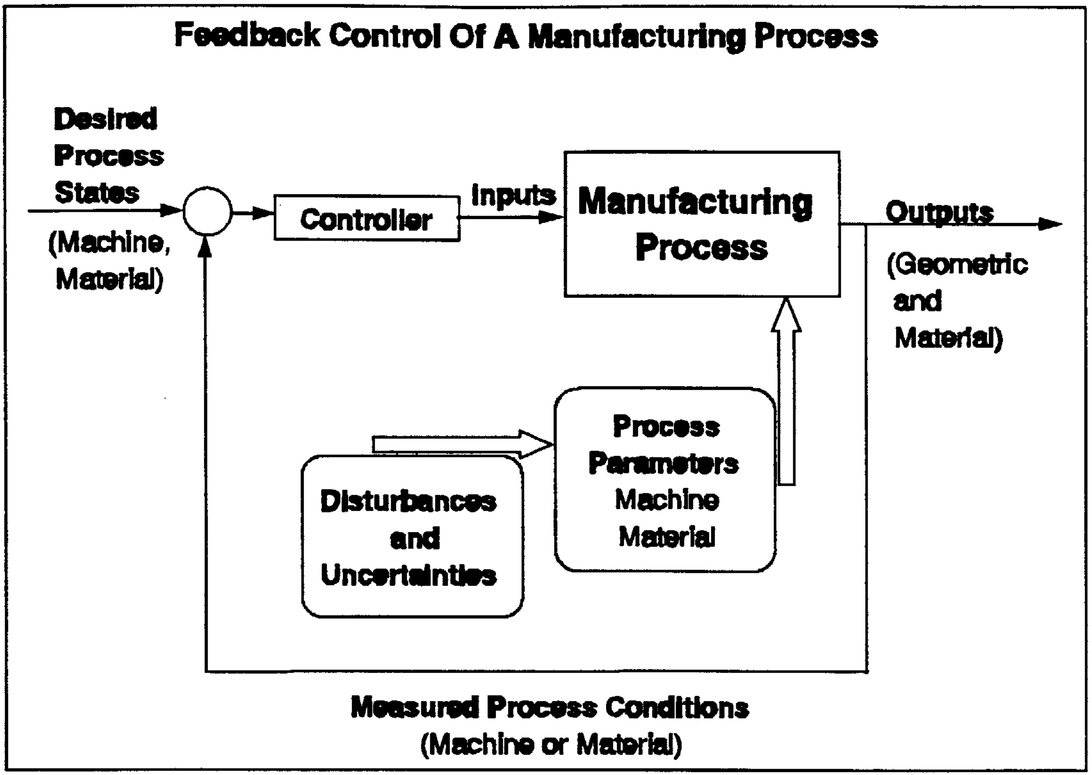

Figure 2

Modes Of Process Control

The objective of control is to minimize the effect of disturbances and uncertainties on output ($\beta_{MATERIAL,t}$ at $t = t_{FINAL}$), and there are several approaches to achieving this.

1) **Process desensitization**

   Create robust processes that are insensitive to changes in process parameters, reduce $\delta(\text{Output})/\delta(\alpha)$. This is the goal of Design of Experiments in many instances [Montgomery, 1991].

Design of Experiments: Prior to production, the appropriate combination of inputs are empirically determined to achieve desired process outputs.

2) **Variation minimization**

- Reduce $\sigma(\alpha)$ directly. This can take two forms:
    - Reduce $\sigma(\alpha_{MACHINE})$ by improving machine design and operation.
    - Reduce $\sigma(\alpha_{MATERIAL})$ by inspecting and sorting incoming materials.

3) **Feedback Control of Process States**

Improve measurement of $\beta_{MATERIAL,t}$ by data sensing and interpretation. Improve actuation of $\beta_{MACHINE,t}$ through υ.

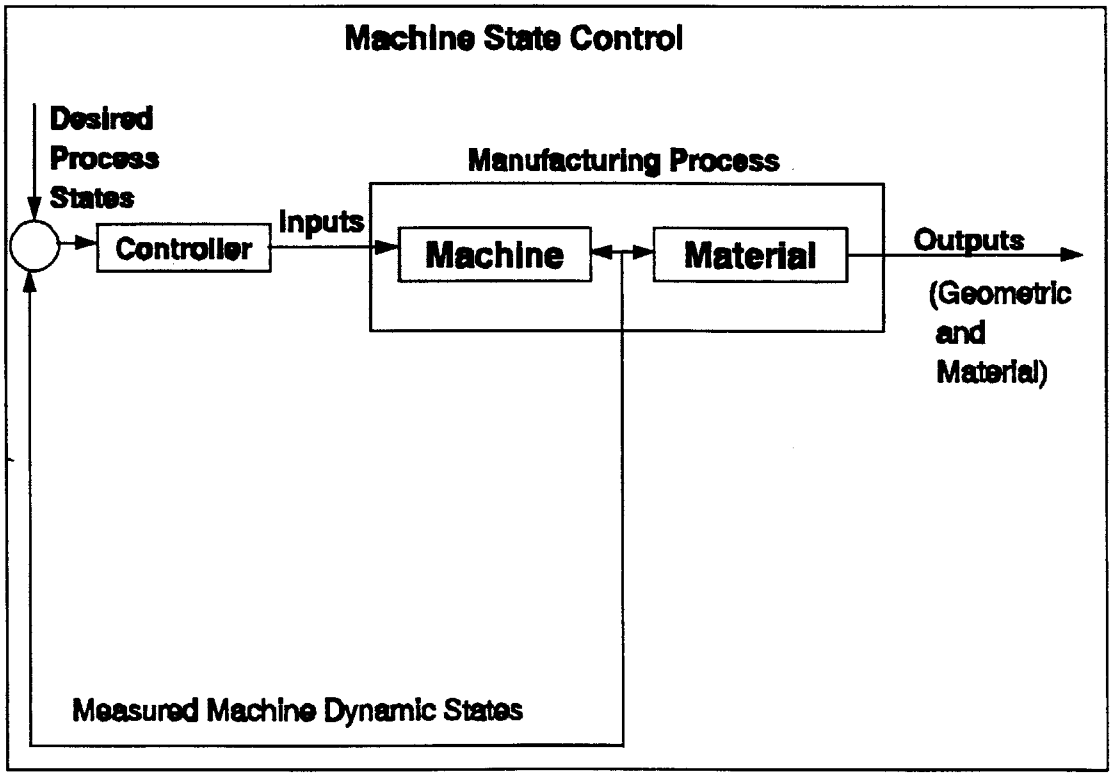

Figure 3

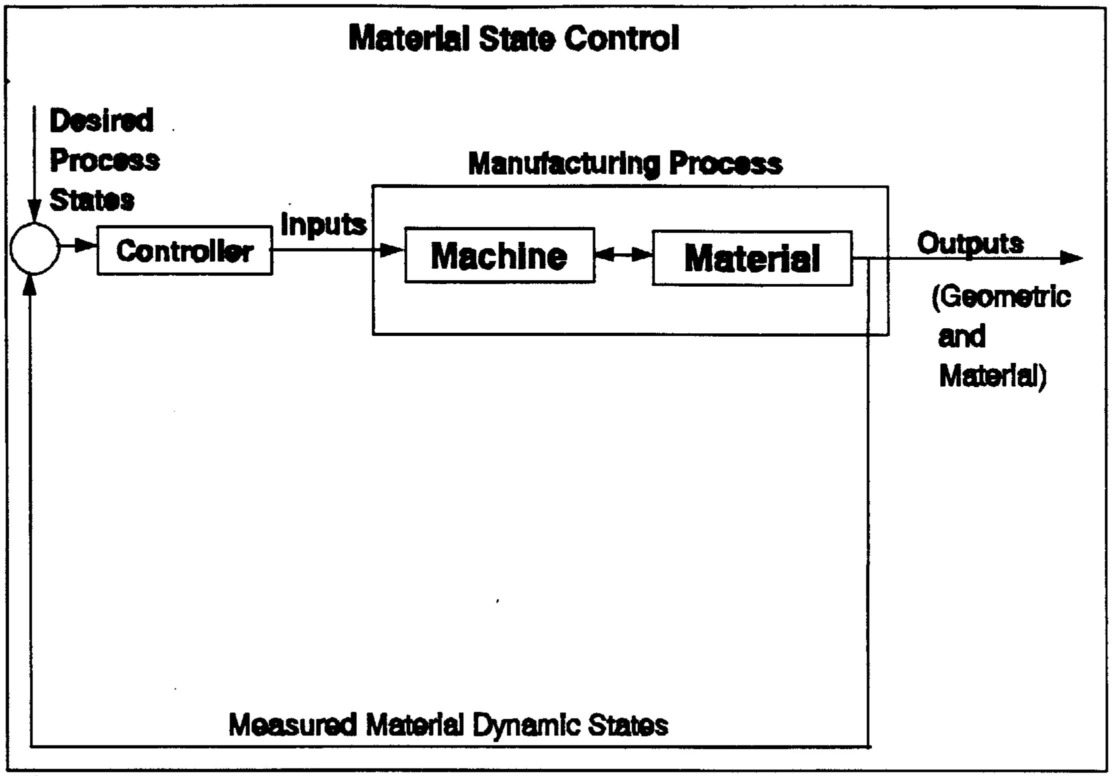

Figure 4

Types of Process-State Control

Within the context of Parameters, Dynamic States and Interactions, several types of Process-State Control can be defined. These include:

- Machine-state control (i.e. injection molding screw velocity)[Figure 3]
- Material-state control (i.e. distribution of melted plastic within a mold)[Figure 4]
- Output control (i.e. final part shape)

This issue of controlling machine states and material states is not limited to qualifying the type of Real Time Control that is being used. In a similar fashion, other control techniques (i.e. iterative or SPC) can be used to measure and control machine states or material states.[5]

Reasons For High Bandwidth Forms Of Control

Production volume and part value are important issues in choosing the appropriate control tool. For instance, sampling techniques that depend on large sample size, and iterative techniques (which may require several cycles to converge) are precluded by small production runs. Control techniques that make process corrections only after defects are detected, like iterative control or Statistical Process Control, offer no protection against costly throw-aways.

The frequency and severity of disturbances in the manufacturing process also encourage the use of real time control techniques. When there are a large number of

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[5] The consequences of controlling machine conditions, material conditions or outputs and of using Real Time Control, Iterative Control, Statistical Process Control, Design of Experiments, etc. are discussed in detail in a 1993 master's thesis by Andrew Parris, MIT-Department of Mechanical Engineering and MIT-Technology and Public Policy Program [Parris 1993].

The specific use of SPC data in a closed loop feedback process controller is discussed in "Run By Run Process Control: Combining SPC and Feedback Control" by Emanuel Sachs (MIT), Albert Hu and Armann Ingolfsson. [Sachs, et al, 1991].

disturbances during the processing cycle, control tools that can detect and compensate for these in a rapid fashion are especially valuable.

For example, the issue of production volume applies to composite manufacturing since many composite products are produced in low volume and have a high cost. Therefore, control techniques that depend on volume sampling (i.e. SPC and recall) can be uneconomic. Consequently, Real Time Control of composite processing is especially desirable.

Furthermore, issues of disturbance and uncertainty are especially germane to composite manufacturing. Operations occur in several energy domains -- fluid mechanical, solid mechanical, thermal, and chemical -- resulting in, at times simultaneously, shape changes, phase changes and chemical reactions of anisotropic materials. Particularly during curing, uncertainties and disturbances abound since resin behavior changes with age, handling and re-enforcement material [i.e. uncertainty about parameters, $\varepsilon(\alpha)$; and uncertainty about conditions, $\varepsilon(\beta)$].

Limits to Control

A Fundamental Point

Process operators cannot arbitrarily choose a feedback control tool; there are constraints imposed by process physics, process monitoring, data interpretation, and actuation. Issues of feedback time, process dynamic state measurement, and process resolution will dominate.[6]

Temporal Limits To Control

The relationship between T_{PART}, defined as the time to make a part, and $T_{CONTROL}$, defined as the time required for all control activities (data gathering, data interpretation, actuation), determine the control tools that can be used. For example:

If $T_{CONTROL} < T_{PART}$	Real Time Control is possible.
If $T_{CONTROL} = T_{PART}$	Iterative Control
If $T_{CONTROL}$ >/= T_{PART}	SPC is the best possibility (especially for large volumes).
If $T_{CONTROL} \gg T_{PART}$	Empirical process optimization (i.e. Design of Experiments).
If $T_{CONTROL}$ >>> T_{PART}	Warrantee recall.

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[6] As discussed in Chapters 3, 4, and 5, process resolution is qualitatively similar to the image processing notions of pixel density and image refresh rate. Processes with high spatial resolution can impart relatively large amounts of detail. Processes with high temporal resolution can change these details relatively quickly.

These relationships have a significant implication.

> **No matter what advances are made in sensing, modeling, or machine actuation, unless these advances contribute to a reduction in $T_{CONTROL}$ relative to T_{PART}, no marked improvement can be made in the accuracy, sophistication or responsiveness of the usable control tools.**

Measurability Limits To Control

Referring again to the process model:

$$\beta_t = \Phi(\alpha + \varepsilon(\alpha),\ \beta_{t-1},\ \varpi_t), \qquad (3)$$

the concern is altering material states by changing inputs.

$$\delta\beta_{MATERIAL} = \phi(\delta\varpi). \qquad (4)$$

However, a problem may arise. If through some shortcoming in process sensing, monitoring or modeling, $\beta_{MATERIAL,t}$ is uncertain, then the appropriate control action $\delta\varpi$ is also unclear. By implication, if

$$\delta\beta_{MATERIAL} = \Phi(\delta\varpi),\ \text{then} \qquad (5)$$

$$(\delta\varpi) = \Phi^{-1}(\delta\beta_{MATERIAL}). \qquad (6)$$

However, if $\beta_{MATERIAL}$ is uncertain, then

$$(\delta\varpi) = \Phi^{-1}(\delta\beta_{MATERIAL} + \varepsilon(\beta_{MATERIAL})), \qquad (7)$$

and $(\delta\varpi)$ is indefinite as well.

Therefore, limitations in measurement impose limitations on control. Consequently:

Only those process dynamic states (β_i's) that can be directly measured (or estimated with accuracy) can be controlled.

Therefore, if material states cannot be measured or estimated, they cannot be controlled, and feedback control is limited to machine states.

Segue

So far, two issues have been addressed. First, the relationship between T_{PART} to $T_{CONTROL}$ was described as a temporal limit on the available choice of process control tools. Second, controllability was said to be limited by measurability.

Now, process resolution will be the third limit on controlling a manufacturing process. In the following section, this issue will be developed qualitatively, and in Chapter 3 and Chapter 4, it will be developed quantitatively.

Process Resolution As A Limit To Control

Certain manufacturing processes seem inherently controllable, able to adjust to changes in material parameters and dynamic states and to compensate for other types of disturbances. Furthermore, the equipment used in these processes often lends itself to flexible production, enabling it to manufacture parts with varying geometries but without arduous retooling. Processes such as machining, arc welding and filament winding share these characteristics.

In contrast, other manufacturing processes are less able to reject disturbances and are also less able to produce a broad range of geometries. For instance, matched-die sheet metal forming can rapidly turn out parts with a particular set of final properties. However, because the tooling in this process is part-specific, an entirely new tool must be fabricated in order to produce parts with a different set of geometric properties. Additionally, the machine may require extended recalibration if material parameters change from one batch of stock to another. Other technologies like forging, injection molding and chemical etching of silicon chips have similar capabilities of high production rate coupled with relative inflexibility.[7]

There is at least one obvious difference between these high flexibility / low rate processes and low flexibility / high rate processes. With all manufacturing processes, material properties change as a consequence of the interaction between the machine and the material. The region of interaction is an energy port, i.e. the location where

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[7] Though the same equipment can etch more than one type of chip, masks (the tooling) are chip specific, and a new mask must be constructed to produce a different circuit pattern.

energy flows between the machine and the material. Processes like machining and welding have interaction regions that are relatively small compared to the overall part-size. Consequently, the process must progress in a serial fashion, progressing from location to location until the entire part is completely processed. Therefore, processes that advance temporally with relatively small interaction regions can be called **Serial Processes**.

In contrast to Serial Processes, other processes are characterized by machine / material interactions that occur in regions that are relatively large compared to the overall part size. Rather than arriving at final material properties in a progressive fashion, these techniques arrive at final states simultaneously, and can be called **Parallel Processes**.

In the following table, examples are given of serial and parallel processes. In general, serial processes have localized machine/material interactions and use tools that are not specific to the part being made. This non-specificity of tooling contributes to the flexibility of serial processes, but the localized interaction of serial processes makes for relatively slow production rates. In contrast, parallel processes employ tooling that is specific to the part being produced, and that interacts with the part as a whole. These features lead to high production rates, but limit the tools' use to one or only a few part types.

Process Classification By Serial and Parallel[8]

Serial Processes

Removal Processes
- Cutting
- Grinding
- Polishing
- Water Jet
- Laser Cutting

Addition Processes
- 3D Printing
- Laser Sintering
- Stereolithography

Solidification Processes
- Ultrasonic welding
- Plasma spray
- E-Beam Welding
- Arc Welding

Deformation Processes
- Bending
- Open forging
- Rolling
- Line Heating

Parallel Processes

Removal Processes
- Die Stamping
- Photolithography
- ECM
- EDM

Addition Processes
- HIP
- Sintering
- Plating

Solidification Processes
- Inertia Bonding
- Casting
- Molding
- Diffusion Bonding

Deformation Processes
- Drawing
- Die forging
- Hydrostatic forging

The spatial relationships of serial and parallel processes impose themselves when attention is turned to controlling particular outputs by manipulating particular inputs. With Parallel Processes, inputs affect the entire workpiece at once. Consequently, altering process inputs in order to change the dynamic state of one portion of the workpiece will affect the dynamic state of other portions, whether or not those effects are intended and desired.

For instance, during sheet metal stamping, several factors can be controlled by the operator. These may include stroke length, closing velocity, clamping force, clamping time, and release velocity. These factors may be changed to reduce

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[8] From Hardt 1991.

buckling, edge wrinkling, or elastic springback, for instance. However, the operator is nonetheless unable to control local part conditions since the tooling is fixed.[9] Similarly, in composite processing, localized degrees of cure within a workpiece cannot be 'tuned' when the only settings the process operator can manipulate are global machine states like overall autoclave temperature and pressure. [Ciriscioli, et al, 1991; Johnson and Roberts, 1989; Tam and Gutowski, 1989].

This distinction between Serial Processes and Parallel Processes, while conceptually useful, still does not offer a measure of the controllability of a process. It is not inevitable that a serial process is a means of achieving a high level of process-state control.

This is so because there is a difference between the **energy-port** and the **energy-affected zone**. The region of interaction between the machine and the material may be quite small relative to the work piece size. However, even though the energy port is small, the size of the affected region may be quite large. For instance, during welding, the heat-affected zone may be large even if a highly focused welding arc is used because of the base metal's high thermal conductivity

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[9] Based on visit to Boeing's Auburn, Washington plant on December 21, 1992 and conversations with a member of the Operations Technology group.

[Doumanidis and Hardt, 1989]. Here, a serial process can assume characteristics of parallel processes because actions in one region have strong implications on the dynamic states of other regions in the workpiece.

This is a consequence of the generally diffusive nature of machine/material interactions and is not limited to heat transfer and conduction. During plastic deformation, for example, strains can propagate from the point of contact where stresses are applied.

Therefore, the fundamental limitation in controlling the process outputs of geometric and material properties is not necessarily determined by the temporal nature of the process, since even serial processes can be difficult to control if the energy affected zone is much larger than the energy port size. Rather, controllability is determined by the minimum size of the regions in the workpiece that can be manipulated independently by changing process inputs. Process resolution increases as the size of this region decreases, just as an image's resolution increases with increases in pixel number and decreases in pixel size.

Sheet metal forming and injection molding are examples of processes with large energy affected zones and consequently low process resolution. For instance, in sheet metal forming process control, because the tooling is fixed, any changes in inputs (i.e. press velocity, clamping force, release velocity, etc.) affect the entire workpiece. The outcome at specific regions cannot be altered without changing the outcome at other regions as well. The energy affected zone of this process is the entire workpiece, and not smaller regions within the workpiece.

A similar control problem exists with injection molding.[10] A multiple cavity mold, with what seem to be identical gates and runners, may produce pieces of varying quality. Some may be underfilled, whereas other pieces from the same mold may be overpacked. Cooling-induced warpage and shrinkage may also differ. This situation leaves the process operator with few control actions that will improve the overall quality of all cavity-outputs. Screw speed, injection pressure, melt temperature and other factors can be altered, but each of these input changes will affect all of the pieces in the mold because the energy affected zone of the process is the entire mold, and not the individual pieces.

These examples of sheet metal forming and injection molding illustrate the point that process output control is limited by the size of the smallest portion of the workpiece that

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[10] The following description is based upon conversations conducted during the course of a visit to United Technologies on December 15, 1992.

Also, Parris 1993.

can be independently manipulated. These two examples also suggest that improved output control is achievable (only) by reconfiguring the manufacturing process to increase process resolution. This can be added to the two other criteria described earlier in this thesis. Together, the three specific criteria of feedback time, process state measurement and process resolution that determine the controllability of a process are:

(1) Sensing, data reduction and machine actuation times relative to part fabrication time (the relationship between $T_{CONTROL}$ and T_{PART}) determine the type of control tools that can be employed.

(2) Only the dynamic states that can be measured can be controlled (i.e. machine settings, machine states, material states).

(3) Process resolution determines the degree to which the process material states can be manipulated and controlled. In order to improve the level of material state control, resolution must be increased. This will involve decoupling the control of material states at

one region from the control of material states at other workpiece regions.[11] [12] [13]

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[11] **Coupled Input/Output** (non-zero values for A_{ij}, all i,j)

$$\begin{array}{ccccccccc}
O_1 & & A_{11} & A_{21} & \cdot & \cdot & \cdot & A_{1n} & I_1 \\
O_2 & & A_{21} & A_{22} & \cdot & \cdot & \cdot & A_{2n} & \cdot \\
\cdot & = & \cdot & & \cdot & & & \cdot & \cdot \\
\cdot & & \cdot & & & & \cdot & \cdot & I_n \\
O_m & & A_{m1} & A_{m2} & \cdot & \cdot & \cdot & A_{mn} &
\end{array}$$

[12] **Decoupled Input/Output** ($A_{ij}=0$, if $j>i$)

$$\begin{array}{ccccccccc}
O_1 & & A_{11} & 0 & 0 & 0 & 0 & 0 & I_1 \\
O_2 & & A_{21} & A_{22} & 0 & 0 & 0 & 0 & \cdot \\
\cdot & = & \cdot & & \cdot & 0 & 0 & \cdot & \cdot \\
\cdot & & \cdot & & & & \cdot & 0 & I_n \\
O_m & & A_{m1} & A_{m2} & \cdot & \cdot & \cdot & A_{mn} &
\end{array}$$

[13] **Uncoupled Input/Output** ($A_{ij}=0$, for i not equal to j)

$$\begin{array}{ccccccccc}
O_1 & & A_{11} & 0 & 0 & 0 & 0 & 0 & I_1 \\
O_2 & & 0 & A_{22} & 0 & 0 & 0 & 0 & \cdot \\
\cdot & = & 0 & & \cdot & 0 & 0 & \cdot & \cdot \\
\cdot & & \cdot & & & A_{ii} & 0 & \cdot & \cdot \\
\cdot & & \cdot & 0 & & & \cdot & 0 & I_m \\
O_m & & 0 & 0 & \cdot & \cdot & \cdot & A_{mm} &
\end{array}$$

Chapter 3: Process Resolution As A Control Problem In Injection Molding and Sheet Metal Forming

Overview

Chapter 2 contains a control taxonomy of manufacturing processes, which are described as input/output systems subject to disturbances and uncertainties. These disturbances and uncertainties necessitate the implementation of process control tools. However, the range of available control methodologies is limited by feedback time, process state measurement and process resolution.

In Chapter 3, Chapter 4, and Chapter 5, process resolution is quantified in frequency domain terms. Processes are characterized as non-parametric sinusoidal transfer functions ("transfer functions"), and the bandwidth of these transfer functions will be a measure of a process's ability to reflect changes in inputs as changes in outputs.

As the basis for developing the idea of process resolution further, the output-control challenges of two processes will be discussed in Chapter 3. First is an injection molding control problem and a suggestion for its solution. The second is a method of sheet metal forming process control being investigated by the Laboratory for Manufacturing and Productivity. This will provide the introduction for using frequency domain techniques to quantify process resolution.[14]

In both situations, conventional tooling is a challenge to ensuring high quality parts. For both injection molding and sheet metal forming, tool design is computationally intensive, and the solutions are not invertible. Therefore, the computational packages can predict part shape as a function of tool shape, but they don't provide tool shape as a function of desired part shape.[15]

Beyond this, once the tools are designed, they are designed for materials with a particular set of properties. However, material properties can vary, and tool-material interactions are also subject to variations, variations which conventional tools may have trouble rejecting.

For both injection molding and sheet metal forming, the solutions given in this thesis focus on improving the process control properties of the processes. For injection molding, there is a suggestion for improving heat transfer control. For sheet metal forming, there is a review of

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[14] A more complete discussion of the LMP's sheet metal process control research follows. [Hardt, et al, 1991; Webb, 1989]

[15] Finite Element Analysis ("FEA") can calculate $\mathbf{P}_{\mathrm{ACTUAL}} = f(\mathbf{D}_{\mathrm{ACTUAL}})$, but FEA cannot calculate $\mathbf{D}_{\mathrm{OPTIMAL}} = f^{-1}(\mathbf{P}_{\mathrm{DESIRED}})$, where **P** is the part shape, and **D** is the die shape. [Webb, 1989]

research being done in the Laboratory for Manufacturing and Productivity.

The process control problems and solutions discussed in Chapter 3 are specific to injection molding and sheet metal forming. In Chapter 4 and Chapter 5, these solutions are generalized, and the frequency domain technique used by the LMP to describe the shape of stamped sheet metal parts is used to quantify process resolution.

The Injection Molding Process Control Problem[16]

Tool Design and Process Control Challenges

Injection molded parts are produced by forcing a liquified thermoplastic material into a mold through a series of gates and runners. Broadly speaking, this presents a challenge during mold design and another challenge during production. During the mold design phase, compensations must be made so that shrinkage and warpage, which occur during cooling, result in a solidified part that possesses the correct final properties. These concerns also influence the design and placement of gates, runners, and fill ports since the tool's geometry affects molecular orientations (and residual stresses) as the thermoplastic sets. During production, particularly for a part with a relatively uncomplicated geometry made in a single cavity mold, the challenge is to

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[16] [Kalpakjian, 1989; Sachs, et al, 1991, United Technologies visit, Dec. 1991]

find the correct combination of temperature and pressure that allow the liquid to fill the mold completely while not overcoming the clamping forces.

Additional problems arise with increases in part complexity and with the use of multi-cavity, rather than single cavity, molds. Increased part complexity magnifies the warping and shrinking distortions caused during cooling. Consequently, the mold-design phase becomes more challenging.

Multiple cavities generate additional problems during production. Runners, gates and cavities may be designed for a single cavity mold so that the correct combination of fill-temperature and fill-pressure result in a solidified and cooled part with the desired material and geometric properties. Yet, when the same runner, gate and cavity patterns are identically replicated in a multiple cavity mold, it is entirely possible that each cavity will produce a part with different qualities. This happens because each cavity, though geometrically equivalent, may have different heat transfer characteristics due to different locations within the mold as a whole.

This problem may not be solvable in a practical and consistent way by adjusting manufacturing process inputs. In conventional injection molding, the operator can only control injection pressure and melt temperature. Altering either of these control values will affect all the cavities in the mold. In turn, attempting to control the output of one cavity may have deleterious effects on the outputs of the other cavities. In this case, the process's spatial resolution is too low (i.e. control affects the entire mold and not the individual cavities).

Potential Solutions

Heat transfer properties are the natural target of process redesign, since the injection molding process is dominated by heat transfer relationships. The viscosity and flow characteristics of the liquified thermoplastic are determined by the its temperature, and the rate and degree of cooling have a strong impact on the shrinkage and warpage. Consequently, even if each cavity in a multiple cavity mold has the same geometric properties, the characteristics of their parts will vary, if each does not have the same heat transfer properties as well.

A Tool Design Approach

There is more than one approach to overcoming this difficulty. One might be to design the molds to compensate for the differing heat transfer characteristics of each cavity (redesigning machine parameters, $\alpha_{MACHINE,}$ for better machine and material states, $\beta_{MACHINE\ AND\ MATERIAL}$). However, this may significantly increase the computational complexity of the design process. Furthermore, this approach leaves the operator with a more highly engineered process that is nonetheless still of low resolution.

A Process Control Approach

Alternatively, the tool (the mold in this case) might be designed to increase process resolution, so that the output of individual cavities can be manipulated (increasing the number of υ_j's and β_i's). Rather than having a system of heating and cooling elements that transfer heat to the mold as a whole, the heating and cooling system might be modularized so that the heat flow to, or temperature of, individual cavities can be actuated. As a result, the properties of individual parts can be manipulated directly without adversely affecting the quality of other parts in the mold. This approach might go one step further to allow temperature gradient control within a single cavity.

Flexible Discrete-Die Forming Of Sheet Metal[17]

Problem Description

The shape of stamped sheet metal parts is primarily determined by the shape of the die. However, purely analytical designs methods are not adequate for the design of tools used to make shallow, doubly curved metal parts. First, the primary numerical analytical tools, Finite Element Analysis ("FEA") packages, predict part shape based

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[17] This material is drawn from the papers by Webb and Hardt, 1989; Hardt, et al, 1991; Webb, 1987.

on tool shape. However, FEA solutions are not invertible and do not give die shape as a function of desired part shape. Consequently, die design is an iterative process of part formation, part shape measurement, and die shape change. However, for conventional fixed dies, this iterative process can be expensive and time-consuming. Both of these are significant drawbacks in the face of pressure to speed development times and shorten production runs.

Even if analytical solutions were invertible and computationally efficient, they would not be necessarily be a sufficient guarantor of high quality parts, since there are disturbances, uncertainties, and variations in machines and materials such as variations in yield strength and material thickness, for instance. Therefore, the value of even ideal analytical solutions would degrade in the face of uncertain material-tool interfacial forces and uncertain material parameters.

General Solution

In response to the pressures for faster and less expensive die design, and in response to the limitations of conventional tooling and conventional tool design procedures, the LMP has been developing an approach using a die composed of an x-y array of pins, the z-altitudes of which can be independently reset between each part forming.

These two properties are the discrete and the flexible characteristics of the device respectively.

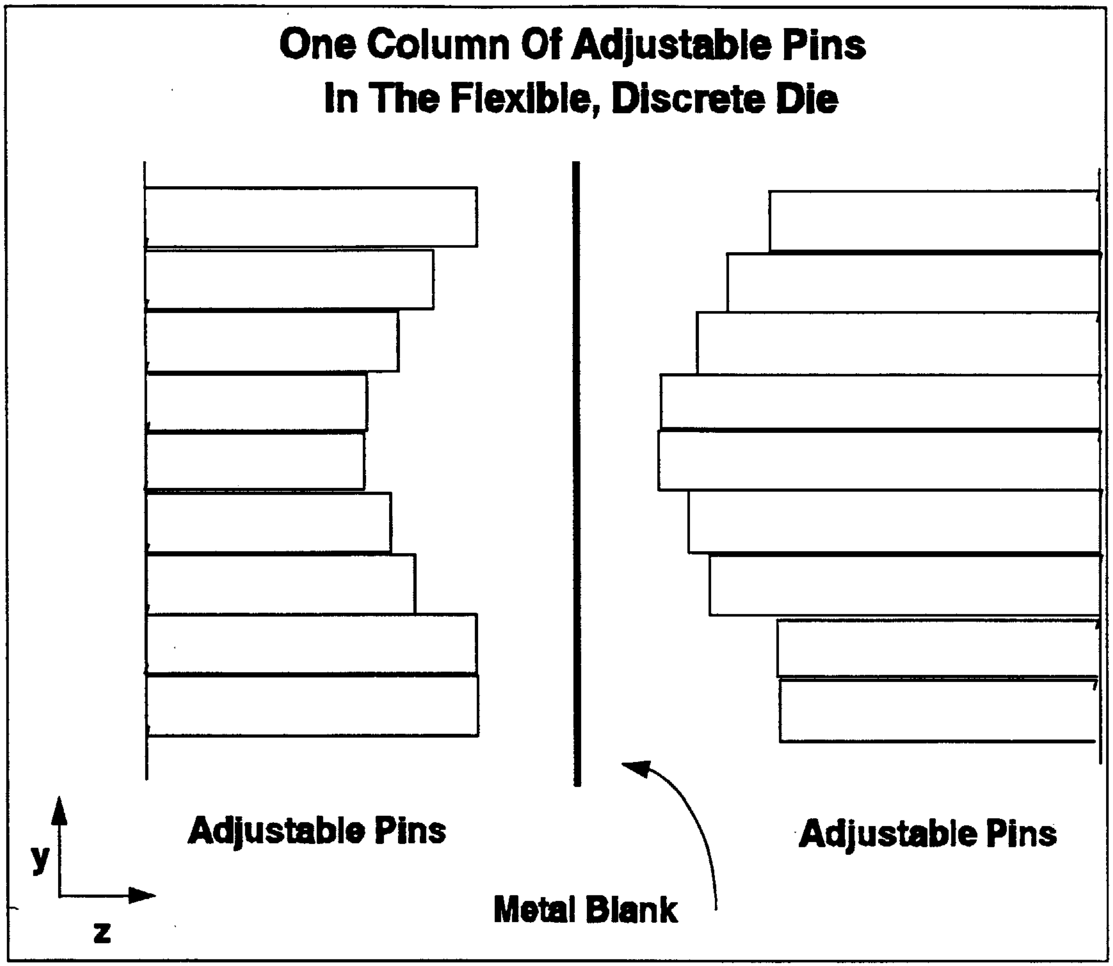


Figure 5

Determining The Appropriate Form Of Feedback

Ideally, in-process measurements of plastic deformation could lead to appropriate in-process adjustments in die shape. Then feedback could be completed in one forming cycle. In earlier LMP work, studying two dimensional roll bending, this was possible since knowledge of the bending moment and the loaded curvature could lead to predictions of the unloaded curvature [Hardt; Constantine; Wright; 1989].

In three dimensions, such in-process measurements and predictions are not feasible. With completely general compound curvatures, there are considerable in-plane flows of material and two dimensional strains. There is the possibility of compressive instability (buckling) and tensile instability (tearing). Consequently, the LMP determined that in-process measurements of <u>overall</u> die force or <u>overall</u> die displacement were inadequate for completely characterizing the mechanical state of the sheet, in much the same way that overall injection pressure and overall injection temperature are inadequate for completely characterizing the dynamic states within injection molding mold cavities. Therefore, the researchers concluded the range of process inputs had to be extended beyond overall die force and die displacement and created the die composed of an array of pins. As a result of this design decision, only unloaded, iterative feedback was feasible (i.e. from Part_t to Part_{t+1}). It was not feasible to take in-process measurements and make in-process adjustments, because of interactions through the workpiece and equipment limitations.

Iterative Feedback And Shape Representation

Because single-cycle in-process measurements and in-process adjustments were considered impractical, the control algorithm which was chosen compares the part shape ($\mathbf{P}_k$) with the desired shape ($\mathbf{P}_0$), and then makes appropriate changes in the die shape ($\mathbf{D}_{k+1} - \mathbf{D}_k$). In making these comparisons though, it was not sufficient to compare the part altitude at a particular coordinate set, $\mathbf{P}_z(x,y)$, strictly as a function of the die altitude at a particular coordinate set, $\mathbf{D}_z(x,y)$. Treating local deformations only as the consequence of local die altitudes would ignore the coupled nature of local plastic deformations with global sheet strains.

Alternatively:

$$\mathbf{P}_z(x,y) = g(\mathbf{D}_z(x,y)) \qquad (8)$$

is incorrect. Rather,

$$\mathbf{P}_z(x,y) = \Sigma_{m=0}\Sigma_{n=0}g(m,n)(\mathbf{D}_z(m,n)), \qquad (9)$$

where g(m,n) is a weighting function, is correct.

Therefore, in order to capture the interactions reflected in equation 9, Discrete Fourier Transforms were used to give a frequency domain description of part shape using the relationships:

$F(u,v) = {}_{m=0}\Sigma^{M-1}{}_{n=0}\Sigma^{N-1} f(m,n)\exp(-j2\pi(mu/M + nv/N))$, and (10)

$f(m,n) = (1/MN)\,{}_{u=0}\Sigma^{M-1}{}_{v=0}\Sigma^{N-1} F(u,v)\exp(j2\pi(mu/M + nv/N))$, (11)

where m,n are x-y coordinates, z=f(m,n), u,v are frequencies, and F(u,v) is a frequency amplitude.

While using Fourier Transforms proves a means of accounting for interactions, in and of itself, it does not facilitate dealing with the non-linear **D-P** (Die/Part) input/output relationship. However, for small changes in **D**, changes in **P** are much more linear. This then leads to a transfer function representation:

$$\mathbf{H}_k(u,v) = \frac{\mathbf{P}_k(u,v) - \mathbf{P}_{k-1}(u,v)}{\mathbf{D}_k(u,v) - \mathbf{D}_{k-1}(u,v)} \qquad (12)$$

Therefore, with each forming cycle, the shape of the die and the part are measured, and their measurements are Fourier Transformed to their frequency domain form. A transfer function can then be calculated, and a new die shape can be prescribed according to the rule:

$$\mathbf{D}_{i+1} = \mathbf{D}_i + \mathbf{E}_i\ \mathbf{H}_i^{-1}, \qquad (13)$$

$$\mathbf{E}_i = \mathbf{P}_{\mathrm{DESIRED}} - \mathbf{P}_i. \qquad (14)$$

Current Research Issues

In the drive to produce higher quality parts with greater levels of detail and accuracy, an effort is being made to reduce the size of the die pins and increase their number per unit area. In a sense, this is motivated by a corollary to Shannon's Sampling Theorem. The theorem says that a sampling rate must be twice the maximum determinable frequency. In this instance, increasing the signaling rate increases the maximum impartible frequency. Therefore, increasing the pins per unit area increases the maximum spatial frequency.

Chapter 4: Spatial and Temporal Frequency Content

Overview

Chapter 2 introduces a control taxonomy for manufacturing processes. It identifies feedback speed, the measurability of machine and material states, and process resolution as limits to improving process control. Chapter 3 develops the idea of process resolution further, and describes it as the responsiveness of process outputs to process inputs.

Injection molding and sheet metal forming were chosen to represent the control difficulties presented by low resolution processes. It is particularly noteworthy that these two processes are dissimilar in important ways. They differ by type of material and by type of material manipulation. Injection molding is a solidification process dominated by heat transfer, whereas metal stamping is a deformation process dominated by stress-strain relationships. However, despite these differences, they share the similarity that their spatial resolution is low, and a potential means of improving process performance, for both, is by increasing spatial resolution through process redesign.

In the discussion of sheet metal forming control, the Laboratory for Manufacturing and Productivity's use of Fourier Transforms to describe the shape of tools and parts was introduced. Because the stamping tool in question is made of movable pins (its source of flexibility and discreetness, respectively), using Fourier Transforms to describe tool shape is akin to describing inputs by their spatial frequency content. Similarly, using Fourier Transforms to describe part shape is akin to describing outputs by their spatial frequency content as well. Therefore, the LMP's specific efforts in sheet metal forming control suggest that, in general, manufacturing process inputs and outputs can be expressed by their frequency content.

This chapter will illustrate the use of Fourier Transforms to approximate physical shapes and time signals as the sum of sinusoids. Then, Chapter 5 will show how this approach can represent inputs and outputs of a heat transfer process as temporal and spatial frequencies.

Explaining Spatial and Temporal Frequency Content

Figure 6 is a picture of a rectangular pulse, which can be interpreted as a time domain pulse or as a spatial pulse.

In the time domain, this would be expressed as:

$$f(t) = -.75, \text{ for } 0 < t < 38 \tag{15}$$

$$f(t) = .75, \text{ for } 39 < t < 79 \tag{16}$$

$$f(t) = -.75, \text{ for } 80 < t < 108. \tag{17}$$

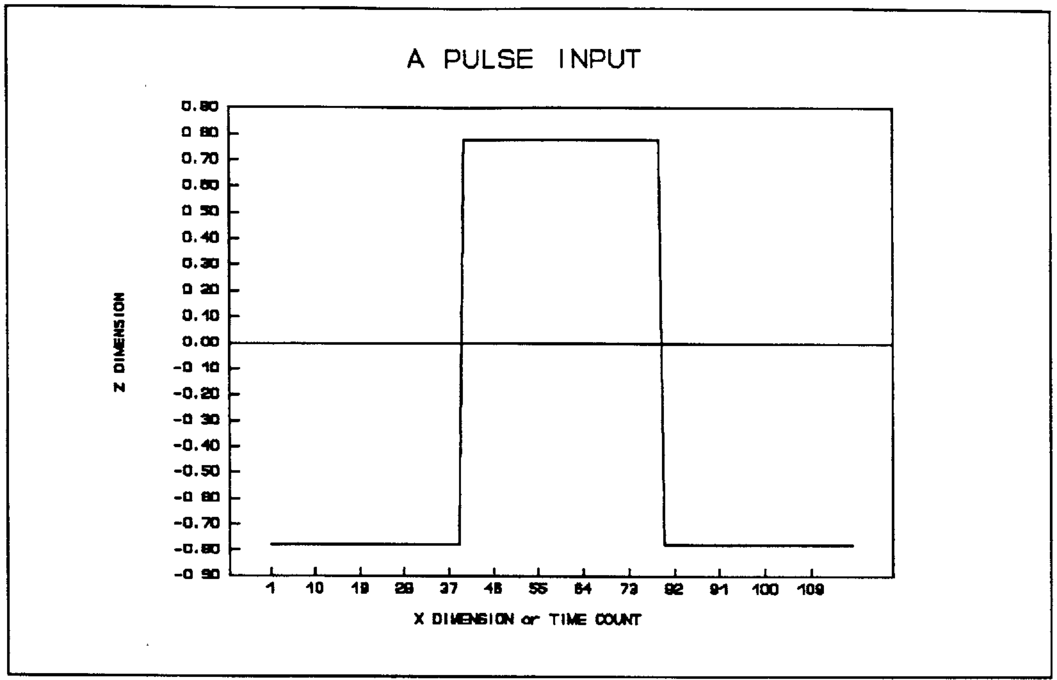


Figure 6

Similarly, if this rectangular pulse were a spatial concept, for instance the cross section shape of a mold or die, it would be represented as:

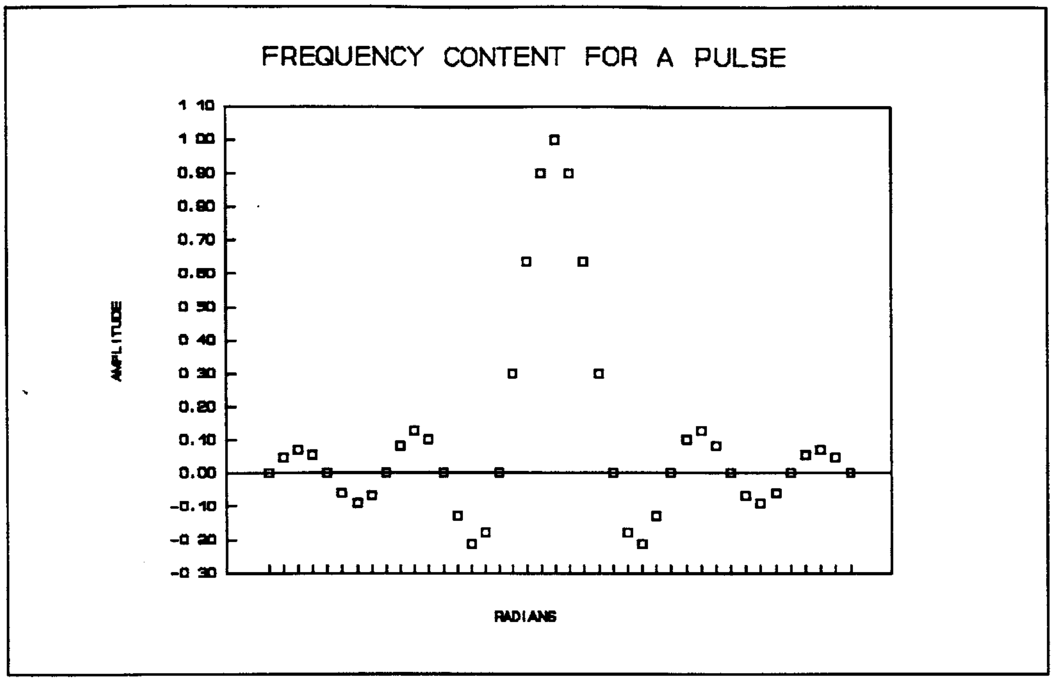
$$z(x,y) = -.75, \text{ for } 0 < x < 38, \ y = C, \quad (18)$$

$$z(x,y) = -.75, \text{ for } 39 < x < 79, \ y = C, \quad (19)$$

$$z(x,y) = -.75, \text{ for } 80 < x < 108, \ y = C. \quad (20)$$

While mathematically precise, these equations are computationally unwieldy. Therefore, Fourier Transforms are used to approximate these spatial or temporal shapes as the sum of sinusoids of increasingly high frequency. Figure 7 shows the frequency content of the pulse (calculated using equation 10), and Figure 8 gives examples of several of the sinusoids that, when summed together, approximate this rectangular pulse. It is notable that the pulse, though dominated by one low frequency, is composed of a spectrum of increasingly higher frequencies.

Figure 9 shows compares the original rectangular shape, with a single sinusoidal approximation.



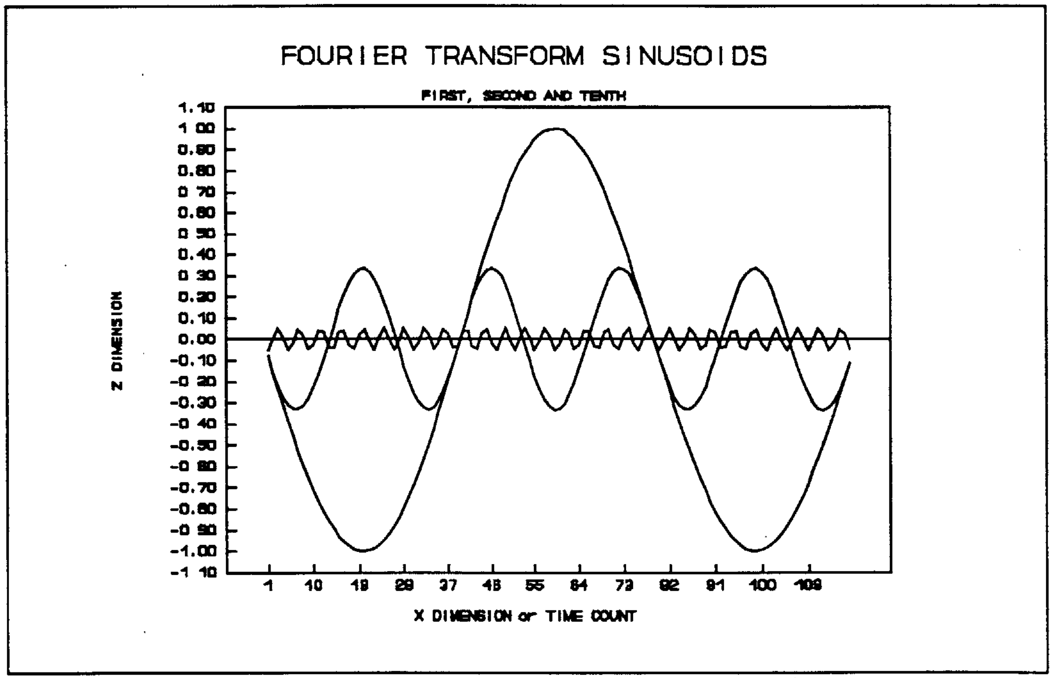


Figure 8: First, Second and Tenth Sinusoids

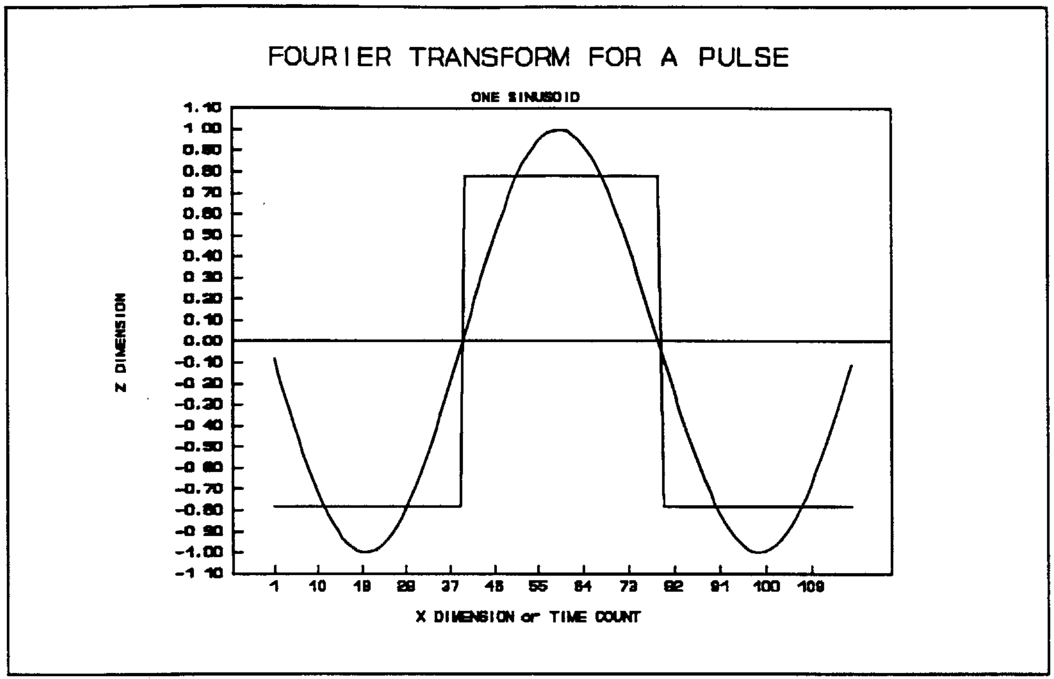


Figure 9: One Sinusoid

Figure 10, Figure 11, Figure 12, and Figure 13 show how summing together increasing numbers of sinusoids, each of increasing frequency, improves the accuracy of the approximation.

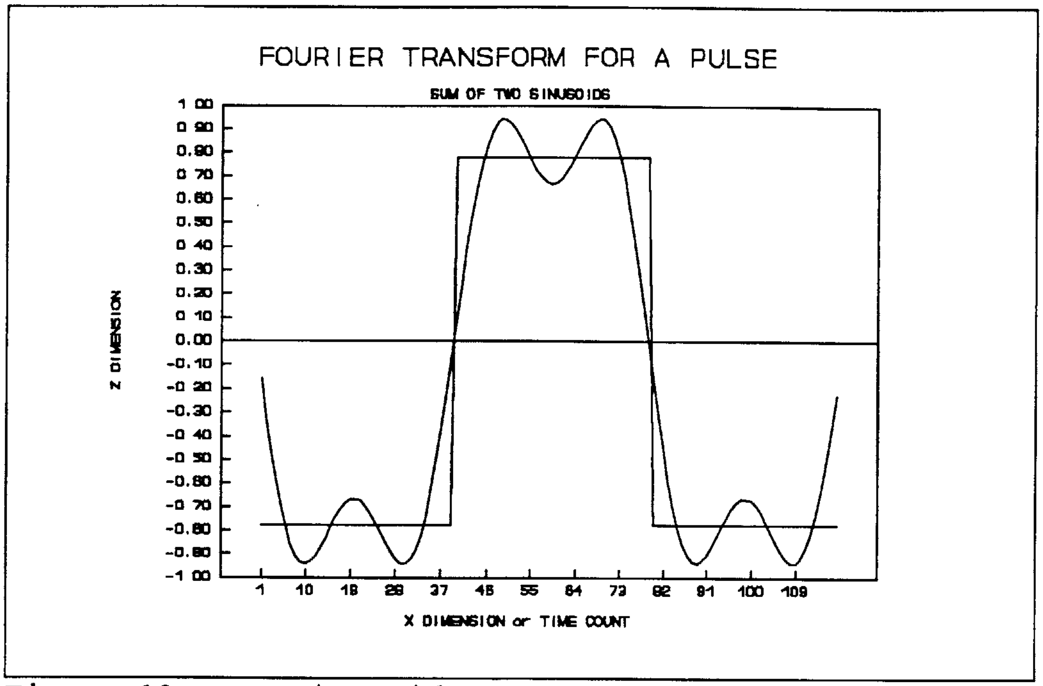


Figure 10: Two Sinusoids

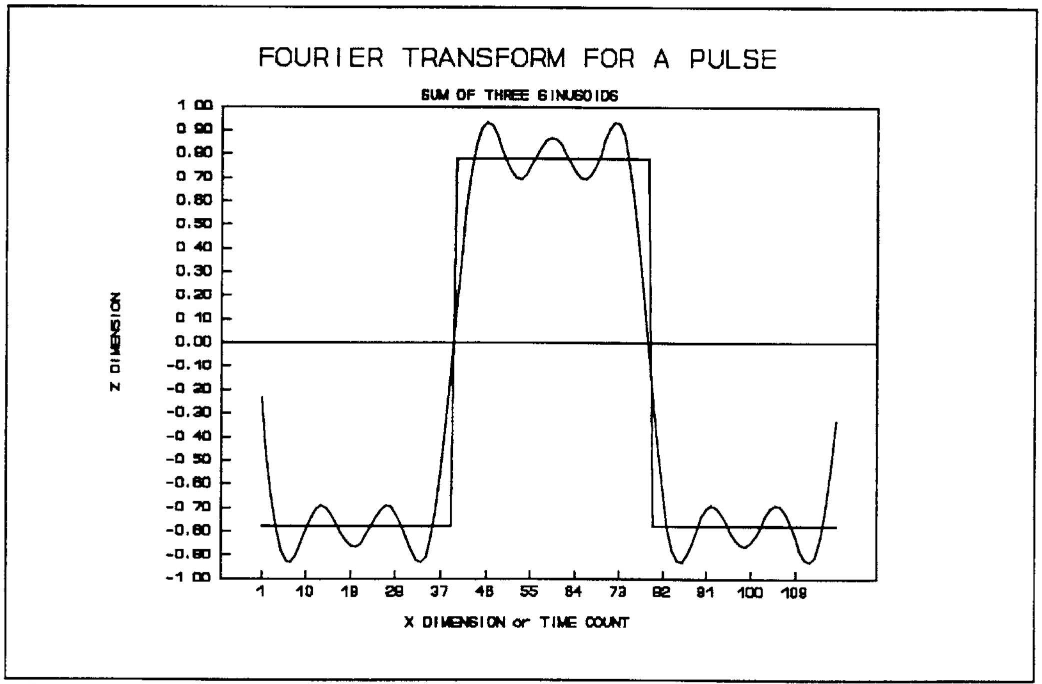


Figure 11: Three Sinusoids

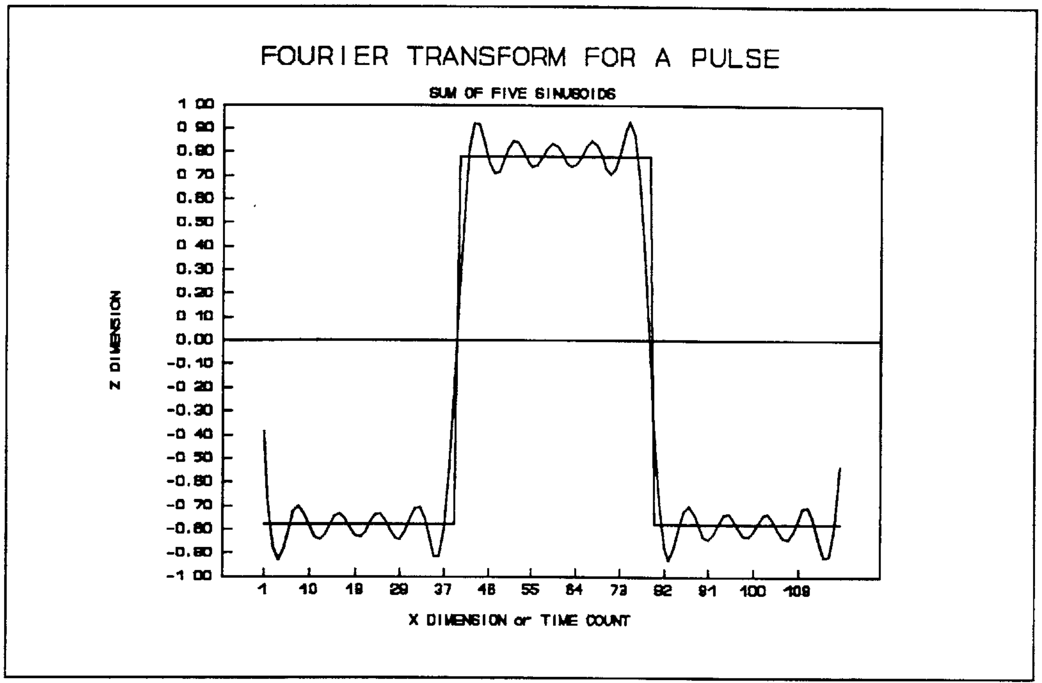


Figure 12: Five Sinusoids

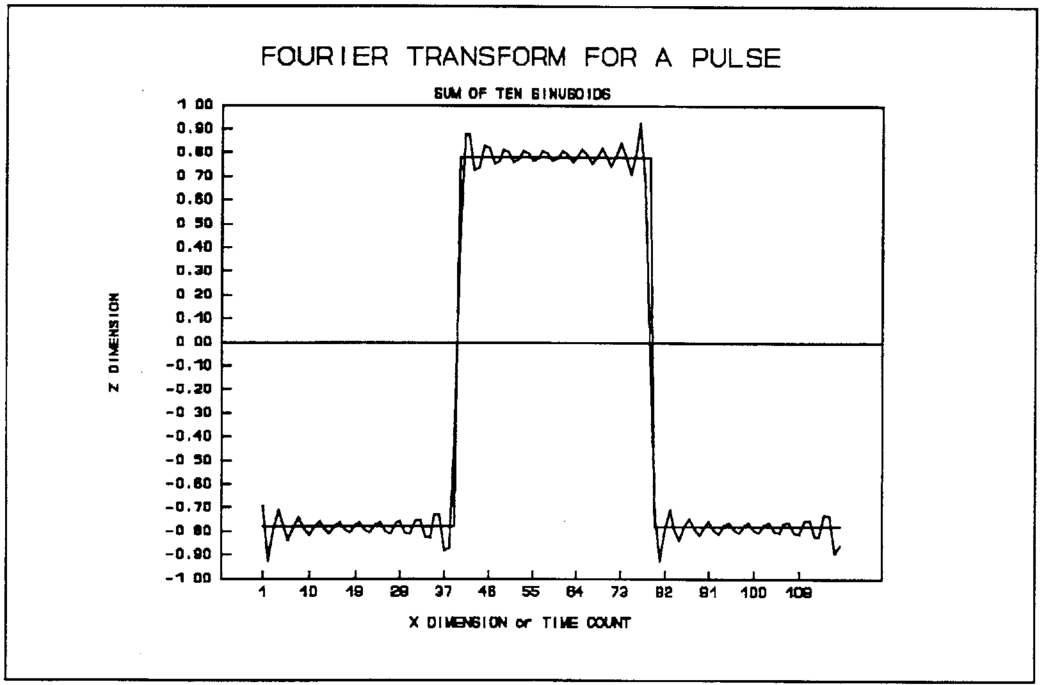
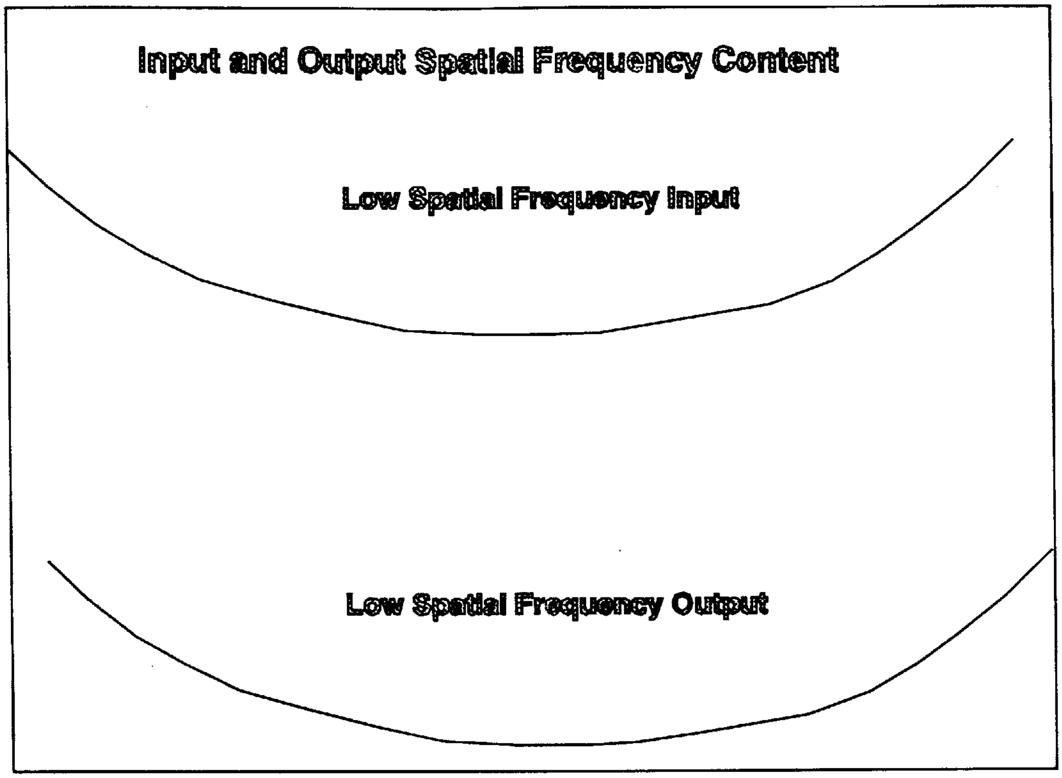


Figure 13: Ten Sinusoids

As these figures show, the approximation improves as higher frequencies are included in the sum. Also evident, the parts of the original shape that are particularly difficult to approximate are the corners. Sharp corners like these are places where physical slopes change rapidly, where gradients are especially steep, and where curvatures are especially small. In frequency terms, these regions contain especially high frequencies, (i.e. they have high frequency contents). By extension, the narrower the pulse, the more important are high frequencies in creating an accurate approximation, and the greater the relative magnitude of the high frequencies. In an extreme, an impulse (which theoretically has no width at all, and only height) can only be approximated by summing all frequencies together, each with the same amplitude.

This previous example had a single input, t or x, and a single output, f(t) or z. However, the Fourier Transform method to represent space-domain shapes and time-domain signals as a sum of sinusoids can be extended to two dimensions, z = f(x,h), as it was in the sheet metal forming control example in Chapter 3, or it can be extended to n-dimensional input/output systems [Lim, 1990]. The general notion holds though; steep gradients and sharp changes in slope have higher frequency contents than do systems that have flatter gradients or gradual slope changes. For instance, Figure 14 shows an input/output system with a very low frequency content.

Figure 14:



The earlier example shows how sinusoids can be summed to approximate shapes (space domain) or signals (time domain). It also demonstrated that including higher frequencies increased the accuracy of the approximation.

Conversely, the worse the approximation, the more those higher frequencies have been excluded. By extension, if an input is considered to have a particular frequency content, than the less the output matches the inputs, the more that higher frequencies have been lost by the process.

For instance, returning to the example of a rectangular pulse, Figure 15 shows an input and an output. This input is a rectangular pulse. However, the output shape has corners that have been smoothed and rounded. From the earlier example, then, this system has lost some of the higher frequencies and has passed only the lower frequencies. If a Fourier Transform were used to approximate the shape of the output, the bandwidth of the system would be the highest frequency contained by the output shape.

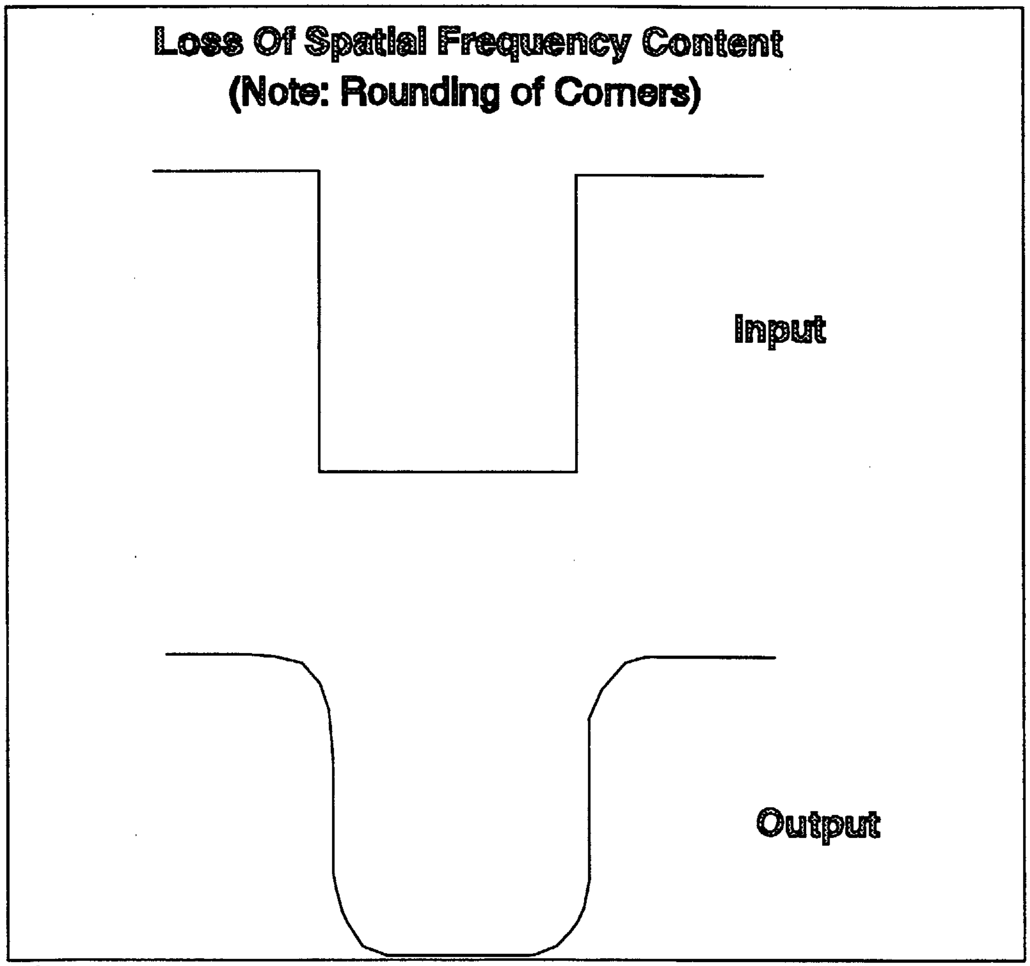


Figure 15

Summary

This chapter illustrated the use of Fourier Transforms to create approximations of spatial shapes and temporal signals by summing a series of sinusoids. The rectangular pulse example shows that the low frequencies are sufficient to approximate gross shapes, but higher frequencies are necessary to approximate greater detail. Conversely, the lower the bandwidth of a shape or of a signal's frequency spectrum, the more there is a loss of detail. Because of this, process bandwidth is a convenient way to quantify process resolution. The less able a process is able to pass the high frequencies, which are contained in the input spectrum, to the spectrum representing the process output, the less able the process is to control outputs by adjusting inputs.

In Chapter 5, the results of a two dimensional heat transfer simulation will demonstrate these concepts.

Chapter 5: Two Dimensional Heat Transfer: Measuring Process Capability By Frequency Content

Overview

This chapter employs a simple conduction heat transfer model to illustrate the concepts of Chapters 2, 3, and 4. Chapter 2 introduces process resolution as one of three constraints on process control implementation. This is presented as part of a control taxonomy of manufacturing processes. The taxonomy holds that machines and materials interact through energy ports, and that it is as a consequence of this interaction that the dynamic states of materials change.

Chapter 3 and Chapter 4 continue the development of process resolution as a limit to controlling dynamic states. Chapter 3 presents the specific use of Fourier Transforms, by the MIT Laboratory for Manufacturing and Productivity, to describe the shape of sheet metal forming tools and parts. Chapter 4 illustrates the notion of frequency content by approximating a rectangular pulse as the sum of sinusoids.

The most important point in Chapter 4 is that the quality of the sinusoidal approximation improves as higher frequencies are included, and that the greater the spatial or temporal detail (i.e. sharp corners, impulses, etc.) the greater the contribution of high frequencies to the accuracy of the approximation. Quantitatively, this means that the amplitude of high frequencies increases with increasing detail. The extreme case is of an impulse of infinitesimal width which is represented as an infinite sum of frequencies, all of the same amplitude.

For input/output systems, the loss of spatial or temporal detail is analogous to filtering of higher frequencies from the input-spectrum. This filtering occurs because energy, which is transmitted from the machine to the material through an Energy Port of finite size, can affect a region, the Energy Affected Zone, that is larger than the Energy Port itself. During the plastic deformation of sheet metal, for instance, energy diffusion occurs because tool induced stresses create strains that are not at the point of contact. Similarly, during heat transfer processes, energy may diffuse from the Energy Port to the Energy Affected Zone by multi-dimensional conduction.

This section presents the results of a conduction heat transfer simulation, and demonstrates that the frequency domain techniques, used to quantify energy inputs and measured dynamic states in sheet metal forming, can be extended to characterize heat flux as an input and the temperature of the workpiece as the measured process state.

Several simulations are presented. They show that varying geometric properties, such as sample thickness, and varying material properties, such as conductivity and other heat transfer coefficients, alters the process bandwidth. Additionally, these simulations show that heat transfer has temporal frequency components in addition to spatial frequency components. Perhaps most interesting, these simulations suggest that the filter like qualities of the process are a function of machine properties alone and not material properties as well.

As a whole, these simulations are relevant because they reflect some of the difficulties of controlling the temperature within a material by heating it on the surface, or, for instance, trying to control the temperature inside a mold by applying a heat source to its exterior.

Description Of The Simulation

A finite difference simulation was conducted in Matlab, based on a two-dimensional array of discrete heat capacitances, as represented in Figure 16.

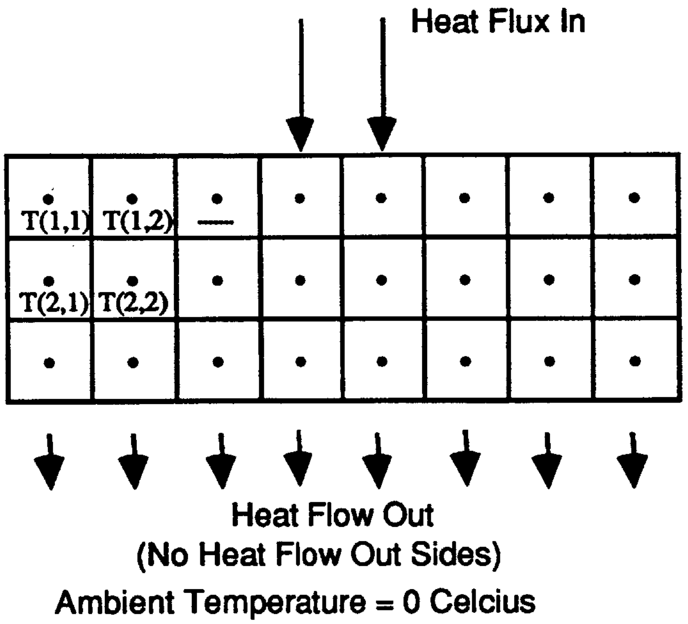
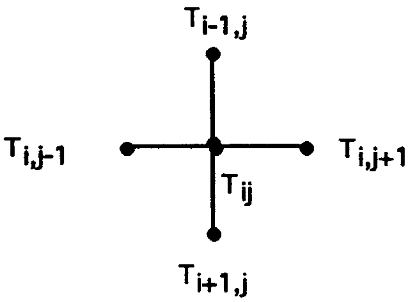


Figure 16:

Heat could flow into the top nodes from a heat source, which was placed above the two central nodes. Heat could only flow out from the plate through the bottom nodes, and heat could flow between nodes by conduction.

Each element is assumed to be a thermal capacitance, with heat following from adjacent nodes or from the source.

The node number convention is given by:



where the index *i* is the row number and *j* is the column number, and array is assumed to have the dimensions m x n.

In all these simulations, the plate was 32 centimeters (n=32) wide. In several series, the plate height was 3 centimeters, and in others, it was 6 centimeters (m=3 and m=6).

Assuming a positive heat flow toward each node, the equations of state for each element is given by

$$\frac{c_p}{\rho}\frac{dT_{ij}}{dt} = \frac{k}{\Delta x^2}((T_{i,j-1} - T_{ij}) + (T_{i,j+1} - T_{ij}) + (T_{i-1,j} - T_{ij}) + (T_{i+1,j} - T_{ij}) + q(i,j)) \tag{21}$$

$$= \frac{k\rho}{c_p\,\Delta x^2}((T_{i,j-1} + T_{i,j+1} + T_{i-1,j} + T_{i+1,j} - 4\,T_{ij}) + q(i,j)) \tag{22}$$

These equations can then be solved using MATLAB given an appropriate set of coupled state equations.

Boundary nodes:

At the top:

$$\frac{dT_{1j}}{dt} = \frac{k\rho}{c_p\,\Delta x^2}(T_{i,j-1} + T_{i,j+1} + T_{i+1,j} - 3\,T_{ij}) + q(i,j)) \tag{23}$$

At the bottom a general convection equation

$q_c = U(T_o - T_{i,j})$ is assumed for each node, so that bottom node equations become:

$$\frac{dT_{mj}}{dt} = \frac{k\rho}{c_p\,\Delta x^2}((T_{i,j-1} + T_{i-1,j} + T_{i,j+1} - 3\,T_{ij}) + U(T_o - T_{i,j})) \tag{24}$$

$$= \frac{k\rho}{c_p\, \Delta x^2} ((T_{i,j-1} + T_{i-1,j} + T_{i,j+1}) - (3+\frac{c_p}{k} U)\, T_{ij} + U\, T_o) \tag{25}$$

It is assumed that the sides are insulated, thus there is no heat transfer at that boundary:

Left Boundary:

$$\frac{dT_{i\,1}}{dt} = \frac{k\rho}{c_p\, \Delta x^2} ((T_{i-1,j} + T_{i,j+1} + T_{i+1,j} - 3\, T_{ij})) \tag{26}$$

and the Right Boundary:

$$\frac{dT_{i\,n}}{dt} = \frac{k\rho}{c_p\, \Delta x^2} ((T_{i,j-1} + T_{i-1,j} + T_{i,j+1} - 3\, T_{ij})) \tag{27}$$

At the corners, the equations become:

$$\frac{dT_{11}}{dt} = \frac{k\rho}{c_p\, \Delta x^2} ((T_{2,1} + T_{1,2} - 2\, T_{11}) + q_{1,1}) \tag{28}$$

$$\frac{dT_{1n}}{dt} = \frac{k\rho}{c_p\, \Delta x^2} ((T_{1,n-1} + T_{2\,n} - 2\, T_{1n}) + q_{1,n}) \tag{29}$$

$$\frac{dT_{m1}}{dt} = \frac{k\rho}{c_p\, \Delta x^2} ((T_{m-1,1} + T_{m,2} - (2+\frac{c_p}{k} U)\, T_{m1})) \tag{30}$$

$$\frac{dT_{mn}}{dt} = \frac{k\rho}{c_p\, \Delta x^2} ((T_{m,m-1} + T_{m-1,n} - (2+\frac{c_p}{k} U)\, T_{mn})) \tag{31}$$

Formulation of the State Equations

The state equations must be formulated in the coupled form to be solved by either linear means or by numerical integration:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \qquad (32)$$

Since x must be a vector, the matrix of node temperature $\mathbf{T}_{m,n}$ must be reconfigured into a column vector $\mathbf{T}_{mn,1}$:

$$\mathbf{T} = \begin{vmatrix} T_{11} \\ T_{12} \\ T_{13} \\ \vdots \\ T_{1n} \\ T_{21} \\ \vdots \\ T_{mn} \end{vmatrix} \qquad (33)$$

and the index formula for the k^{th} element of $\mathbf{T}$ is given by:

$$k = (i-1)*n+j. \qquad (34)$$

In this formulation, therefore, the product of the rows of matrix A with the state vector x are the node equations given above. However, since they are now expressed as vectors, the subscripting has changed. For example, the basic node equation is now given by:

$$\frac{dT_k}{dt} = \frac{k\rho}{c_p\,\Delta x^2}\left((A_{k,k-n} + A_{k,k-1} + A_{k,k+1} + A_{k,k+n} + A_{k,k})\,\mathbf{T} + B_{k,k}\mathbf{U}\right) \qquad (35)$$

Where $A_{k,k-n} = 1$
$A_{k,k-1} = 1$
$A_{k,k+1} = 1$ (36)
$A_{k,k+n} = 1$
and $A_{k,k} = -4$

And clearly **B** is **I**.

The input vector U contains the input heat fluxes $\mathbf{q_{1,n}}$ in the first n elements and the ambient temperature on the bottom $\mathbf{T_o}$ in the last n elements.

$$U = \begin{vmatrix} q_{11} \\ q_{12} \\ \vdots \\ q_{1n} \\ \vdots \\ T_o \\ T_o \end{vmatrix} \tag{37}$$

The top and bottom elements are changed according to the above equations as are the sides and corners.

State Equation Example

Consider a plate of minimum 3 x 3 discretization, one that has a least one interior node:

$$\begin{array}{|c|c|c|}\hline T(1,1) & T(1,2) & T(1,3) \\ \hline T(2,1) & T(2,2) & T(2,3) \\ \hline T(3,1) & T(3,2) & T(3,3) \\ \hline \end{array} \quad -> \quad \begin{vmatrix} T_{11} \\ T_{12} \\ T_{13} \\ T_{21} \\ T_{22} \\ T_{23} \\ T_{31} \\ T_{32} \\ T_{33} \end{vmatrix} \qquad (38)$$

$$\frac{d}{dt}\begin{vmatrix} T_{11} \\ T_{12} \\ T_{13} \\ T_{21} \\ T_{22} \\ T_{23} \\ T_{31} \\ T_{32} \\ T_{33} \end{vmatrix} = \frac{k\rho}{c_p \Delta x^2} \begin{vmatrix} -2 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & -3 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -2 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & -3 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & -4 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & -3 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & -(2+\frac{c_p}{k}U) & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & -(3+\frac{c_p}{k}U) & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & -(2+\frac{c_p}{k}U) \end{vmatrix} \begin{vmatrix} T_{11} \\ T_{12} \\ T_{13} \\ T_{21} \\ T_{22} \\ T_{23} \\ T_{31} \\ T_{32} \\ T_{33} \end{vmatrix} + \begin{vmatrix} 100000000 \\ 010000000 \\ 001000000 \\ 000100000 \\ 000010000 \\ 000001000 \\ 000000100 \\ 000000010 \\ 000000001 \end{vmatrix} \begin{vmatrix} q_{11} \\ q_{12} \\ q_{13} \\ 0 \\ 0 \\ 0 \\ UT_o \\ UT_o \\ UT_o \end{vmatrix}$$

(39)

With **A**, **B** and **U** defined as above, the equations can be solved using MATLAB. The key is the correct generation of **A** given the dimension of the problem and the parameters $\mathbf{c_p}$, **U** and **k**. The following MATLAB function generates the **A**, **B**, **C**, and **D** matrices.

NUMERICAL CONDUCTION SOLUTION

```
% Routine to create the parameter matrices for a 2-D conduction problem

function[a,b,c,d]=Amat(m,n)
Cp = 475;       % The specific heat for steel
kc  = 25;       % The thermal conductivity coefficient for a low conductivity steel
p   =  8000;    % Density of steel consistent with the units of Cp and kc
U   = 5 ;       % Represents a high interfacial transfer rate. Simulation also done with
                U=1
dx  = 0.01;     % To make the dimensions of each node 1 centimeter square.
To  = 0;
mn=m*n;         % Dimensions for the simulation were n=32, and m = 3 and m =6.
a=zeros(mn,mn);
%
% First fill the A matrix assuming all interior nodes, but keeping within the bounds of
the mn x mn matrix:
%

                a(i,i) = -4;
                        if (i-n)>=1,
                                                a(i,i-n)=1 ;end
                        if (i+n)<= mn,
                                                a(i,i+n)=1;end
                        if (i-1)>=1,
                                                a(i,i-1)=1;end
                        if (i+1)<= mn,
                                                a(i,i+1)=1;
                        else
                        end
end


%
% Now deal with edges of plate, by assuming no heat transfer
% which means dropping the exterior nodes
% left edge first
%
        for k=1:m
                                i=(k-1)*n +1;
                                        a(i,i) = -3;
                                 if (i-1)>0       a(i,i-1) = 0; end; % "if" prevents indexing
error
%
% then right edge
%
                                i=(k-1)*n + n;
                                        a(i,i)=-3;
                                        if (i+1)<(mn+1)  a(i,i+1) = 0; end;
        end
```

```
%Now the bottom
        for k=1:n
                        i=(m-1)*n +k;
                        a(i,i) = -(3+Cp/kc*U);
                        if (i+n)<(mn+1) a(i,i+n) = 0; end;
        end

%Now the top
        for k=1:n
                        a(k,k) =-3;
                        if(k-n)>0 a(k,k-n) = 0; end;
        end

%And finally the corners
%upper left
        a(1,1) = -2;
%upper right
        a(n,n) = -2;
%lower left
        a(mn-n+1,mn-n+1) = -(2+Cp/kc*U);
%lower right
        a(mn,mn) = -(2+Cp/kc*U);
        a=a*((kc/(Cp*dx*dx*p)));

%now other matrices
% this version for sine distributed heat input
b=zeros(mn,1); for i=1:n; b(i) = 100*(1-cos((i-1)/(n-1)*2*pi)); b((mn-n)+i)=U*To; end;
b=b*(1/p*dx*dx*Cp));
plot(b(1:n));
c=diag(ones(1,mn),0);
d=zeros(mn,1);

end
```

Simulation Parameters

Other properties varied in addition to plate height. The thermal conductivity coefficient was changed from 50 watts/meter-C to 25 watts/meter-C (within the range of steel conductivities given in Kalpakjian), and the coefficient specifying the interfacial heat transfer rate from the plate bottom to the environment was altered also. The specific heat coefficient was kept constant at 475 watts/kg-C.

The spatial pattern of the heat input was that of a rectangular pulse, as shown in Figure 17, above the two center nodes of the 32 node-wide plate. It had an intensity of 2500 watts per node. As is said earlier, a narrowly focused input was chosen to approximate trying to control temperatures in the bottom of a plate by heating its top, or to control temperatures inside a mold by applying heat to the outside. Furthermore, as is discussed in Chapter 4, a rectangular pulse has relatively rich frequency content, and so makes for a good test input when determining the filtering properties of a process.

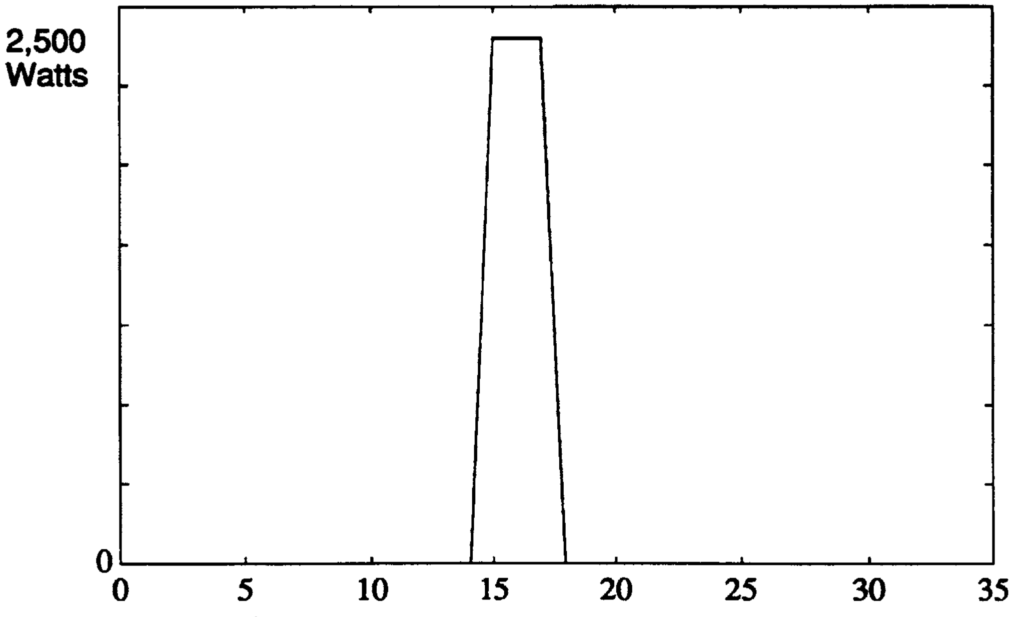


Figure 17: Heat Flux, Pulse Input

From the start of the simulation until the system reached steady state, the pulse input looked like:

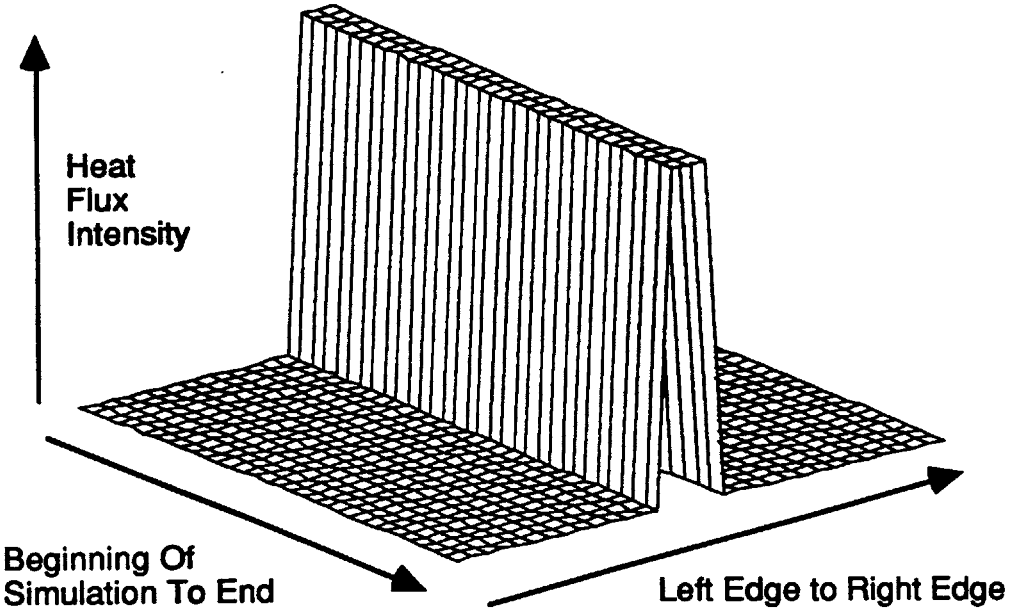


Figure 18:

Simulation Results

Effect Of Changing Plate Thickness

The rectangular shape of the input was lost as the heat energy dissipated through the plate. For instance, the temperature profiles for the bottom plate in a three layer and a six layer plate are shown in Figures 19 and 20, respectively. Figure 21 compares the final temperature on the bottom plate for both tests.

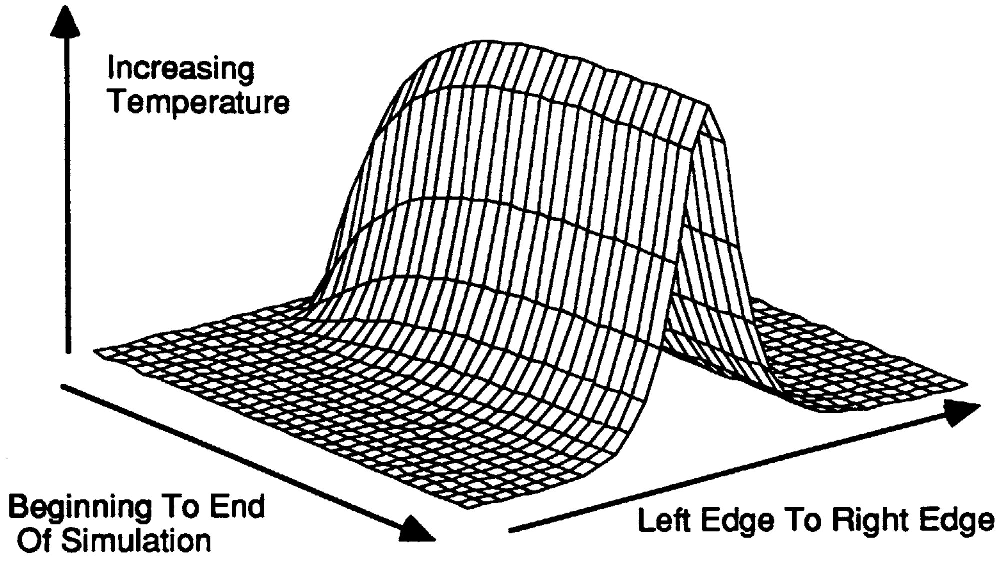


Figure 19: Bottom Layer Temperature For Three Layer Example

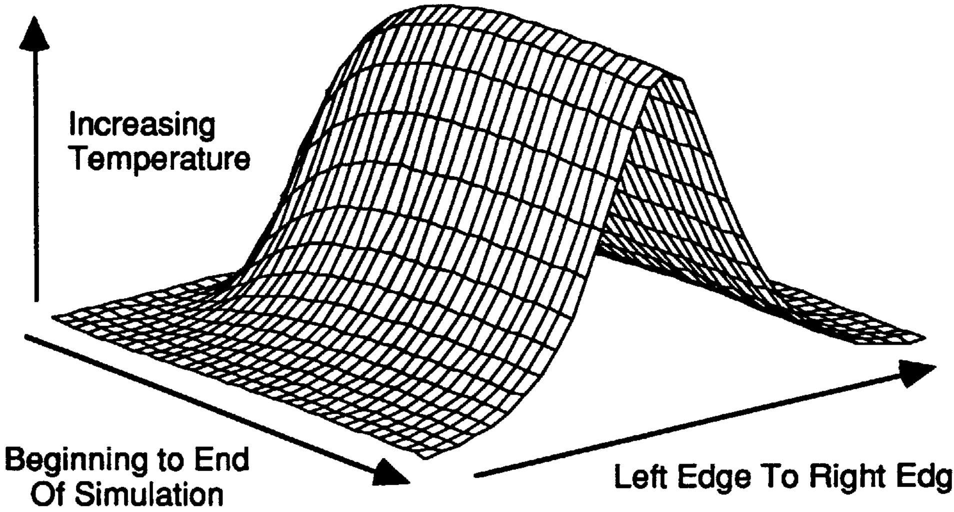


Figure 20: Bottom Layer Temperature For Six Layer Example

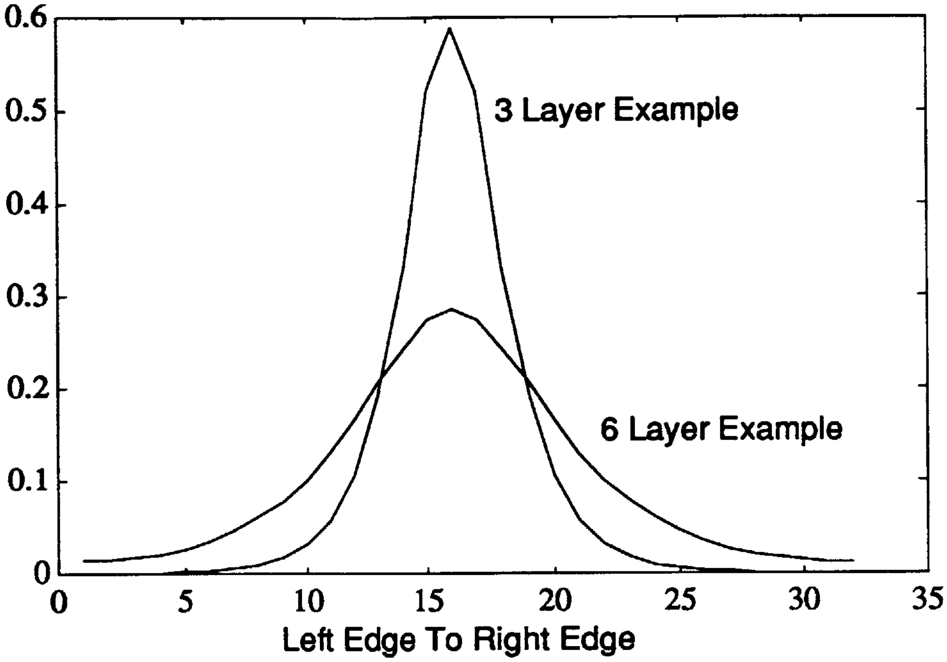


Figure 21: Final Bottom Layer Temperatures

The spatial shape of the heat input and the measured bottom plate temperatures are re-expressed by their frequency content in Figure 22. In Figure 23, Output to Input Ratios are shown as a measure of frequency filtering due to heat diffusion.

[The frequency contents of the inputs and outputs were calculated using the Matlab **FFT**, and **FFT2** functions, which return complex coefficients for each frequency. The **ABS** (absolute value) function can be used to convert these coefficient values into magnitudes. Ratios of output magnitude/input magnitude is done by element by element division (both for vectors and matrices).]

As the temperature profiles in Figure 21 suggest, the six layer sample was a stronger filter. It is especially interesting that the shape of the three layer and the six layer frequency content curves are different. Whereas the curve corresponding to simulations for a 3 centimeter thick plate has the same shape as the input curve, the curve for simulations done with a 6 centimeter thick plate is smoother.

Figure 21 suggests two possibilities for this. One cause may be attributable to the real physical consideration that the input diffused much further in the six centimeter sample than in the three centimeter sample. The other explanation for the difference in shapes may be due to a computational quirk. In Figure 21, the heat profile for the three centimeter sample is very pointy, largely because of the size of the nodes. For instance, had the nodes between 1 millimeter rather than one centimeter, the curve might have been smoother in its center. However, because of the curves sharp corners, the Fourier Transform may have calculated greater high frequency magnitudes than it might have otherwise.

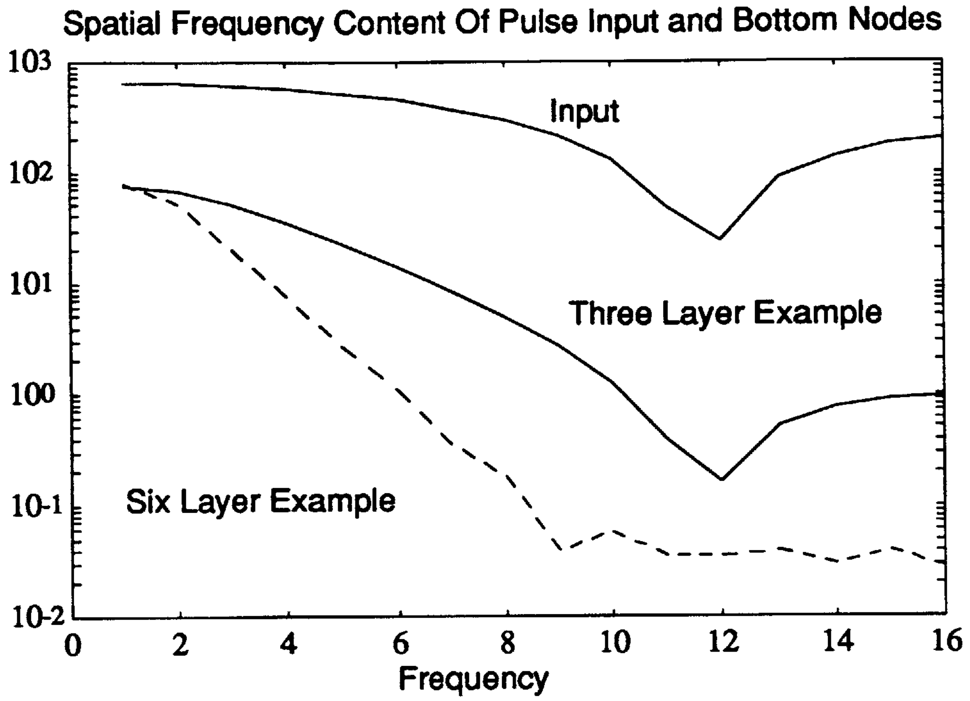


Figure 22:

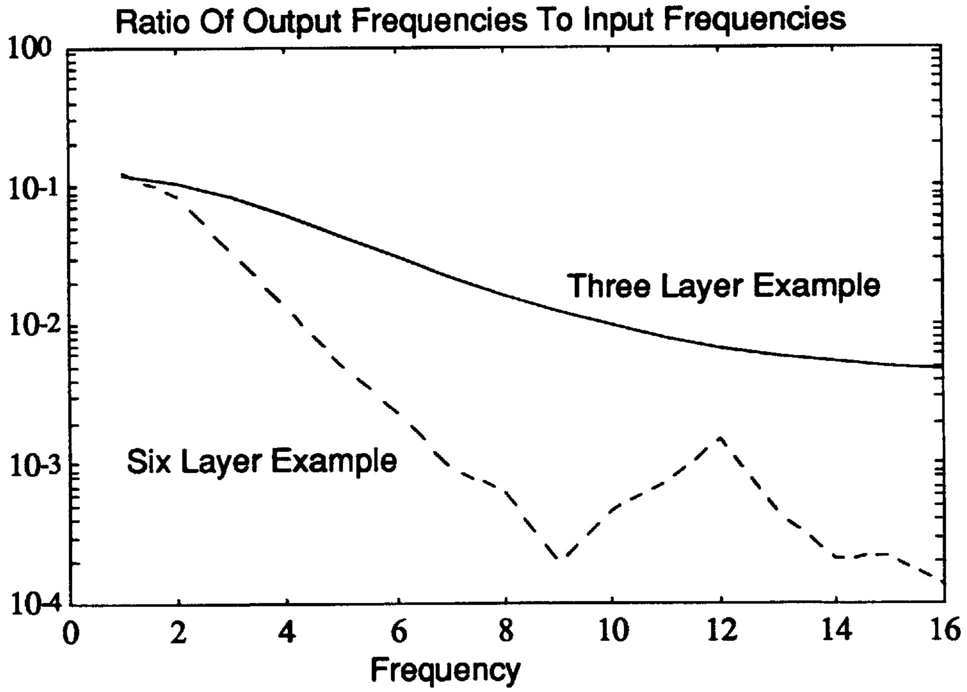


Figure 23:

Effect Of Changing Thermal Conductivity

A similar series of comparisons was made for samples with different thermal conductivities, one of 50 watts/meter-C, and the other with a conductivity of 25 watts/meter-C. Figure 24 compares the steady state temperature in each plate for the high conductivity and the low conductivity example. Shown more clearly in Figure 25 and Figure 26, the temperatures in the bottom plates don't vary, whereas the temperatures varied considerably in the other layers.

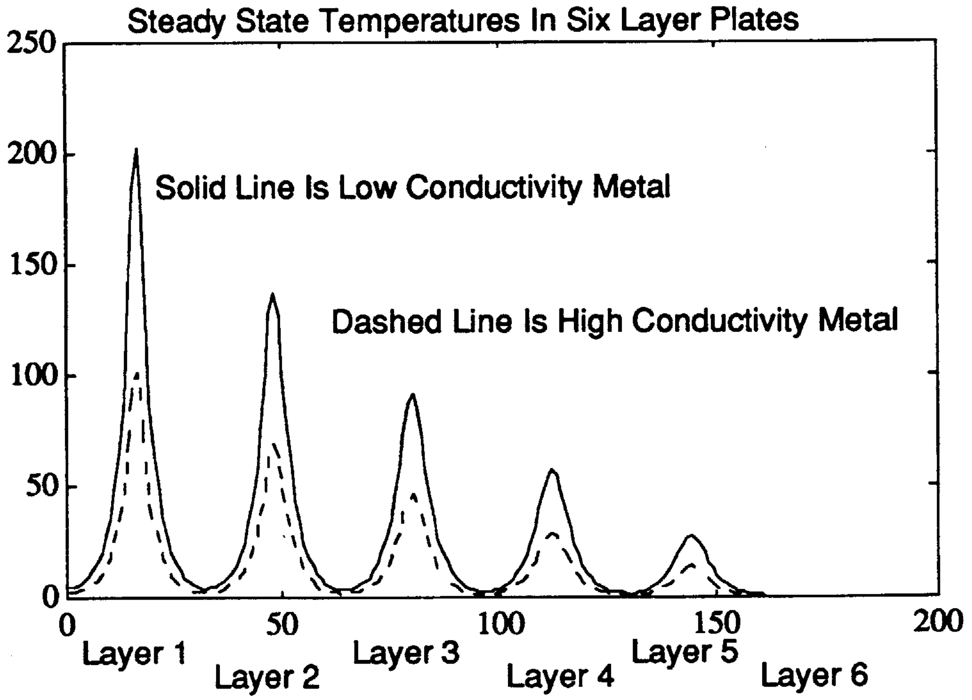


Figure 24:

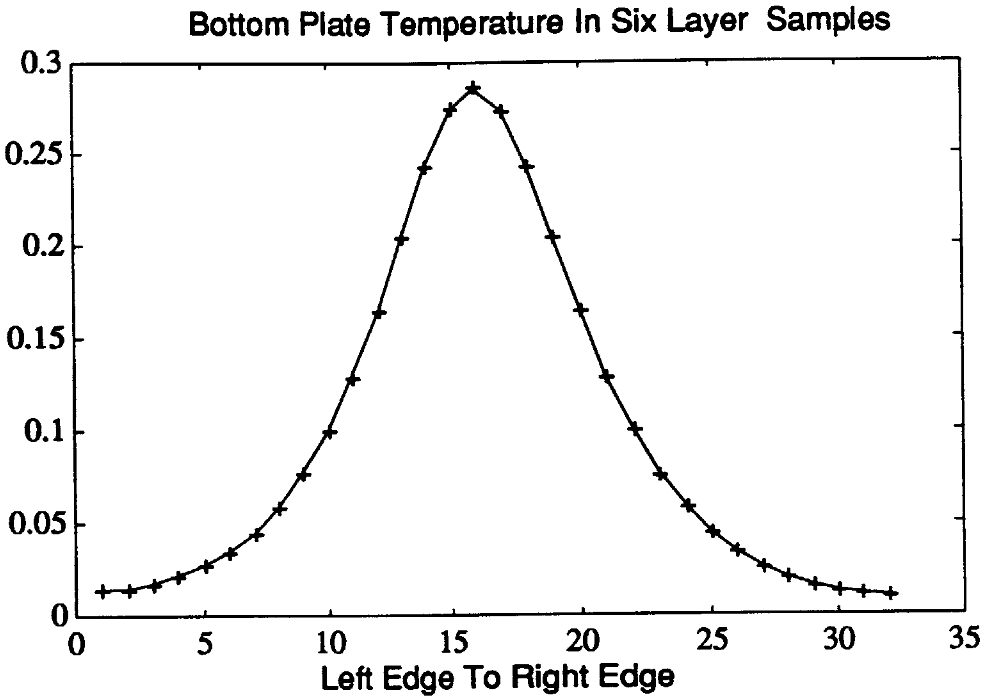


Figure 25:

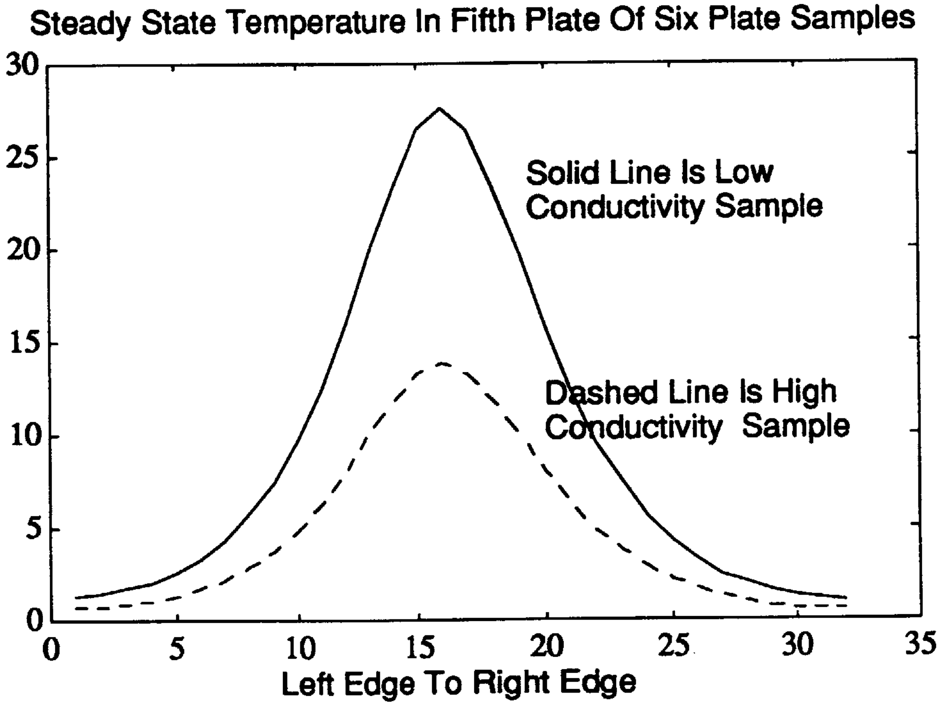


Figure 26:

Effect Of Changing Interface Heat Transfer Rate

Even though temperatures were substantially different in all the other layers, bottom layer temperatures were consistent between the low conductivity and the high conductivity samples. Therefore, bottom steady state temperatures seemed dominated by the heat transfer rate between the sample and the environment, rather than by its internal conductivity. As a test, simulations were conducted to compare the effect of altering the interfacial heat transfer rate (**U** in equation 24) from 5 to 1. Figure 27, Figure 28, and Figure 29 compare the results of these tests with the results when a high interfacial heat transfer rate was assumed.

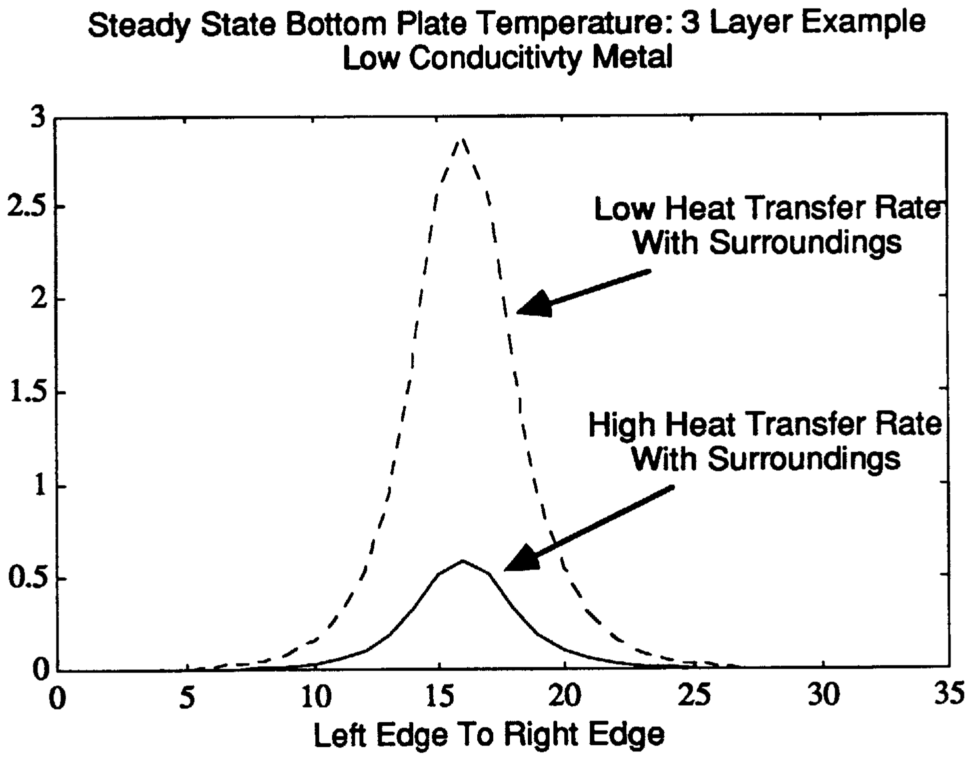


Figure 27:

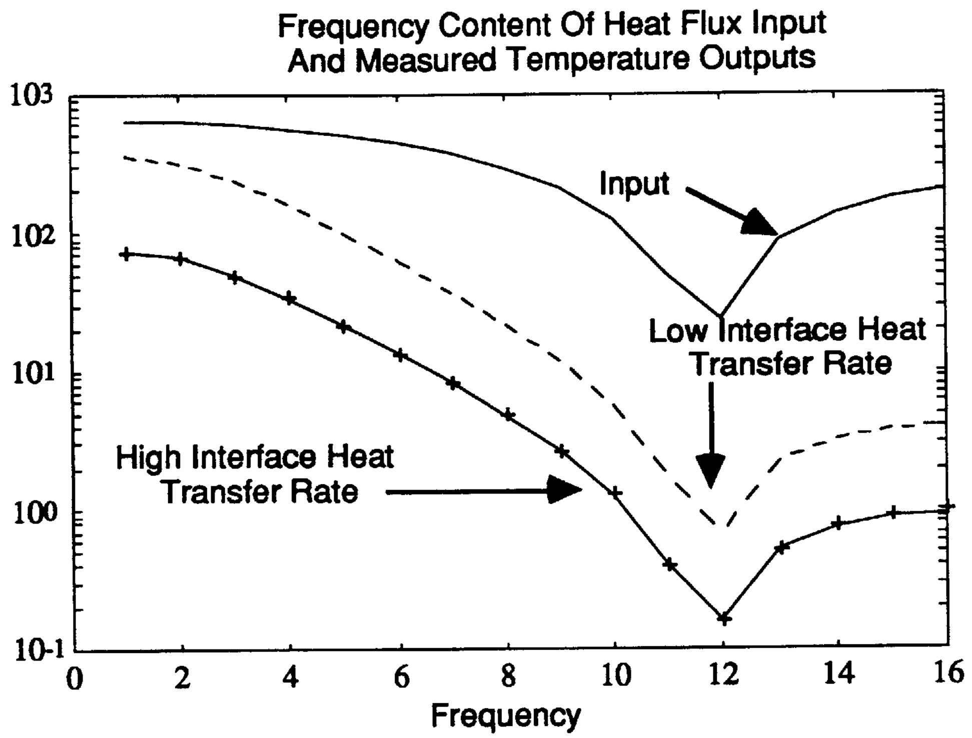


Figure 28:

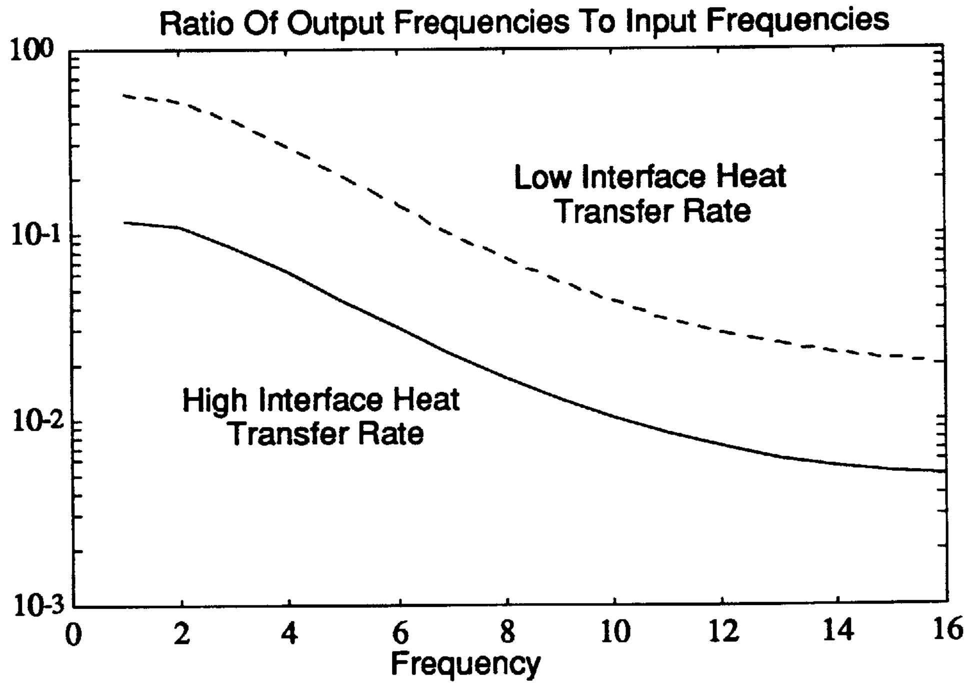


Figure 29:

There is an interesting comparison between Figures 28 and 29 and Figures 22 and 23. In Figures 22 and 23, the shape of the curves for the 3 centimeter and the 6 centimeter samples are noticeably different. However, in Figures 28 and 29, the shape of the curves corresponding to the high interfacial heat transfer rate and to the low interfacial heat transfer rate, have the same shape, even though they are shifted.

In this example, the metal plate can be considered to be the machine, in contact with material along its bottom row of nodes. Since changing the thickness of the plate changes its filter-like properties, but changing the nature of the machine/material does not, this suggests that the spatial-frequency content of this process is determined only by machine.

In this section, only spatial frequencies have been examined. In the next section, temporal frequency content is considered as well.

Temporal Components Of Frequency Content

The previous examples all focus on the spatial qualities of heat transfer. However, heat transfer also has temporal characteristics, and these are especially important in determining the quality of cured composite parts and injection molded parts. These last demonstrations indicate that the temporal characteristics of heat transfer can also be described by frequency content. To illustrate this, an heat flux impulse input was simulated. As shown in Chapter 4, narrow spatial shapes such as the rectangular pulse have relatively rich frequency contents, and impulses are an extreme of this, with all frequencies of equal magnitude. Therefore, an input like that in Figure 30, will have a spatial frequency content like that of the pulse input, but its temporal amplitude will be constant (Figure 31).

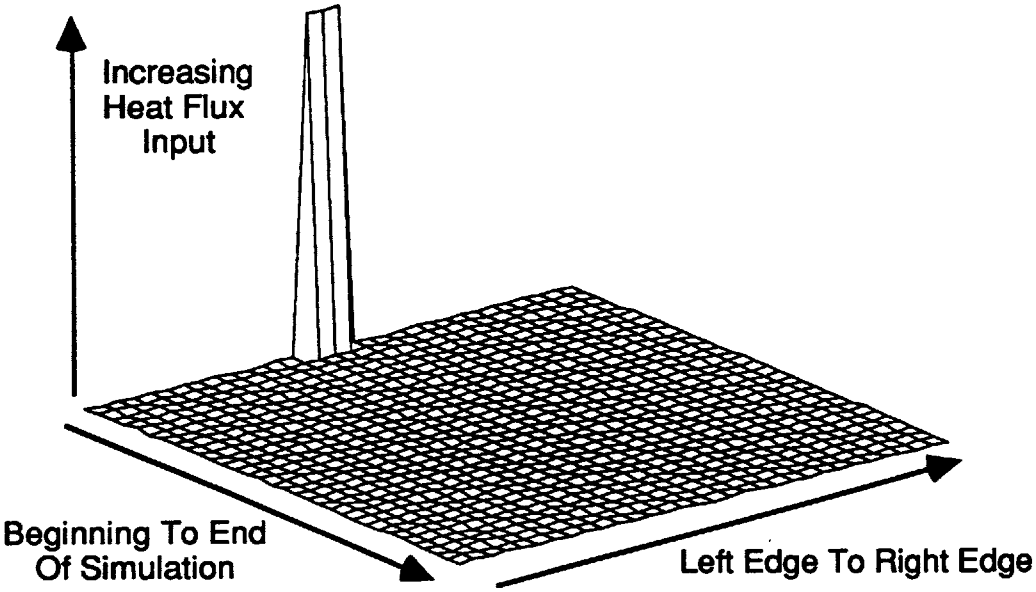


Figure 30:

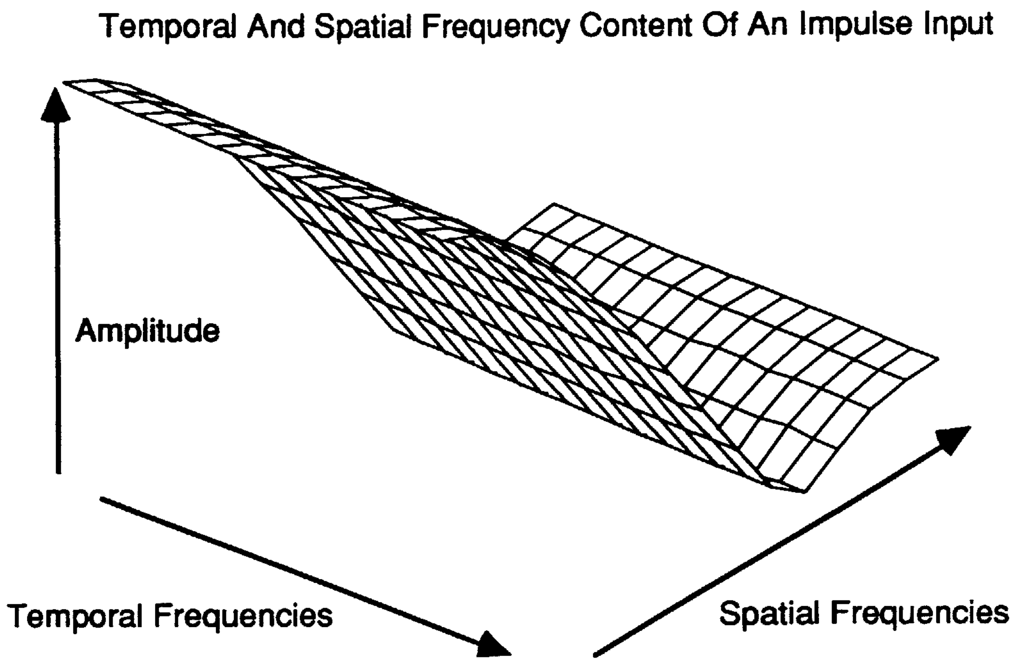


Figure 31: (Magnitudes Only)

The temperature profile in the bottom plate of the three layer sample is shown in Figure 32.

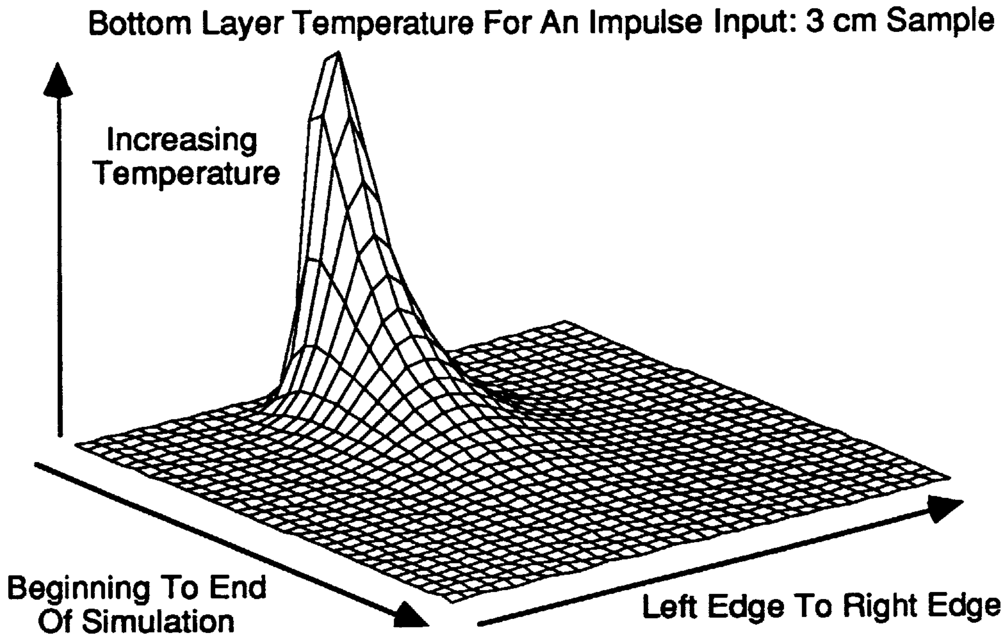


Figure 32:

Figure 33 shows the magnitude of the frequency components the bottom plate temperature, and Figure 34 compares the temporal frequency content of the input to the temporal frequency content of the output. Both the temporal and spatial filtering effects are evident.

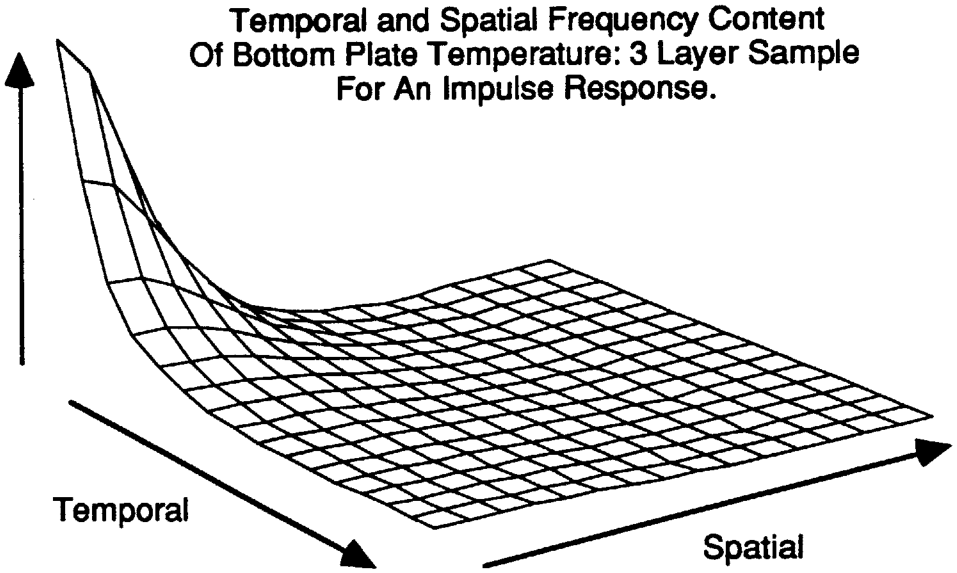


Figure 33:

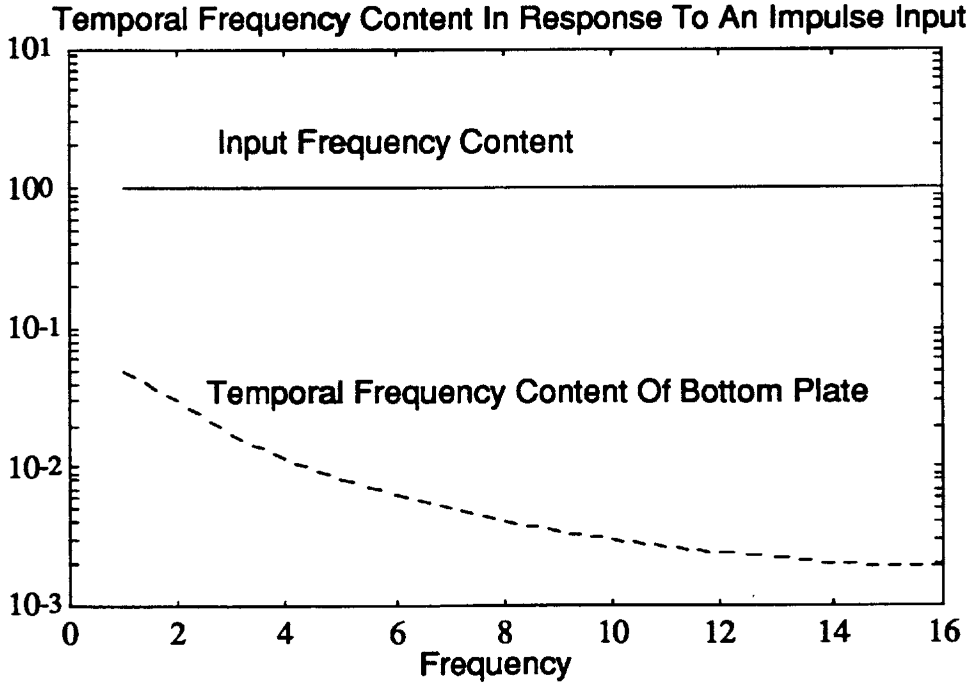


Figure 34:

Heat Transfer Example: Summary

The main premise of this thesis is that resolution determines the controllability of manufacturing processes, and that process resolution can be quantified by using Fourier Transforms to describe inputs and outputs by their frequency content. The examples in Chapter 5 apply this frequency domain approach to determining the temperature at the bottom of a metal plate by heating it from above.

The simulations in this chapter demonstrate that the dynamic responses which occur during heat transfer processes can be characterized as spectrums of input and output frequencies. Furthermore, the simulations indicate that spatial and temporal frequencies are both filtered during heat transfer. The strength of the filtering effect is influenced by the thickness of the metal plate, the conductivity of the base metal, and the heat transfer rate at the material/ environment interface. The shape of the filtering effect is influenced by the machine properties only.

These examples are abstractions of closed-mold processes such as injection molding and composite curing. In these, the quality of outputs is determined by the spatial configuration of heat gradients, and also by heating and cooling rates, the equivalent of temporal gradients. Consequently, the frequency domain spatial and temporal resolutions of the processes indicate limits to the quality of the parts they can produce.

Chapter 6: Summary, Conclusions And Recommendations

Summary

This thesis presents a model of manufacturing processes as dynamic systems subject to closed loop control. Control tools are used in response to disturbances, uncertainties and variations in materials and machines so that the desired Geometric and Material Output Properties can be achieved. However, control tools cannot be arbitrarily applied. Rather, the underlying dynamic characteristics of processes determine which control tools can be used and which control tools are not applicable. Furthermore, these process characteristics determine which machine or material dynamic states are controllable and which are not.

The relationship between part fabrication time and feedback loop time establishes one limit to employing process control tools. A second limit is imposed by the measurability of process conditions, since only those dynamic states that can be determined by observation or accurate approximation can be controlled. However, control of dynamic states is constrained by more than measurability. Even if it were possible to measure specific conditions, were it not possible to manipulate those conditions, those conditions would not be controllable.

The main proposition of this thesis is that process controllability, and manipulatability of process dynamic states, can be quantified by using frequency domain techniques. Process inputs and process outputs can be re-expressed as frequency spectrums by using appropriately dimensioned Fourier Transforms. Then, processes can be characterized as filters that pass some frequencies and reject others. Because higher frequencies correspond to higher levels of control, process bandwidth is a convenient metric for process resolution and dynamic state controllability.

Several specific cases in this thesis illustrate using frequency content to characterize the controllability of processes. Chapter 3 presents the techniques used by the LMP to describe sheet-metal part and tool shape as a way to characterize the inputs and outputs of a deformation process by frequency content. By generalizing the sheet metal forming control methodology of Chapter 3, it is possible to characterize the inputs and outputs of a heat transfer process by temporal and spatial frequency components in Chapter 5.

Conclusions

(1) Processes are subject to closed loop control in reaction to disturbances, variations and uncertainties. Rapid forms of feedback are particularly desirable for low volume production that is of high value.

(2) The minimum feedback and control time is limited by the time required for data measurement (dynamic state determination), data interpretation, and machine re-actuation. Consequently, no matter what advances are made in sensing, modeling or machine control, unless these advances contribute to a reduction in $T_{CONTROL}$ relative to T_{PART}, no marked improvement can be made in the accuracy, sophistication or responsiveness of usable control tools.

(3) Only those process dynamic states that can be directly measured or estimated with accuracy can be controlled. Therefore, if material states cannot be measured or estimated, they cannot be controlled, and feedback control is limited to machine states.

(4) Energy flows between machines and materials through interactions that occur at an energy port. As a consequence, it is only by altering the nature of these interactions that the operator can control the dynamic state of the material.

(5) Because of energy diffusion, the Energy Affected Zone is larger than the Energy Port. This diffusive nature of machine/material interactions limits the ability of changes in process inputs to influence machine and material dynamic states.

(6) The relative size of the Energy Port to the workpiece, and the relative size of the Energy Affected Zone to the Energy Port, determine process resolution. In turn, process resolution determines the degree to which the process material states can be manipulated and controlled. In order to improve the level of material state control, resolution must be increased.

(7) Process resolution can be increased by decreasing the size of the Energy Port or by reducing the diffusive nature of the machine/material interaction.

(8) Process resolution can be quantified by using Fourier Transforms to re-express inputs and outputs as input frequency spectrums and output frequency spectrums. With the process as a filter between input frequencies and output frequencies, process resolution is the output/input bandwidth.

Definition: Machine Resolution is a frequency domain measure of a process's ability to convert changes in inputs $(\delta \upsilon)$ into changes in machine states $(\delta\beta_{MACHINE})$. Low resolution processes have low bandwidths and act as low pass filters. This is one measure of machine-state controllability.

Definition: Material Resolution is a frequency domain measure of a process's ability to convert changes in inputs (δU) into changes in material states ($\delta\beta_{MATERIAL}$). Low resolution processes have low bandwidths and act as low pass filters. This is one measure of material-state controllability.

(9) Process bandwidth is determined by machine properties and not material properties, as suggested by the heat transfer simulations in Chapter 5.

Recommendations For Further Research

The motivation for developing this control taxonomy of manufacturing processes was to create a system for categorizing processes by dynamic behavior rather than by type of material or type of material manipulation. Frequency domain descriptions of process inputs and outputs are an attractive alternative because the input and output spectrums are non-parameterized, so they lend themselves to the sort of categorization that was originally sought.

Therefore, a first step would be to validate the proposition that processes with similar frequency domain characteristics represent similar control problems that can be addressed in similar fashions. One way to do this might be to simulate a variety of physical systems and express their inputs and outputs by frequency components. Then, similar control actions could be applied to models with similar frequency input/output relationships. An analysis could be performed to see if 'process resolution' was sufficient in determining the response of processes to control actions.

The sheet metal forming example is two dimensional, with altitude as a function of 'x' and 'y'. The conductive heat transfer simulation in Chapter 5 is also two dimensional with temperature as a function of location in the plate and time. It would be interesting to analyze a process with larger dimensions, and try and understand the significance of its spectrums along each dimension.

The heat transfer simulation suggests that the bandwidth of a process is determined by machine properties. This proposition should be further explored to see if it holds generally.

Though the primary focus of this thesis is process resolution, this work was carried out as part of a larger effort to develop a control based taxonomy of manufacturing. Andrew Parris [Parris 1993] focuses on different aspects on the control taxonomy, and it would be exciting to compare, contrast and combine the findings he reached with the ones presented here.

Appendix: Composite Processing - Overview and Summary

Processing composite materials is inherently complex because of multiple requirements during production and associated disturbances and uncertainties. The load bearing fibers must be given shape and orientation, and the fiber structure must be infiltrated with the resin matrix, steps which may occur sequentially or simultaneously. Then the fibers and the resin must be consolidated by temperature and pressure application to achieve the desired fiber fraction volume and curing cycle. This application of temperature and pressure must be done properly so that the desired post-processing-engineering properties are achieved.

This is all made more difficult because the aspects of forming, consolidating and curing involve a variety of physical processes like shaping, material addition and material removal. Also, they involve processes like melting, heating, cooling and chemical reaction.

Finally, composite material processing is challenging because the operations that contribute to forming, consolidating and curing can be highly coupled. In general, this means that attempts to alter or influence one material state (i.e. fiber location and orientation, resin viscosity) will have consequences, which may be undesirable, on other material states.

Curing especially has highly coupled outputs. For instance, pressure is applied in autoclaves to cause resin flow and material consolidation. The resins, like other viscous liquids, flow better at higher temperatures. However, with higher temperatures, the rate of molecular cross-linking increases, making the resin irreversibly more viscous.

Because of the inherent complexity of composite material processing, research efforts have occurred on a variety of fronts with the overall goal of improving the quality and the range of applications. These investigations aim at:

- Empirically determining the properties of particular resins, and determining optimal cure cycles,
- Monitoring material states (resin flow rates and directions, temperature and viscosity) during curing by improving data collection (sensing) and data interpretation (modeling) techniques,
- Controlling cure cycles through feedback,
- Improving the performance of particular forming techniques like pultrusion and filament winding,
- Improving the performance of particular resin introduction techniques like Structured Reaction Injection Molding ("S/RIM") and Resin Transfer Molding ("RTM") by modeling fluid flow and fluid flow effects on fiber orientation,

- Employing thermoplastics in lieu of thermosetting matrices.

Several observations follow from examining this research literature. For instance, it is important to characterize the chemical behavior of individual resins, and the behavior of individual resins in the presence of particular fiber types. However, empirical modeling is not sufficient to determine optimal cure cycles. Resin age, part dimensions, fiber fraction volume, and other factors determine the proper combination of pressure and temperature that will bring about satisfactory consolidation and cure. These are all sources of disturbances and uncertainties, therefore necessitating feedback control.[18]

However, there are limitations on the potential for closed loop control. Most important of these is that curing is an especially low resolution process. As illustrated in Chapter 5, heat transfer is a diffusive low bandwidth process even for high frequency content inputs. However, in general, inputs during cure begin as low frequency spatial spectrums since temperature and pressure inputs effect the entire part and not local and specific sites. Second, the time frequency

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[18] For example, Ciriscioli, Springer and Wang show that cure cycles recommended by manufacturers may lead to suboptimal results. ["Autoclave Curing - Comparisons of Model and Test Results"; Peter Ciriscioli, George Springer, and Qiuling Wang; <u>Journal of Composite Materials</u>; Vol. 26, Jan. 1992, pg. 90]

content of the process is low because heat transfer relationships of conduction and convection dominate, and many resins conduct heat poorly.

This leads to the observation that increasing the temporal and spatial frequency bandwidth of curing equipment (as was suggested on page 41 when discussing Injection Molding) has potential for improving cure control.

As for process state determination, sensing and monitoring devices, and the software to interpret their readings, have improved [U.S. Department of Commerce, 1991]. Nevertheless their ability to gather reliable in-situ, point-specific data about the degree of cure in a composite part is still limited.

Forming is generally done in a serial fashion by hand lay-up, numerically controlled machine lay-up, or filament winding, for instance. Consequently, it is ordinarily a high resolution process, presenting fewer obstacles to accurate control than the low resolution aspects of composite processing.

RTM and S/RIM research focus primarily on characterizing flow profiles during resin introduction. The design driven focus is on gate and runner placement. The production driven focus is on determining appropriate fill temperatures and fill pressures. As with injection molding though, the fill phase of RTM and S/RIM is low resolution. Hence, there are significant limits to improving process control. Finally, thermoplastics, because of the reversibility of the setting process, lend themselves to high resolution serial processing.

High Resolution Composite Material Production Processes

Shaping	Wetting	Curing
Tape laying	Tape laying	Pultrusion
Wet layup	Filament winding	Pulforming
Filament winding	Pultrusion	
Pultrusion	Pulforming	
Pulforming		

Low Resolution Composite Material Production Processes

Shaping	Wetting	Curing
Compression molding	RTM	Autoclave curing
	S/RIM	Mold curing
	Compression molding	

Appendix: The Control Taxonomy and Composite Curing

Overview

From the perspective of the control taxonomy presented in Chapter 2, cure sensing and cure modeling are attempts to improve on two limits to process control progress: feedback time and process state measurability. However, the third limit identified in the control taxonomy, process resolution, still looms as an imposing barrier to much greater progress.

Cure Monitoring [19]

Sensing and modeling are inexorably linked in facilitating on-line control of the composite curing process. Sensors collect data of material states during cure. However, the electrical, mechanical and chemical measures taken by monitors do not directly measure resin viscosity and resin degree-of-cure. Consequently, models must interpret data, predict process trajectory, and prescribe control actions.

In this section, the state-of-the-art in sensors will be reviewed. Types of sensors will be described with their attendant advantages and disadvantages. Following, there will be a review of efforts to empirically characterize

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[19] This information on sensing is drawn from a NIST [U.S. Department of Commerce, 1991] document which is a comprehensive overview of the current state of composite cure monitoring. Other sources will be cited explicitly.

curing. This type of information is necessary to build cure models that perform the roles of data interpretation, process prediction, and control prescription.

Sensor Types

The three main types of sensors are:

- Dielectric sensors,
- Ultrasonic sensors,
- Spectroscopic and optical sensors.

Dielectric Sensors

These sensors take measurements of capacitance and conductance, which, because they change with changes in molecular structure and molecular mobility, are correlated with resin viscosity and degree-of-cure. Researchers have used these properties with success to monitor the curing cycle and to signal its completion.

Tests by Peter Ciriscioli and George Springer [May 1989] showed that dielectric monitors were able to indicate the times when viscosity was at a minimum and the degree-of-cure was nearly complete. However, despite this utility in determining the completion of the cure cycle, the dielectric monitors could not provide the viscosity, the degree-of-cure or the rate of cure during the cure process. Day, Shepard and Craven [Nov. 1990] also reported success in determining the completion of the cure cycle using dielectric sensors by monitoring Ion Viscosity during cure.

Frequency Dependent Electromagnetic Sensing techniques ("FDEMS") have been used by Kranbuehl, Hooff, Eichinger, Loos, and Freeman [1988, 1991] to monitor chemical and physical changes throughout the entire cure process rather than just at its end. The dielectric impedance of the sensors is used to calculate a value called 'complex permittivity', which is a function of capacitance and conductance. This permittivity value has ionic components which dominate in low viscosity media, and it has the dipolar components which are dominant in high viscosity media. As a result, these measure translational and rotational diffusion and can be used to estimate viscosity and degree of cure both at low levels of viscosity, and at the high viscosity levels revealed by the dipolar components alone. Therefore, FDEMS can be used for continuous in-situ estimates of viscosity and degree of cure.

Advantages and Limitations

The main advantage of electrical measurement methods is that instruments for monitoring dielectric loss are well developed and there are already commercial devices available.

There are two main limitations of electric monitoring techniques. First, there may be geometric incompatibility between the sensor and the part since the device is an interruption in the matrix. Second, composite fibers may disrupt sensors that would perform well in the presence of resin alone. If the fibers are good insulators and match the properties of the resin matrix, they do not significantly alter the results found for pure resins. However, carbon fibers are conductive and can make measurements useless.

Wave Propagation Techniques[20]

This method uses sonic and ultrasonic waves to reveal geometric features and material properties. Oscillatory disturbances are generated in the sample and the propagation characteristics of the wave are determined.

Advantages and Limitations

These sensors are already a common tool for post-processing part inspection. The equipment is inexpensive and it is rugged enough for industrial applications. Additionally, these sensors are capable of revealing important material states. For example, the potential exists to determine geometric properties like voids, porosity and fiber volume fraction. Also, there is the potential to reveal material properties like viscosity, modula, glass transition temperatures, and degrees of cure since these measures of been empirically correlated in wave propagation experiments.

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[20] U.S. Department of Commerce, NIST, 1991

However, wave propagation techniques have shortcomings as well. They are sensitive to a wide variety of features, but they have trouble distinguishing between different types of features. Moreover, these techniques measure average properties over relatively large material volumes, so local dynamic states may be difficult to discern.

Spectroscopic and Optical Sensors[21]

Spectroscopy provides the most direct measure of degree-of-cure since these methods directly monitor the chemical state of reactants. For instance, one approach works by including fluorescent dyes in the matrix in dilute concentrations. Viscosity and degree of cure can be estimated since the fluorescent intensity of the dyes is sensitive to local mobility, and can be monitored through optical fibers.

Advantages and Limitations

This approach to cure monitoring has several advantages. The optical fibers are stable over a broad range of temperatures and pressures, so the equipment is relatively compatible with the part. Furthermore, these methods give more direct measures of chemical states than do other sensors that reveal bulk properties which are less directly related to chemical structure. Moreover, data acquisition and analysis times are relatively rapid, facilitating more rapid means of

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[21] U.S. Department of Commerce, NIST, 1991

control. Also, the optical fibers can later be used for post-processing stress and strain monitoring when the composite part is in use.

The major problem is that spectroscopic techniques are still immature technologies according to NIST. The equipment is experimental, and correlations between observations and chemical states still have to be empirically determined.

Cure Modeling

Substantial work has been done characterizing the cure process in three ways, first to determine empirically the relationship between process inputs and measurable process states, second, to determine the relationship between measurable process states and important material states like viscosity, degree of cure, and level of consolidation, and third, to characterize the properties of specific resins. These efforts are necessary to translate improvements in sensor capability into greater understanding of important material states. This section will give examples of research that has been conducted.

Bogetti and Gillespie [March 1991] conducted two dimensional cure simulations of thick thermosetting composites to determine the dependency of degree-of-cure spatial gradients with part geometry, thermal anisotropy, cure kinetics and temperature cure cycle. This research is important because degree-of-cure gradients influence part quality and performance, since warpage and residual stresses are induced during curing.

Grenier-Loustalot and Grenier [1992] explored the changes that the presence of fibers brought about during resin cure. They found that reaction mechanisms and network structures didn't change, but reaction rates were affected. This, in turn, affects the choice of temperature and pressure cycles.

Liou and Suh [1989] conducted experiments to characterize the link between the cooling process and residual stresses in order to find an optimal thermal history which would minimize residual stresses. The low thermal conductivity of the matrix required slow cooling in order to avoid steep temperature gradients.

Nakamae, Nishino, et al [Polymer Journal, Vol. 23, No. 10] examined the impact of cure pressure on the mechanical and thermal properties of cured epoxy resin. They concluded that high pressures during cure increased the glass transition temperature, restricted the diffusion and collision of molecules and slowed the rate of curing. Consequently, they found that this led to the insufficient curing of the resins and resulted in diminished mechanical and thermal properties.

Vitrification is the transformation from a liquid or rubbery state to a glassy state as molecular cross-linking increases. This conversion from one state to another dramatically affects the rate of cure reaction. Therefore, Montserrat [1992] investigated the correlation between the curing parameters of temperature and time with the onset of vitrification.

These last few citations are examples of the inquiries being made in the behavior of specific resin systems. For instance, Soni, Patel, and Patel [1991] reported on the curing reactions of a liquid epoxy resin using several different curing agents. Suzuki, Nagai, Suzuki and Takahashi [1992] attempted to improve the mechanical performance of bismaleimide based resins with the addition of rubber and pre-polymers. As a final example, Ohtsuka, Hasegawa, Fukuda and Uede [1992] investigated the curing behavior and viscoelastic properties of o-cresol-type epoxy resin with hydroxymethyl groups.

Cure Control

Overview

Efforts to develop automated or 'intelligent' curing controllers take advantage of improved data collection and data interpretation capabilities like those described in the previous sections on sensors and cure modeling. Improved cure control also depends on improved control of process dynamic states. In this section, several efforts in the area of cure control will be reviewed. By and large, these efforts benefit from improvements in data collection and data interpretation methods, including advances in expert systems and advances in computational hardware. In general, however, these process control programs don't make improvements in process resolution in either a temporal or spatial sense. Consequently, their ultimate utility is predetermined by their narrow bandwidth.

Ciriscioli, Springer and Lee [Dec. 1991]
These researchers created a rule based system for controlling the autoclave temperature and pressure during the cure of a composite part. The system had several goals and could monitor many process states. However, during the cure process, only a few controls could be adjusted, and these affected the autoclave as a whole, not specific regions of the workpiece in particular. Nevertheless, it should be added that the system Ciriscioli, Springer and Lee created resulted in reduced cure times and produced laminates with good mechanical properties even though tests were run on samples ranging from 0.1 inches (16 plies) to 6.5 inches (1,000 plies).

The expert system's goals included limiting temperatures and pressures to prescribed ranges, achieving full compaction and complete cure, minimizing void content, and keeping residual stresses low. These were part of the overall aim of producing a high quality part in the shortest possible time.

During cure, the system monitored representative process states. These included the machine states of autoclave temperature and pressure, and the material states of composite midpoint temperature, part thickness and interior dielectric properties. The composite surface temperature was also tracked.

These measurements were feed to the expert system which was responsible for machine actuation. It could adjust autoclave heaters, autoclave coolers, and autoclave pressure.

Johnson and Roberts [May 1989]
These researchers developed, what they called, an event based method of closed loop cure control. The success of this approach depends on understanding and interpreting material states during cure in order to determine the appropriate control actions. Therefore, it exemplifies the mutual dependence of advances in sensing for data collection, modeling for data interpretation, and actuation for process control. Their basic approach was to use measurements of volatile generation and rheological changes to signal different phases in the cure cycle. These signals then triggered changes in autoclave temperature and pressure. In this case also, despite advances in measurement

and feedback time, the low spatial and temporal resolutions of the autoclave represent an unavoidable barrier to process control improvement.

Jow, Hawley, DeLong [September 1988]
Because of the low thermal conductivity of epoxy/glass composites, significant temperature gradients can occur during heating, exotherming, and cooling. This research aims at reducing these heating related temperature gradients by using a dual thermal/microwave heating process. Molecules at differing stages of cure absorb microwave radiation at differing rates. Consequently, microwave frequencies can be tuned to heat workpiece interiors. Particularly for resin-fiber composites of low-thermal conductivity, this represents an approach towards reducing steep temperature gradients during the heating portion of the cure cycle. If this approach is successful in larger applications, it represents an opportunity to assault the process resolution obstacle to improved cure control.

Composite Curing: Conclusions

The research emphasis on composite curing is driven by the high cost of composite parts, the low volume in which they are produced, the complexity of the curing processes, and the critical role the curing process has in determining the quality of finished composite parts. Furthermore, in industrial applications especially, cure equipment is extremely expensive (on the order-of-magnitude of several hundred thousand dollars to several million dollars) and is often the bottleneck stage in composite processing. Consequently, this is a major incentive for reducing cure cycle times.

Research in the area of composite curing has occurred on several fronts, the most important of these being sensing and monitoring, process modeling and process control. Each of these has potential to improve process speed and output quality. Improved in-situ on-line sensors improve the ability to measure process states in a rapid and timely fashion. Better process models advance the interpretation of monitored process data to material states of concern like degree of cure. Process control extends process modeling by employing interpretative tools for the purpose of machine actuation.

From the perspective of the control taxonomy given in the first chapter of this thesis, these research efforts focus on the first two limits to process control progress. These are feedback control-loop speed, and process dynamic state measurability. However, by and large, these efforts don't improve process resolution by increasing the controllability of process states at sub-regions within the workpiece.

Appendix: Other Issues In Composite Processing

Overview

Curing occupies the bulk of the attention given to composite processing. This is understandable given the complexity, irreversibility, and cost of the cure cycle. Other issues do attract interest though, and this appendix is intended to give a sense of the research being done. In Resin Transfer Molding ("RTM") and Structured Reaction Injection Molding ("S/RIM") the major question is characterizing fluid flow during resin introduction. Interest in forming control seems to be limited to filament winding. Thermoplastic composites present opportunities and challenges different from those of thermosets, since thermoplastic resins can be processed in a serial fashion.

Resin Transfer Molding (RTM) and S/RIM

Resin Transfer Molding ("RTM") and Structured Reaction Injection Molding ("S/RIM") related research is primarily concerned with modeling resin fluid flow during mold filling. This issue, in general, has received considerable attention to improve injection molding. As a result, a variety of software packages already exist that can characterize the pressurized introduction of non-isothermal viscous fluids. However, RTM and S/RIM are more complex for two primary reasons, one chemical and the other geometric. First, thermosetting resins are more demanding than are thermoplastics because gelation and solidification is irreversible and because the curing reaction releases volatiles. Second, in S/RIM and RTM, the resin must navigate a more complicated pathway because of the preform insert.

During injection molding, solidification of the thermoplastic melt reduces the effective diameter of runners and necessitates increased compensatory injection pressure. However, thermoplastic hardening is reversible, and heating the mold and its network of runners and gates is a feasible means of delaying or even reversing thermoplastic hardening.

Such a luxury does not exist when thermosetting resins are used as the RTM and S/RIM matrices, since curing is irreversible. Therefore, mold heating is not as clear a solution for reducing resin viscosity as it might be with thermoplastic matrices. Additional heat may cause an immediate reduction in resin viscosity, but it may also accelerate the rate of cure and irreversibly increase the material molecular weight.

Mold venting is also more complex when thermosetting resins are employed. During thermoplastic injection molding, vents have to be placed in the mold so that air can escape. With thermosetting materials, even greater attention has to be paid to mold venting, because the chemically reacting resin generates and releases various gases.

When compared to thermoplastic injection molding, RTM and S/RIM of thermosetting resins has an additional complexity. Whereas the melt during conventional injection molding must only navigate the runner system, the RTM and S/RIM resins must make their way through the tiny conduits of the preform. Therefore, the fibrous insert adds to the filling difficulty. Higher fill pressures or greater fill times are needed. Again, the same problem arises that irreversibly curing thermoset resins are being used, so there are chemically imposed limits on the maximum fill time.

Forming[22]

Because of their anisotropic nature, composite materials can be fabricated with specific load bearing characteristics. While this presents opportunities and challenges to designers, forming is not a significant process control difficulty, judging by the available, or lack of available, research literature. This is not terribly surprising, because fiber placement is done in a serial fashion, and even in 'high-tech' aerospace applications, much of the prepreg layup is done by hand. For large scale applications like wing skins, tape is laid done by automated, numerically controlled machines.

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[22] For complete citations please see page 126.

Filament winding is one of the few forming operations that seems to have attracted research. Lee and Springer [Lee and Springer 1990, 1990] developed a model to relate process variables like winding speed, fiber tension, and applied temperature to the thermal, chemical and mechanical behavior of the composite cylinder and mandrel. The intent of this research was to determine a means of selecting and controlling process states that must be maintained during production. The model was used to calculate temperatures in the cylinder and mandrel, fiber tensions and fiber positions, stresses and strains in the workpiece, and voids within the workpiece. In later studies, Calius, Lee and Springer [1990] confirmed the validity of this process model. With similar intent, Hirai, Yunshu, Zhenlong, and Renjie [1989] developed means of characterizing filament winding tension in order to produce uniform residual stresses in the anisotropic material.

Thermoplastics[23]

Because thermoplastic matrices don't irreversibly set, thermoplastic composite processing has been typified by a research emphasis different from that which distinguishes thermoset associated research. Rather than concentrating on curing, attention has been given to various forming techniques that take advantage of thermoplastics'

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[23] For complete Thermoplastic citations please see page 128.

manipulability. For instance, Manson, Schneider, and Seferis [1990] explored the connection between post-processing material properties of press-formed parts. Muzzy, Wu, and Colton [1990] also sought to study material deformation during press-forming, as did DuCloux, Vincent, Poitou, and Agassant [1992].

Thermoplastic composites naturally lend themselves to high resolution serial forming processes because consolidation can occur simultaneously with shaping. As for pultrusion, Lee, Springer, and Smith [Dec. 1991] worked to develop a model of the required pulling force with the temperature, crystallinty, pressure and consolidation within the die. Anderson and Colton [February 1990] worked on a model of pre-preg lay-up, and Dickman, Lindersson, and Svensson [1990] looked to relate filament winding process parameters with mechanical properties. Miller, Gur, Peled, Payne, and Menzel [1990] and Strong [May 1989] each considered means of using universal tooling for incremental forming of thermoplastics.

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Biographical Note

A native of New York City, the author is a 1986 graduate of Princeton University, where he received a Bachelor's degree in Economics. His senior thesis was a macroeconomic model of dollar-yen exchange rate determination.

Before beginning graduate studies at MIT, he worked for two years as a Capital Markets Officer, underwriting investment grade corporate bonds, on the syndicate desk of the investment banking firm, Prudential Bache Capital Funding. He then worked for a year for the Office of Technology Assessment, an agency of the United States Congress. While at the OTA, he was part of a four-member team that studied the role of information technologies in the financial markets. The team's reports are titled Trading Around The Clock: Global Securities Markets and Information Technology (July 1990), and Electronic Bulls and Bears: U.S. Securities Markets and Information Technology (September 1990). The reports were written at the request of the US House of Representatives Committee on Energy and Commerce and the House Committee on Government Operations.

While at MIT, the author has been a teaching assistant, for an introductory information technologies course, and a research assistant, helping prepare a managerial and financial accounting course, in the Sloan School of Management. In the School of Engineering, he has been a Leaders For Manufacturing research assistant in the Laboratory for Manufacturing and Productivity ("LMP"). This thesis was prepared during the LMP research assistantship, and the thesis's initial results were presented by LMP Director, David Hardt, at the "Science and Innovation in Composite and Polymer Processing Conference", held in Cambridge in July 1992.

After graduation from MIT, the author will spend a year as a visiting researcher at the University of Tokyo at the invitation of Professor Hiroyuki Yoshikawa. Professor Yoshikawa is a university vice president and is director of the Intelligent Manufacturing Systems Consortium, a MITI sponsored multi-national collaborative effort to develop advanced manufacturing technologies.