ADAPTIVE AND SENSOR BASED CONTROL OF MACHINE TOOLS

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Introduction

This report provides an introduction to and review of the Adaptive and Sensor Based Control of Machine Tools study and the results from Phase I of this research effort. These results include: the literature review, initial model development and initial experimental data. These items are discussed followed by an outline of activities for Phase II.

Background

The productivity of the factory of the future and the quality of products it produces will, in part, depend on the intelligent utilization of computers to monitor and control the machines that produce the products. This demands that the supervising personnel and the computer systems be provided with accurate and reliable information about the state of the machine and the quality of the operations they perform. This requires, therefore, developing a much better understanding of the machine and the functions they perform and so that sensors and the associated signal processing can be designed to provide this information.

This project specifically deals with understanding and, therefore, subsequently controlling the material removal operation (turning, milling, drilling, etc.). Controlling these cutting operations is expected to result in the following:

1) increased productivity
2) improved machine and part protection
3) increased machine independence
4) simplified part programming
5) optimization of the cutting process
6) efficient tool change policies
7) improved dimensional control
8) lower tool costs.

In order to achieve some of these goals a better understanding of the cutting process, and the dynamics of the machine tool is necessary. This implies good in-process monitoring of the machine tool and the workpiece. Currently the cutting conditions that are thought to be important and therefore desirable to monitor include:

1) tool wear (flank and crater)
2) workpiece size

3) workpiece surface roughness
4) workpiece temperature
5) machine elements and fluid temperature
6) cutting temperature
7) forces or loads acting on the tool
8) tool chatter.

This investigation is focused on measuring the loads acting on the tool. This is known as load sensing.

Load Sensing

Load sensing is the measurement of forces and torques at the tool/workpiece interface resulting from the cutting action. The interpretation of this load information has been used for:

1) tool wear monitoring
2) tool breakage detection
3) chatter detection
4) chip condition monitoring
5) collision detection
6) machine reserve load capacity monitoring

The ability to provide such a wide range of important information is the reason that load monitoring techniques are so prevelant,

There are, unfortunately, many engineering trade-offs associated with the implementation of load sensing. No method currently exists to measure the stresses at the tool/workpiece interface and, therefore, all sensing is done remotely by determining the magnitude and direction of the total load on the tool tip [1]. Consequently a fundamental trade-off in the implementation of a load sensing device exists. The further away from the tool/workpiece interface the sensor is placed the more the desired load signal is distorted but typically both the cost of the sensor and the cost for installation are lower. In addition, when the sensor is close to the interface it is subjected to the very harsh environment present in production machining. Therefore, the sensor must be designed to be insensitive to high temperature gradients, high vibration loads and yet physically constrained to be easily fit onto the machine tool slide without causing any physical interference or extensive retrofitting. When the sensor is placed far away from the interface, and thus outside of the harsh cutting environment, the intervening machine tool components corrupt the signal. This project is concerned with a remote load sensing technique known as power monitoring. The load information is sensed by measuring the power consumed by the spindle or feed motors on the machine tool. Part of the purpose of this study is to identify and quantify the machine tool components which alter the load sensing signals as measured by monitoring the motor power consumption.

Remote Load Sensing - Power Monitoring

Power monitoring is an especially attractive technique for load sensing on existing machine tools. For a rather small investment of capital time for purchasing and installation, a power monitor can be attached to the motor of an industrially based machine tool. The motor can be either electric or hydraulic. The hydraulic motor output can be easily measured with a pressure transducer and tachometer. The electric motor's power consumption is measured with a shunt and "voltmeter". Since electric drive systems are more common for standard cutting type machine tools, they will receive our initial attention. The typical installation of power monitoring equipment on a lathe is shown schematically in Figure 1. The spindle motor power consumption measures the load on the workpiece due primarily to the

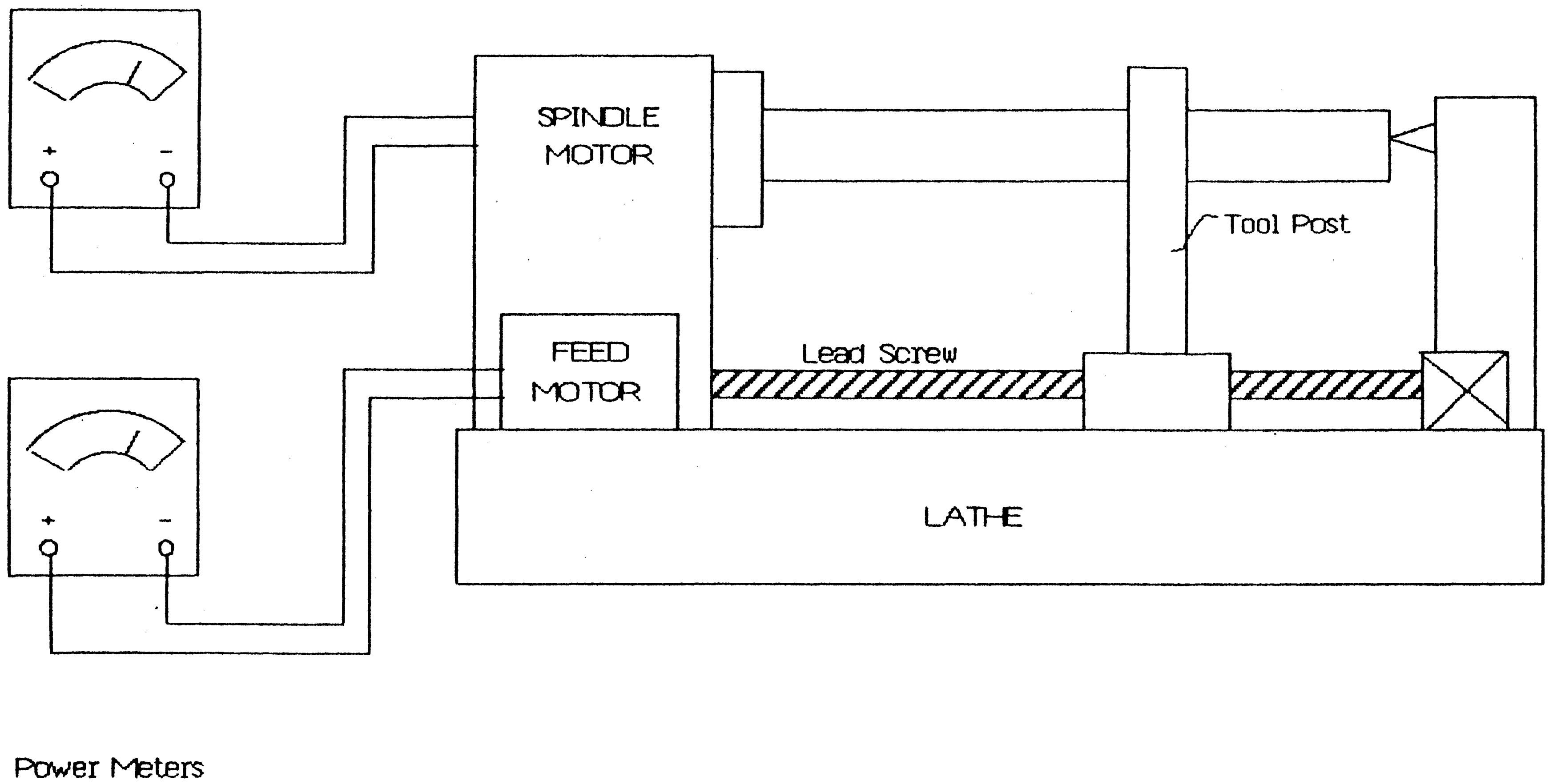

Fig 1: Power Monitoring on a Single Point Turning Operation

cutting (tangential) force. The feed motor power consumption measures the load on the tool in the direction of the motion of the tool (feed force). Typically the meters will be used to detect tool wear and tool breakage.

RESULTS FROM PHASE I

Power Monitoring - Literature Review

As the first part of this project a literature review was undertaken to determine if any research has been done in the following areas: power monitoring for load sensing and modeling of machine tool feed or spindle systems.

A few studies have been published to correlate electric motor power with tool condition. These studies discuss methods that are successful for some applications, but their successful application is not predictable. There are four basic methods which have been documented in the literature which include: 1) Threshold detection, L. Beer [2]; 2) Integrated power spectrum, R. Auble [3]; 3) Energy signature, S.J. Bailey [4]; 4) Breakage detection by spindle motor current pattern, Matsushima [5].

The threshold detection technique involves the machine tool operator observing the power levels as a standard part is being cut. On successive parts the tool begins to wear and eventually removes material less efficiently, as a result the cutting and feed power increases. This is observed in the power consumption levels. When the tool is worn out or breaks a threshold level of power consumption is established. The meter is then set to turn off the machine tool if the power level exceeds this threshold.

The integrated power spectrum approach uses an increase in the rms value of the power consumed to detect tool wear. The electrical power signal is low-pass filtered at 50 Hz and transformed into the frequency domain by a Fourier transform. The transformed signal is then converted into polar form by summing the squares of the real and imaginary components. The D.C. component is removed and the resulting magnitude plot is integrated in order to get the area under the power/frequency plot for a single cut. When this area starts to increase it is time to replace the tool. This method has not been tested on a widespread commercial basis.

The third method, energy signature, involves determining the difference in the power signal from a new and old tool. The signals are compared in the frequency domain. During the cutting operation a test is made to see if the spectrum difference is now indicating that the tool is old. No experimental validation of this method has been published.

The fourth method, is really a method for detecting tool breakage. The spindle power signal is coded as a function of time to reflect if it is increasing decreasing or remaining constant. Certain pattern of this trinary code signify tool breakage. If a pattern is detected the machine tool is stopped. An 85% success rate is reported in the laboratory on one machine tool. The authors did not account for the machine tool components affect on the power signal. This may be necessary if generalization of this procedure is to be realized.

In summary, these techniques are successful under some applications but not all. For reasons that are not currently understood some machines are more amenable to these tool wear detection techniques. To understand this problem and to be able to use power monitoring for more sophisticated load sensing it is necessary to understand what is the contribution of each machine tool element between the tool and the power meter. Some of these components would include for the spindle motor system: the workpiece, chuck, spindle motor, tachometer, motor controller, gearing and bearings. For the feed system these component would include: the tool, toolpost, slide, oil pump, bearings, lead screw, feed motor, tachometer, and feed motor controller. It is clear that the predictable use of remote load sensing by power monitoring will require a clear understanding of the effect of the intervening machine tool components.

Modeling of Machine Tool Drive Systems - Literature Review

Very little published material is available on the modeling and/or experimentally analysis of machine tool drive and feed systems. In addition, while it seems clear that these components do effect the load signal and therefore the applicability and reliability of the tool wear sensing techniques described above, there appears to be no published research exploring these effects as they relate to power monitoring.

P. Mulders et al [6] and H. Khong* et al [7] are the only authors who have published studies on the drive systems of a machine tool as a dynamic system. Specifically Mulders determined the natural frequencies and mode shapes of the feed

*This paper has been difficult to procur, but is expected to be obtained within the month.

system on an N.C. lathe. This was first done experimentally using frequency response techniques. White noise was applied as an input to the feed motor while the tachometer voltage was recorded as the output signal. The Fourier transform of the output was computed to determine the system's natural frequencies. The tool was not engaged in the workpiece. A model was then developed to predict the observed resonances. The model included: mass of the slide, inertia and torsional stiffness of the lead screw, inertia of the feed motor armature, inertia of the tachometer armature and the torsional stiffness of the shaft connecting the armatures of the motor and the tachometer. The parameters of the model we obtained from component data for inertias and stiffnesses but damping values were obtained from the frequency response data.

In general the data was matched by the model. The following conclusions were obtained: 1) An input-output transfer function analysis is sufficient to demonstrate the dynamic mechanical filtering properties of an N.C. feed system; 2) Moment of inertias and torsional springs systems are appropriate structure for modeling the feed system; 3) Model parameters can be easily derived from components data; 4) Natural frequency calculations for the whole feed system require methods such as the Rayleigh-Ritz techniques due to the inherent continuous properties of the leadscrew; 5) The moment of inertia of the carriage is negligible with respect to the energy stored by the rotating leadscrew; 6) The leadscrew stiffness is nonlinear but its behavior can be bounded by a model containing a series of discrete spring mass elements and a model containing a continuous leadscrew considered to have uniform dimensions.

The implications of Mulder's work to the modeling of machine tool drive systems when monitoring power is obvious. However, certain fundamental questions must be explored before using his results. For example, what affect does the tool/workpiece load have on the validity of the the above data and model? What are the appropriate data and model for the spindle system? Since the important output variable in power monitoring is the voltage and/or current consumed by the motor, how do the dynamics of the motor controller effect the above results. We conclude, therefore, that while Mulders' paper is relevant to this project, much more work is needed in the area of machine tool modeling.

Experimental Data

During the month of August the experimental part of this research project was started. The purpose of this initial acquisition of experimental data, is to provide some verification of the structure and parameters of the models under development.

The first series of data was obtained using the Joseph and Lamb Numerically Controlled Lathe at the Manufacturing Development Laboratory at the General Motors Technical Center. The main objective was to record the cutting loads and the motor power consumption for a typical cutting operation. Since the machine was currently being used in facing operations this cutting operation was used. The general test conditions were the following:

Tool: Carboloy-CNMG-434, diamond shaped, coated carbide
Workpiece: 52100 steel tube, O.D. 3.875 in., I.D. 2.5 in.
Spindle Speed: 2000 RPM
Feed Speed: 30 inches/minute
Depth of Cut: .150 inches

The data was digitized and recorded on a DEC PDP 11/34 and transferred to a VAX 11/780 for post processing. The data recorded included: feed and cutting power, motor speed, voltage and current. This data is currently being analyzed and will be presented during the next progress report.

Modeling of Drive Systems

Preliminary work in this area was begun during the summer. The objective of this initial model was to obtain some general insight into which components are responsible for the filtering of the load information.

The first task was to use the results of Mulders [6] and basic D.C. motor theory [8-11] to determine the mechanical/electrical elements that affect the open loop drive (feed or spindle) system. Figure 2 shows the open loop model used. All of the system's mass is lumped into one equivalent inertia and all the frictional components are lumped into one viscous damper. The motor windings inductance is neglected for this simple model. Typically, the energy stored in the windings due to inductance is small compared to the energy stored due to the rotating inertia. In addition the natural frequency associated with the winding's inductance is well above the lowest and dominant inertia/damping break frequency.

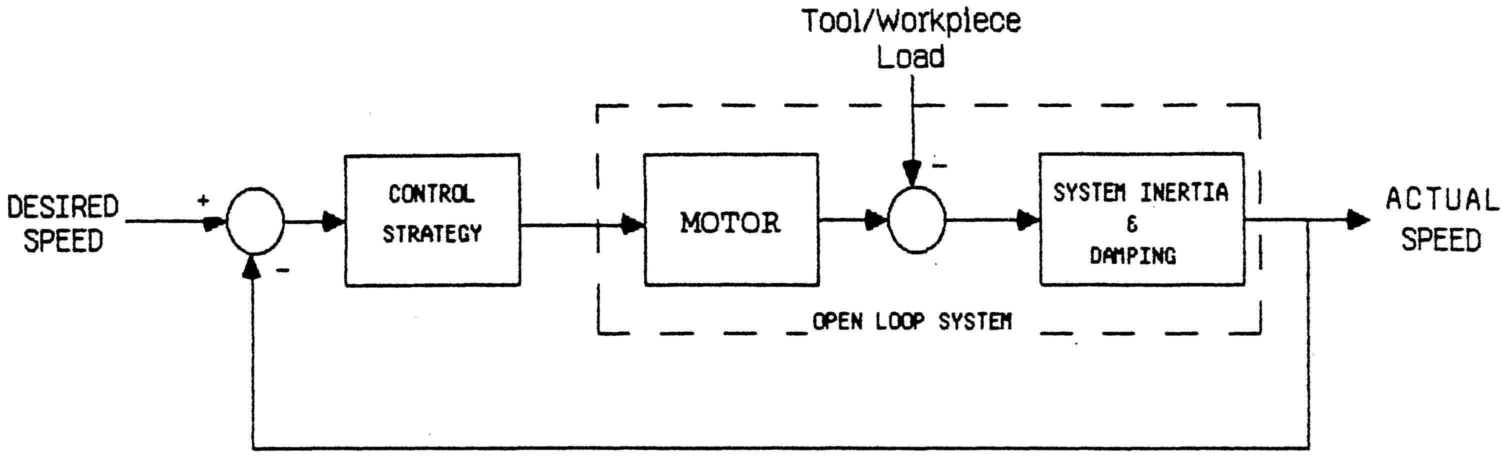

Fig 2a: Generalized Closed Loop Drive System

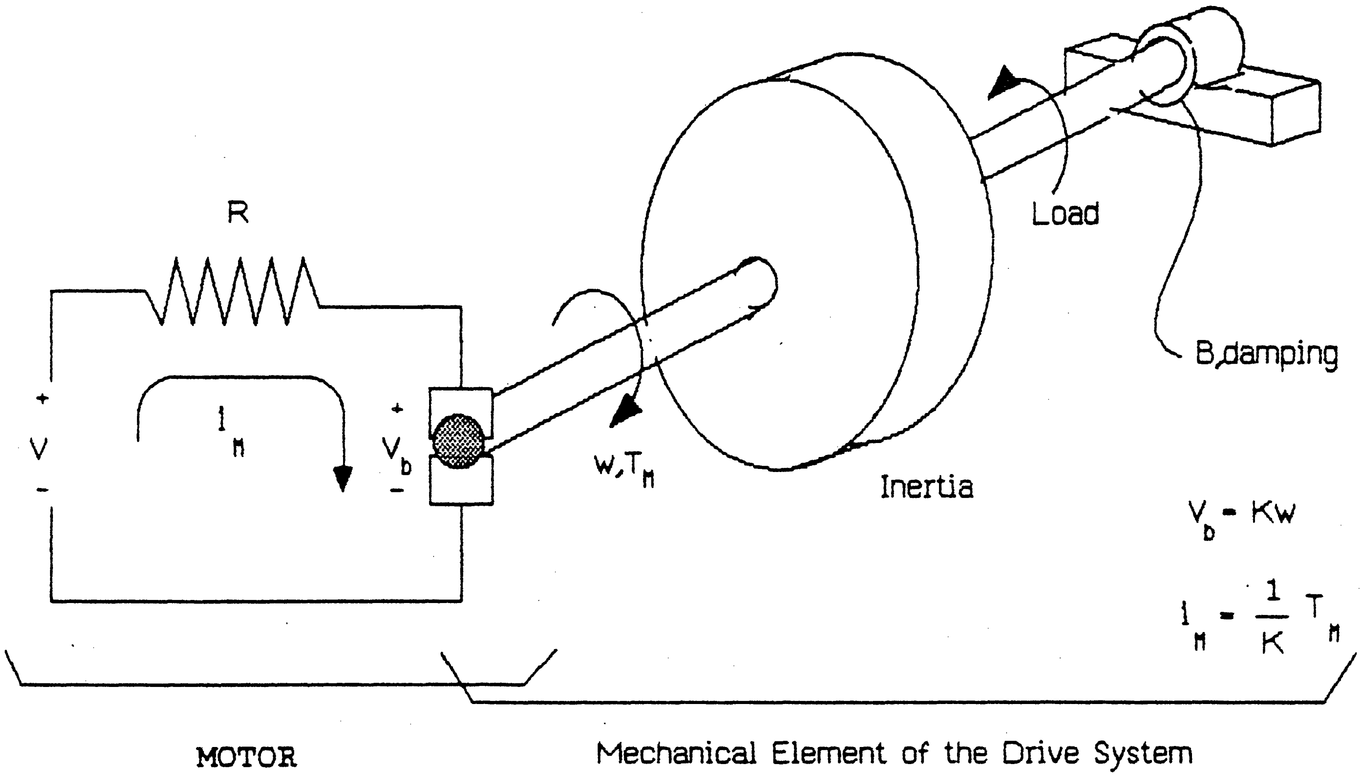

Fig 2b: The Mechanical Tool Drive System

Fig 2: The Machine Tool Drive System

The equation of motion for this open loop system is given below:

$$\frac{d\Omega}{dt} + \frac{1}{\tau}\Omega = \frac{K}{RI} V - \frac{T_D}{I} \qquad (1)$$

where

$$\tau = \frac{IR}{RB+K^2}$$

I = Equivalent Inertia of Drive System Components

R = Resistance of Motor Windings

B = Equivalent Viscous Damping in Drive System Components

K = Motor Constant as Defined in Figure 2

V = Voltage Applied to Motor Windings

T_D = Disturbance Torque Resulting from Load Forces

Ω = Motor speed

$\frac{d\Omega}{dt}$ = Time Derivative of the Motor Speed

This equation is useful for determining the system open loop time constant. This can be done by determining the numerical value for I, R, B and K and/or measuring the step response of the open loop system. This will be done as part of the experimental work in Phase II.

Since the load torque is more closely related to the motor current, it is useful to rewrite Equation (1) in terms of the motor current. This is presented below

$$\frac{di_m}{dt} + \frac{1}{\tau} i_m = \frac{\dot{V}}{R} + \frac{B}{RI} V + \frac{K}{RI} T_D \qquad (2)$$

where i_m = Motor Current.

If the applied voltage is held constant and Equation (2) is rewritten about the steady state current, i_{mo}, and the steady state load T_{DO}, then the following equation is obtain:

$$\frac{d(\delta i_m)}{dt} + \frac{1}{\tau}\delta i_m = \frac{K}{RI}\delta T_D \qquad (3)$$

where $\delta i_m = i_m - i_{mo}$

i_{mo} = Steady State or Equilibrium Motor Current

$\delta T_D = T_D - T_{Do}$

T_{Do} = Steady State or Equilibrium Load Torque.

A transfer function can now be written with the motor current as the output and the load torque as the input. Using the Laplace transform on Equation (3), the following transfer function is obtained:

$$\frac{\delta I_m(s)}{\delta T_D(s)} = \frac{A}{\tau S+1} \qquad (4)$$

where $\delta I_m(s) = L[\delta i_m(t)]$

L = is a Laplace transform operator

S = the independent variable in the s-domain

$$A = \frac{K}{BR + K^2}$$

The magnitude of Equation (4) is

$$\left|\frac{\delta I_m(j\omega)}{\delta T_D(j\omega)}\right| = \frac{A}{(1-\tau^2\omega^2)^{1/2}} \qquad (5)$$

ω = Frequency in Radians/Second.

$j = (-1)^{1/2}$

Note that the amplitude ratio A is related to the inverse of the inertia cubed. This means that the signal to noise ratio of motor current to load torque is a strong function of the system inertia. All of the above relationships will be verified and parameterized during Phase II of this project.

Figure 2 shows that in order to use the actual motor current measurements a model of the closed loop system is necessary. This requires knowledge concerning the control strategy an individual machine tool uses. This is currently being determined for the Joseph and Lamb N.C. Lathe and will be presented in the next progress report. In addition the complete closed loop equations and transfer function will be presented.

<u>Statement of Work</u>

The statement of work in the original proposal for Phase I of this research project included the following items:

<u>Phase I: Research Tasks (May through August, 1983)</u>

(1) A review of the literature related to motor power measurement techniques for machine tools. (100%)

(2) A study of the typical elements of machine tools, and their configurations. (30%)

(3) Dynamic modeling of the machine tool elements identified above. (10%)

(4) Formulation of an experimental system for model validation. (100%)

(5) Preparation of a Progress Report and a Statement of Work for the next phase. (100%)

All of these items have been addressed in this report. Items 1, 4 and 5 have been completed or have progressed beyond the goals set for Phase I. Items 2 and 3 have lagged slightly due to the emphasis during August on obtaining experimental data. They are currently receiving the major focus of the project and should be on scheduled during Phase II.

Phase II will include work on the following items:

<u>Phase II: Research Tasks (September through February, 1984)</u>

(1) Further development of experimental system for evaluating open and closed loop models.

(2) Model parameterization and validation by

- step response tests and/or
- frequency response techniques

(3) The continued indentification of the important elements of the machine tools.

(4) Dynamic modeling of the machine tool elements identified above.

(5) The development of a process model (adaptive observer) based on state and parameter estimation techniques.

(6) Preparation of a Progress Report and Statement of Work for the next phase.

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