

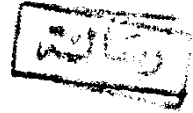
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AN INVESTIGATION INTO THE CUTTING  
PROCESS DYNAMICS IN TURNING

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The Degree of Doctor of Philosophy



In

MECHANICAL ENGINEERING

By

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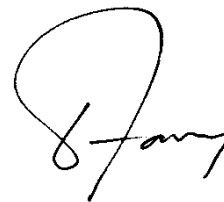
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## CONTENTS

	Page
SUMMARY. ....	i
NOMENCLATURE. ....	vii
INTRODUCTION. ....	1
CHAPTER 1: REVIEW OF LITERATURE. ....	3
CHAPTER 2: THEORETICAL STUDY. ....	16
- The cutting process as a closed loop system..	16
- Effect of the relative vibration amplitude on the uncut chip thickness.. ....	18
- The cutting force mechanism. ....	21
- Nature of friction on the tool face. ....	23
- Effect of vibrational energy on the mechanical properties of materials. ....	24
- Effect of the vibration level on the cutting forces. ....	28
- Dynamic cutting force due to regeneration. ..	30
- Dynamic cutting force due to the variation of the tool geometry (rake and clearance angles). ....	30
- Dynamic cutting forces due to penetration resistance. ....	35
- Flank damping force. ....	35
- Modelling of the dynamic cutting force. ....	36
- Self excited force. ....	37
- Role of damping during cutting. ....	41
- The chatter loop. ....	44
- Determination of the transfer function of the closed loop system. ....	45
- Calculation of the characteristic equation...	48
- Calculation of the threshold of stability....	49
CHAPTER 3: MATHEMATICAL MODELLING OF THE MACHINING SYSTEM....	57
- Machining System Analysis: ....	57
- MFTW system analysis ....	58
- Fixed parameters. ....	58
- Time varying parameters. ....	58
- Nonlinear system parameters. ....	58
- The cutting process dynamics. ....	59
- The cutting stiffness function. ....	59
- Constant value function. ....	59
- Random function. ....	59
- Nonlinear function. ....	60
- Random - nonlinear function. ....	60

	Page
- The negative damping function. ....	60
- Constant value. ....	60
- Random function. ....	60
- Nonlinear function. ....	60
- Random and nonlinear function. ..	61
- Regenerative feedback function. ....	63
- The uncut chip thickness function... ..	64
- constant value. ....	64
- Gradually increased during the first workpiece revolution... ..	64
- The width of cut function. ....	64
- constant value. ....	64
- variable width of cut during first workpiece revolution. ....	66
- variable width of cut during successive revolutions. . ....	66
- The disturbance function. ....	66
- Pulse disturbance... ..	66
- Harmonic disturbance. ..	69
- Periodic disturbance. ..	69
- Random disturbance... ..	69
- Simulation of the machining system... ..	69
 <b>CHAPTER 4: COMPUTER PROGRAM. ....</b>	 <b>77</b>
- Program flow charts. ....	77
- "SIMUL" program. ....	98
 <b>CHAPTER 5: THEORETICAL RESULTS. ....</b>	 <b>105</b>
- System response in standstill and idle running conditions. ....	107
- System response in machining without negative damping during the first workpiece revolution. ....	114
- Investigation of the system response in machining during the first workpiece revolution (Negative damping and direct feedback effect). ....	114
- Linear MFTW system parameters, constant width of cut and constant uncut chip thickness... ..	116
- Linear MFTW system parameters with a gradually increased width of cut... ..	119
- Linear MFTW system parameters with random cutting force coefficients... ..	121
- Linear MFTW system parameters with parametric variations in damping and stiffness. ....	123

	Page
- Response of nonlinear system during the first workpiece revolution. ....	123
- Investigation of the system response during successive workpiece revolutions. ....	138
- Response of the linear system with zero negative damping during successive workpiece revolutions....	139
- Effect of the different types of disturbances on the system response. ....	140
- Response of the linear MFTW system with negative damping during successive revolutions. ....	153
- Response of the nonlinear system (generalized system). ..	160
- Effect of system nonlinearities on the response to initial pulse disturbance. ..	169
- Effect of the system parameters and cutting conditions on the response of the nonlinear system (generalized MFTW system model)....	174
- Effect of the directional static stiffness. . ....	174
- Effect of the system damping....	176
- Effect of the cutting variables. ....	181
<b>CHAPTER 6: EXPERIMENTAL TECHNIQUES. ....</b>	<b>183</b>
- Technical specifications of machine tool used. ....	183
- Technical specifications of the cutting tool used....	183
- Measurement of the spindle speed. ....	184
- Experimental test rig....	186
- Dynamic testing of MFTW system....	188
- At standstill condition. ....	188
- Under idle running conditions. . ....	192
- Preparation of the workpieces used in the tests. ..	194
- Specifications of the MFTW systems used..	198
- Effect of the width of cut on the vibration amplitude. ..	198
- Determination of the dynamic cutting force coefficients. ....	204
- Negative damping coefficient. ..	204
- Cutting stiffness coefficient....	204
- Measurement of the limiting width of cut. ....	204
- Determination of the damping during cutting	
- Factors affecting the damping during cutting. ....	207
- Measurement of the parametric variations in the system. ..	213

	Page
- Measurement of the vibration wave form during cutting...	217
<b>CHAPTER 7: RESULTS AND DISCUSSION...</b>	<b>219</b>
- Dynamic characteristics of the used MFTW system under standstill and idle running conditions. . . . .	219
- Determination of the dynamic cutting force coefficients. . . . .	227
- Cutting stiffness coefficient. . . . .	227
- Negative damping coefficient. . . . .	231
- Effect of the cutting conditions on the threshold of stability... . . . .	236
- Effect of the cutting speed. . . . .	236
- Effect of the feed. . . . .	239
- Determination of the limiting width of cut during successive revolutions. . . . .	242
- Determination of the limiting width of cut on the MFTW systems using original tool holder. . . . .	242
- Damping measurement during cutting... . . . .	245
- Application of the damping measurement during cutting for: . . . . .	247
- Calculation of the specific negative damping. . . . .	247
- Determination of the limiting width of cut. . . . .	247
- Determination of the flank damping coefficient. . . . .	250
- Effect of the cutting conditions on the damping ratio during cutting.....	250
- Determination of a dimensionless relationship of the threshold of stability (Q-v) relationship. . . . .	260
- Determination of ( $b_{lim}$ -v) relation ship from (Q-v) curve. . . . .	260
- Comparison between theoretical and experimental results. . . . .	266
- The limiting width of cut... . . . .	266
- (X-b) relationship. . . . .	269
- The vibration wave form during cutting..	269
<b>CONCLUSION. . . . .</b>	<b>274</b>
<b>REFERENCES. . . . .</b>	<b>281</b>
<b>APPENDICES. . . . .</b>	<b>290</b>
<b>ARABIC SUMMARY. . . . .</b>	

## NOMENCLATURE

Symbol	Computer symbol	Units.	Definition
$A_1(t)$	A1(I)		Damping function of the system response.
$A_2(t)$	A2(I)		Stiffness function of the system response.
$b$	B	mm	Width of cut.
$b_{lim}$	Blim	mm	Limiting width of cut.
$b(t)$	B(t)	mm	Time function of the width of cut.
$C_0$	CO	Ns/mm	The system damping coefficient at standstill or idle running conditions.
$C$	C	Ns/mm	Total positive damping of the MFTW system during cutting.
$C_t$	CT	Ns/mm	Total damping of the MFTW system at any width of cut.
$\Delta C_0$	DCO	Ns/mm	Variation of the damping around the workpiece spindle system.
$d$	d	mm	Workpiece diameter
$F_C$		N	Main static cutting force component.
$F_t$		N	Static feed force component
$\tilde{F}_C(t)$		N	Main dynamic cutting force component.
$\tilde{F}_t(t)$		N	Dynamic cutting force component in feed direction*.
$\tilde{F}(\dot{x})$		N	Dynamic cutting force due to the relative vibration velocity * $\dot{x}$ .
$\tilde{F}(x)$		N	Dynamic cutting force due to the relative vibration displacement * $x$ .
$\tilde{F}_\mu(x)$		N	Dynamic cutting force due to the regenerative effect*.

-----  
 \* In the direction of the uncut chip thickness.



$\tilde{F}(\infty)$		N	Dynamic cutting force due to the variation of the clearance angle*.
$\tilde{F}(\delta_e)$		N	Dynamic cutting force due to the variation of the rake angle*.
$\tilde{F}_g(\dot{x})$		N	Dynamic cutting force due to the variation of the tool geometry with $\dot{x}$ .
$\tilde{F}_p(t)$		N	Dynamic cutting force due to the penetration resistance*.
$\tilde{F}_{Rt}(t)$	FR(I)	N	Resultant dynamic force.
$f_n$	FN	Hz	System natural frequency.
$h$	H	mm	Instantaneous chip thickness.
$h_o$	HO	mm	Uncut chip thickness.
$h_o(t)$	H(I)	mm	Uncut chip thickness function.
$K_m(t)$	KM(I)		stiffness function.
$K_m$	KM	N/mm	Static stiffness.
$K_d$	KD	N/mm	Dynamic stiffness.
$K_{dm}$	KDM	N/mm <sup>2</sup>	Dynamic stiffness corresponding to the maximum negative real part of the harmonic response locus for the MFTW system.
$K^*_d$	KD1	N/mm	Modified dynamic stiffness.
$K^{**}_d$	KD2	N/mm <sup>2</sup>	The modified dynamic stiffness corresponding to $K_{dm}$ .
$m$	—	g	Equivalent mass of MFTW system.
$n$	n	rpm	Workpiece rotational speed.
$Dl$	Dl	N	Pulse disturbance level.
$Dl(t)$	Dl(I)	N	Disturbance function.
$F_o$	$F_o$	N	Amplitude of harmonic disturbance function.
$R$	R		Ratio between the specific negative damping and the specific cutting stiffness coefficients.
$r_d$	—	Ns/mm	Damping coefficient due to penetration resistance.
$r_f$	Rf	Ns/mm	Flank damping coefficient.

\* In the direction of the uncut chip thickness.

$r_h$	RHO	N/mm	Cutting stiffness coefficient.
$r_h^*$	RH1	N/mm <sup>2</sup>	Specific cutting stiffness coefficient.
$r_h(t)$	RH(I)	N/mm	Cutting stiffness function.
$r_s$		N/mm	Cutting stiffness coefficient due to the penetration resistance.
$r_v$	RVO	Ns/mm	Negative damping coefficient.
$r_v^*$	RV1	N/mm <sup>2</sup>	Normalized specific negative damping coefficient.
$r_v^{**}$	RV2	Ns/mm <sup>2</sup>	Specific negative damping coefficient.
$r_v(t)$	RV(I)		Negative damping function
$r_\alpha$		Ns/mm	Positive damping coefficient due to the variation clearance angle with the vibration velocity * $\dot{\chi}$ .
$r_\gamma$		Ns/mm	Face damping due to the variation of the rake angle with the vibration velocity * $\dot{\chi}$ .
S			Laplace operator.
So		mm/rev	Feed.
t	T	s	System response time.
Tl	Tl	s	Disturbance time duration.
U	U	N	Input force to the system.
U(t)	U(I)	N	Input force function.
v	v	m/min	Cutting speed.
X(t)	X(I)	$\mu\text{m}$	Relative vibration displacement between the tool and workpiece in the horizontal direction*.
$X_w(t)$		$\mu\text{m}$	Vibration displacement of the workpiece in the horizontal direction*.
$X_t(t)$		$\mu\text{m}$	Vibration displacement of the tool in the horizontal direction*.

-----  
 \* In the direction of the uncut chip thickness.

$X_d(t)$		$\mu\text{m}$	Vibration displacement due to the disturbance in the (X) direction*.
$\dot{X}(t)$	$XD(I)$	$\text{mm/s}$	Relative vibration velocity between the tool and workpiece*.
$Y(t)$		$\mu\text{m}$	Relative vibration displacement between the tool and workpiece in the vertical direction**.
$Y_w(t)$		$\mu\text{m}$	Vibration displacement of the workpiece in the vertical direction**.
$Y_t(t)$		$\mu\text{m}$	Vibration displacement of the tool in the vertical direction**.
$Y_d(t)$		$\mu\text{m}$	The vibration displacement of the MFTW system due to the disturbance in the vertical direction**.
$\delta_f$	$Df$		Damping ratio due to the flank damping.
$\delta_t$	$DT$		Total damping ratio during cutting at any width of cut b.
$\delta$	$D$		Total positive damping ratio during cutting.
$w$		$\text{rad/s}$	Angular frequency.
$\bar{\sigma}_f$		$\text{N/mm}^2$	Normal stress on the tool face
$\bar{\sigma}_\theta$			Normal stress on the shear plane.
$\tau_f$		$\text{N/mm}^2$	Shear flow stress on the tool face.
$\tau_\theta$		$\text{N/mm}^2$	Shear stress on the shear plane.
$\alpha$		$[\circ]$	Clearance angle.
$\alpha_e$		$[\circ]$	Effective clearance angle.
$\beta$		$[\circ]$	Friction angle.
$\gamma$		$[\circ]$	Rake angle.
$\gamma_e$		$[\circ]$	Effective rake angle.
$\theta$		$[\circ]$	Shear plane angle.

\* In the direction of the uncut chip thickness.  
\*\* The direction of the main cutting force.

$\mu_1$	-		Coefficient of friction on the tool face.
$\mu$	MEUI		Overlap factor.
$\gamma$	NUI		Phasing factor.
$\theta$	-	[o]	Phase angle between upper and lower chip surfaces.
$\lambda_c$			Chip compression ratio.
$\delta_o$	DO		Damping ratio of MFTW system at stand still condition.
$j$			$\sqrt{-1}$
$\tau$			$1/n$

## SUMMARY

Machine tool chatter is an undesirable phenomenon usually encountered in machining due to its adverse effects on the cutting tool, machine tool and work-piece. The explanation of machine tool instability and hence the prediction of the stability conditions are based on the correct description of the cutting process dynamics. The aim of the present investigation is therefore to establish a generalized mathematical model of the machining process in turning taking into consideration the probable factors affecting the stability of the machining system.

The overall cutting system was investigated applying the system theory approach. Both the cutting process and the machine tool dynamics were represented by a feedback loop system with three feedback paths reflecting the mutual interaction between the cutting process and the machine tool. The total dynamic cutting force was represented by its individual coefficients; negative damping coefficient ( $r_v$ ), cutting stiffness coefficient ( $r_h$ ) and flank damping coefficient ( $r_f$ ). The different factors affecting the dynamic cutting force coefficients were investigated. The system was simulated on the digital computer to study its performance under different conditions such as for example the different types of disturbances encountered in machining, cutting conditions, nonlinearities and parametric variations of the systems. As a start an idealised linear model was studied for the sake

of comparison with the generalized system incorporating nonlinear, random and parametric variations. The investigation was carried out at both stable and unstable conditions to study the performance before-and during chatter respectively.

In order to explain the different dynamic phenomena involved in cutting such as for example; the occurrence of chatter in the cases where the cutting tool does not overlap surface undulations (absence of regenerative effect) e.g. during the first workpiece revolution and thread cutting, chatter onset due to an impulsive force in initially stable systems ...,etc., the effect of each of the three feedback paths was considered separately as far as such separation did not affect their usual interaction in practice. Such separation has been made quite easy through the use of the developed simulation technique.

The present work covers the investigation of the performance of the following MFTW<sup>★</sup> systems, open loop system (standstill-and idle running conditions), closed loop system with direct feedback path only, closed loop with direct-and negative damping feedback paths (thread cutting or turning during the first workpiece revolution), closed loop with both direct-and regenerative feedback paths and finally closed loop system with direct-, negative damping-and regenerative feedback paths (generalized system in usual successive revolutions).

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★ Machine - Fixture - Tool - Workpiece system.

The results of the study reveal that, instability of machining systems during the first workpiece revolution may occur due to the negative damping coefficient alone for both linear and nonlinear systems. The different types of disturbances (impulse, periodic and random) affected the stability conditions for nonlinear systems only. The harmonic disturbance with the system natural frequency excites the linear system at its resonance frequency but did not affect its stability limit.

✓ A method has been developed for the prediction of the stability conditions based on the negative damping effect, being the main cause of machine tool instability, taking into consideration the operative receptance during cutting.✓

✓ An experimental investigation was carried out to evaluate the coefficients required in the theoretical investigation and to verify the theoretical results.✓ The determination of the dynamic cutting force coefficients and the system parameters apart from the variation of the machine tool flexibility during carriage movement, implied the development of a special flexible tool holder (FTH) with a sufficiently low dynamic stiffness compared to that of the machine tool workpiece system.✓

✓ The developed mathematical models were applied to three different MFTW systems, varying widely in their dynamic characteristics, which were obtained by the impulse technique using a two channel FFT