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AN INVESTIGATION INTO THE CUTTING PROCESS DYNAMICS IN TURNING

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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_o	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.
Δc_o	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
$\breve{F}_c(t)$		N	Main dynamic cutting force component.
$\breve{F}_t(t)$		N	Dynamic cutting force component in feed direction*.
$\breve{F}(\dot{X})$		N	Dynamic cutting force due to the relative vibration velocity * $\dot{X}$.
$\breve{F}(X)$		N	Dynamic cutting force due to the relative vibration displacement * X.
$\breve{F}_\mu(X)$		N	Dynamic cutting force due to the regenerative effect*.

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* In the direction of the uncut chip thickness.

$\widehat{F}(\alpha)$		N	Dynamic cutting force due to the variation of the clearance angle*.
$\widehat{F}(\gamma_e)$		N	Dynamic cutting force due to the variation of the rake angle*.
$\widehat{F}_g(\dot{X})$		N	Dynamic cutting force due to the variation of the tool geometry with * $\dot{X}$.
$\widehat{F}_p(t)$		N	Dynamic cutting force due to the penetration resistance*.
$\widehat{F}_{Rt}(t)$	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^2	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^2	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.

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* In the direction of the uncut chip thickness.

r_h	RHO	N/mm	Cutting stiffness coefficient.
r^*_h	RH1	N/mm^2	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^2	Normalized specific negative damping coefficient.
r_v^{**}	RV2	Ns/mm^2	Specific negative damping coefficient.
$r_v(t)$	RV(I)		Negative damping function
r_α		Ns/mm	Positive damping coefficient due to the variation clearance angle with the vibration velocity * $\dot{x}$.
r_γ		Ns/mm	Face damping due to the variation of the rake angle with the vibration velocity * $\dot{x}$.
S			Laplace operator.
So		mm/rev	Feed.
t	T	s	System response time.
T1	T1	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)	µm	Relative vibration displacement between the tool and workpiece in the horizontal direction*.
$X_w(t)$		µm	Vibration displacement of the workpiece in the horizontal direction*.
$X_t(t)$		µm	Vibration displacement of the tool in the horizontal direction*.

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* In the direction of the uncut chip thickness.

$X_d(t)$		µm	Vibration displacement due to the disturbance in the (X) direction*.
$\dot{X}(t)$	XD(I)	mm/s	Relative vibration velocity between the tool and workpiece*.
$Y(t)$		µm	Relative vibration displacement between the tool and workpiece in the vertical direction**.
$Y_w(t)$		µm	Vibration displacement of the workpiece in the vertical direction**.
$Y_t(t)$		µm	Vibration displacement of the tool in the vertical direction**.
$Y_d(t)$		µm	The vibration displacement of the MFTW system due to the disturbance in the vertical direction**.
δ_f	Df		Damping ratio due to the flank damping.
δ_t	DT		Total damping ratio during cutting at any width of cut b.
δ	D		Total positive damping ratio during cutting.
w		rad/s	Angular frequency.
σ_f		N/mm^2	Normal stress on the tool face
σ_ϕ			Normal stress on the shear plane.
τ_f		N/mm^2	Shear flow stress on the tool face.
τ_ϕ		N/mm^2	Shear stress on the shear plane.
α		[o]	Clearance angle.
α_e		[o]	Effective clearance angle.
β		[o]	Friction angle.
γ		[o]	Rake angle.
γ_e		[o]	Effective rake angle.
ϕ		[o]	Shear plane angle.

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

μ_1	-		Coefficient of friction on the tool face.
μ	MEUI		Overlap factor.
ν	NUI		Phasing factor.
θ	-	[o]	Phase angle between upper and lower chip surfaces.
λ_c			Chip compression ratio.
δ_o	DO		Damping ratio of MFTW system at stand still condition.
j			$\sqrt{-1}$
τ			$1/n$

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* 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