

Mehmet Nureddin Bennett

# Active Tip-Over Prevention for Mobile Excavators

# Active Tip-Over Prevention for Mobile Excavators

## Aktive Kipp-Prävention für Mobilbagger

Von der Fakultät für Maschinenwesen  
der Rheinisch-Westfälischen Technischen Hochschule Aachen  
zur Erlangung des akademischen Grades eines  
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Nureddin Bennett



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## List of Symbols

<b>Symbol</b>	<b>Unit</b>	<b>Description</b>
$a_n$	$m$	mDH translation distance
$\vec{b}_n$	$m$	tipping line vector
$\hat{b}_n$	$m$	unit vector along tipping line n
$d_n$	$m$	mDH translation distance
$\hat{e}_x$	$m$	x-axis unit vector
$\hat{e}_y$	$m$	y-axis unit vector
$\hat{e}_z$	$m$	z-axis unit vector
$\vec{f}_n$	$N$	force vector in joint of link $n$ in NE
$g$	$m/s^2$	gravitational acceleration
$\vec{g}$	$m/s^2$	vector of gravity
$h$	$m$	height
$k$	—	index variable
$\vec{k}_n$	$m$	tip-over normal vector
$\vec{k}_{s,n}$	$m$	vector from reference center to TL
$k_{or}$	—	hydraulic orifice flow constant (empirical)
$k_{99.9\%}$	—	constant factor of 0.999
$l_1$	$m$	horizontal lever length for $F_{machine}$
$l_1^*$	$m$	length $l_1$ for inclined machine
$l_2$	$m$	horizontal lever length for $F_{payload}$
$l_2^*$	$m$	length $l_2$ for inclined machine
$m_n$	$kg$	mass of body n
$m_n^*$	$kg$	mass of replacement body n

$m_{total}$	$kg$	overall mass of machine/robot
$n$	—	index variable
$\vec{p}_{cna}$	$m$	barrel axis vector of cylinder $n$
$\vec{p}_{cnb}$	$m$	piston axis vector of cylinder $n$
$\vec{p}_n$	$m$	main axis vector of body $n$
$\hat{p}_n$	$m$	normalized main axis vector of body $n$
$\vec{p}_{r1}$	$m$	main axis vector of yoke link $r1$
$\vec{p}_{r2}$	$m$	main axis vector of crod link $r2$
$\vec{q}$	$rad$	vector of generalized angular coordinates
$\vec{q}'$	$rad$	coast down position in generalized coordinates
$\dot{q}_{min,n}$	$rad/s^2$	minimal velocity for coast down compensation of joint $n$
$\ddot{q}_{max,n}$	$rad/s^2$	maximum deceleration of joint $n$
$\vec{r}_c$	$m$	position vector of total COG
$\vec{r}_{cna}$	$m$	barrel joint position vector of cylinder $n$
$\vec{r}_{cnb}$	$m$	piston joint position vector of cylinder $n$
$\vec{r}_{pinE}$	$m$	vector to equipment base joint
$\vec{r}_{r1}$	$m$	base joint position vector of yoke link
$\vec{r}_{r2}$	$m$	base joint position vector of crod link
$\vec{r}_{s,n}$	$m$	local COG of excavator body $n$ in frame $K_n$
$\vec{r}_{s,total}$	$m$	total COG of excavator in frame $K_0$
$\vec{r}_{\Delta sa}^*$	$m$	vector from COG of replacement body to the COG of the appended physical body
$\vec{r}_{\Delta sn}^*$	$m$	vector from COG of replacement body to the COG of the physical main body
$s_n$	—	support contact point $n$
$\vec{s}_a$	$m$	position vector of axle pivot support point point
$\vec{s}_n$	$m$	position vector of support contact point $n$
$\vec{s}_{o,n}$	$m$	position vector of outrigger support contact point $n$
$\vec{s}_{w,n}$	$m$	position vector of wheel support contact point $n$

$t_{crit}$	$s$	physically last moment to securely stop machine
$t_{trig}$	$s$	moment of predicted tip-over
$\vec{t}_n$	$Nm$	joint moment in NE
$\vec{v}_{cog}$	$N/s$	linear speed of total COG
$\vec{v}_n$	$N/s$	linear speed of link frame $n$
$\dot{\vec{v}}_n$	$N/s$	linear acceleration of link frame $n$
$\vec{v}_{s,n}$	$N/s$	linear COG speed of link $n$
$\dot{\vec{v}}_{s,n}$	$N/s$	linear COG acceleration of link $n$
$x_n$	$m$	cylinder $n$ stroke
$\dot{x}_n$	$m/s$	cylinder $n$ stroke velocity
$\ddot{x}_n$	$m/s^2$	cylinder $n$ stroke acceleration
$\ddot{x}_{decel,n}$	$m/s^2$	mean cylinder $n$ stroke deceleration
$\dot{x}_{max,n}$	$m$	cylinder $n$ maximum stroke
$\dot{x}_{min,n}$	$m$	cylinder $n$ minimum stroke
$A_{or}$	$m^2$	valve opening area
$B_n$	—	body (link) with index $n$ in MBS
$E$	$J$	energy
$E_{TL,n}$	$J$	energy required for tip-over about TL $n$
$F$	$N$	scalar force
$F_{machine}$	$N$	balancing force of excavator
$F_{max,n}$	$N$	force limit of cylinder $n$
$F_{payload}$	$N$	payload force
$\vec{F}$	$N$	force vector
$\vec{F}_G$	$N$	gravitational component of net resulting force
$\vec{F}_I$	$N$	inertia components of net resulting force
$\vec{F}_M$	$N$	manipulation components of net resulting force
$\vec{F}_R$	$N$	net resulting force
$\vec{F}_{RI}$	$N$	non-gravitational components of net resulting force

$J_c$	$kgm^2$	inertia tensor of total machine after collision w.r.t. COG
$J_{cs,n}$	$kgm^2$	inertia tensor of total machine w.r.t TL $n$
$J_n$	$kgm^2$	inertia tensor of link $n$ w.r.t. COG
$J_n^*$	$kgm^2$	inertia tensor of simplified replacement body
$J_s$	$kgm^2$	inertia tensor w.r.t. COG
$J_{s,n}$	$kgm^2$	inertia tensor w.r.t. COG for link $n$
$J_{s,total}$	$kgm^2$	total inertia tensor w.r.t. COG
$K_n$	—	coordinate frame $n$ in NE and mDH
$L$	$kgm^2/s$	scalar moment of inertia
$\vec{L}$	$kgm^2/s$	moment of inertia vector
$L_n$	$kgm^2/s$	moment of inertia w.r.t. TL $n$
$\vec{L}_{total}$	$kgm^2/s$	resulting moment of inertia of manipulator motion
$M$	$Nm$	scalar moment
$M_{machine}$	$Nm$	balancing moment of excavator
$M_{manipulator}$	$Nm$	base joint moment of manipulator
$M_{payload}$	$Nm$	(unbalancing) moment from payload force
$\vec{M}$	$Nm$	moment vector
$\vec{M}_G$	$Nm$	gravitational component of net resulting moment
$\vec{M}_I$	$Nm$	inertia components of net resulting moment
$\vec{M}_M$	$Nm$	manipulation components of net resulting moment
$M_{meas}$	$Nm$	measured manipulator base moment in OPS
$M_{ref}$	$Nm$	reference threshold for critical manipulator base moment in OPS
$\vec{M}_R$	$Nm$	net resulting moment
$M_{s,n}$	$Nm$	net scalar moment about TL $n$
$P$	$W$	power
$\mathbb{P}_n$	—	prediction success of single test sequence
$\bar{P}$	—	Average prediction success rate
$Q_{or}$	$m^3/s$	hydraulic flow rate

$R$	—	rotation matrix
${}^A_B R$	—	rotation matrix for transformation from B to A
$S_a$	$m$	support configuration matrix (wheel support)
$S_b$	$m$	support configuration matrix (rear wheels and axle pivot)
$S_c$	$m$	support configuration matrix (dozer blade and outriggers)
$S_{DSM}$	—	stability index of DSM
$S_{FASM}$	—	stability index of FASM
$S_{LHN}$	—	stability index of Lehen
$S_{NDESM}$	—	stability index of NDESM
$S_{NTOpv3}$	—	stability index of NTOpv3
$S_{OPS}$	—	stability index of OPS
$T$	—	homogenous transformation matrix
${}^A_B T$	—	homogenous transformation matrix from B to A
${}^A_B \mathbf{T}$	—	mDH transformation matrix from B to A
$U$	$J$	potential energy
$U_F$	$J$	potential energy equivalent due to non-gravitational forces
$U_G$	$J$	potential energy due to gravity
$U_M$	$J$	potential energy equivalent due to non-gravitational moments
$\bar{U}$	—	overall workspace utilization rate
$U_n$	—	workspace utilization in test
$V$	$J$	kinetic energy
$\bar{V}$	—	ratio of false trigger events
$V_n$	—	false trigger occurrence in test
$\alpha_n$	$rad$	mDH rotation angle
$\tilde{\alpha}_n$	—	FASM angle
$\theta_n$	$rad$	mDH rotation angle
$\vec{\tau}$	$Nm$	vector of joint actuation moments
$\varphi$	$rad$	arbitrary angle



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$\phi$	<i>rad</i>	deflection angle of critical equilibrium plane
$\chi$	<i>rad</i>	deflection angle of machine base from initial position
$\psi$	<i>rad</i>	angle of COG to vertical plane through TL
$\omega$	<i>rad/s</i>	angular velocity
$\vec{\omega}$	<i>rad/s</i>	angular velocity vector
$\vec{\omega}_n$	<i>rad/s</i>	angular velocity vector of link <i>n</i>
$\vec{\omega}_{cs}$	<i>rad/s</i>	resulting angular velocity after elastic collision
$\vec{\omega}'_{cs}$	<i>rad/s</i>	angular velocity with horizontal components of $\vec{\omega}_{cs}$
$\dot{\vec{\omega}}_n$	<i>rad/s</i>	angular acceleration vector of link <i>n</i>
$\Delta h$	<i>m</i>	elevation height of COG
$\Delta p$	<i>Pa</i>	hydraulic pressure difference
$\Delta t_{crit}$	<i>s</i>	lead time of tip-over prediction
$\Delta t_{valve}$	<i>s</i>	reaction delay of safety valve

## List of Abbreviations

<b>2D</b>	two-dimensional
<b>3D</b>	three-dimensional
<b>AR</b>	axis of rotation
<b>CAD</b>	computer aided design
<b>CAN</b>	controller area network
<b>CESM</b>	compliance energy stability measure
<b>COG</b>	center of gravity
<b>COPM</b>	center of pressure margin
<b>DAS</b>	driver assistance system
<b>DH</b>	Denavit-Hartenberg
<b>DOF</b>	degrees of freedom
<b>DSM</b>	dynamic stability margin
<b>EESM</b>	extended energy stability measure
<b>EMC</b>	effective mass center
<b>ESM</b>	energy stability measure
<b>FASM</b>	force-angle stability measure
<b>FL</b>	front left
<b>FR</b>	front right
<b>FRI</b>	foot rotation indicator
<b>FTL</b>	front tipping line
<b>GUI</b>	graphical user interface
<b>GPS</b>	global positioning system
<b>GRP</b>	ground reference plane

<b>HMI</b>	human-machine interface
<b>IMU</b>	inertial measurement unit
<b>LP</b>	lift point
<b>LPH</b>	lift point height
<b>LPR</b>	lift point radius
<b>MBS</b>	multi-body-simulation
<b>mDH</b>	modified Denavit-Hartenberg
<b>MEMS</b>	micro-electromechanical systems
<b>MHS</b>	moment height stability
<b>MMAE</b>	multiple model adaptive estimator
<b>NE</b>	Newton-Euler
<b>NDESM</b>	normalized dynamic energy stability margin
<b>NTOP</b>	NDESM based tip-over prevention system
<b>NTOPv1</b>	NDESM based tip-over prevention system version 1
<b>NTOPv2</b>	NDESM based tip-over prevention system version 2
<b>NTOPv3</b>	NDESM based tip-over prevention system version 3
<b>OEM</b>	original equipment manufacturer
<b>OPS</b>	overload protection system
<b>OWD</b>	overload warning device
<b>RL</b>	rear left
<b>RR</b>	rear right
<b>RTL</b>	rear tipping line
<b>RCI</b>	rated capacity indicator
<b>SSM</b>	static stability measure
<b>STL</b>	side tipping line
<b>TL</b>	tipping line
<b>TPR</b>	tipping point radius
<b>TSM</b>	tumble stability margin

- VDMA** German Association of Mechanical Engineering Industry  
(Verband Deutscher Maschinen- und Anlagenbau)
- ZMP** zero moment point