International Journal of Mechanical and Industrial Technology ISSN 2348-7593 (Online)
Vol. 3, Issue 1, pp: (94-101), Month: April 2015 - September 2015, Available at: www.researchpublish.com

Optimization of Abrasive Water Jet Machining Process Parameters Using Particle Swarm Optimization

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Abstract: **Abrasive water jet machining is a non-traditional machining Process that offers a productive alternative to traditional technique. Process parameters of machining are optimized for maximum material removal rate using Particle Swarm Optimization (PSO) Technique. PSO is a relatively new and powerful method for optimization and which is used to obtain optimum solution in given circumferences. This research work attempts to achieve maximum metal removal rate in abrasive water jet machining under all constraints which are for different process parameters such that water pressure, nozzle transverse speed, diameter of nozzle, mass flow rate of water and mass flow rate of abrasive. Obtained results are better than Genetic Algorithm which is other optimization technique.**

Keywords: **AWJM, PSO, MRR, Titanium.**

I. INTRODUCTION

Abrasive water jet cutting is a novel machining process capable of processing wide range of hard-to-cut materials. The cutting power is obtained by means of a transformation of a hydrostatic energy (400MPa) into a jet of an ample kinetic energy (nearly 1000 m/s) to disintegrate the material. The required energy for cutting materials is obtained by pressurizing water to ultrahigh pressure and forming an intense cutting stream by focusing high-speed water through a small orifice. The use of the AWJ cutting is based on the principle of erosion of the material by the impact of jets. Each of the two components of the jet, i.e. the water and the abrasive material has a specific purpose. The primary purpose of the abrasive material within the jet stream is to provide the erosive Forces. Abrasive water jet process is similar to AJM excluding that in this case water is used as a carrier fluid in place of gas. These processes offer merit of cutting electrically non conductive as well as difficult to machine materials comparatively more rapidly and efficiently than other processes. Figure 1 shows the cutting head of AWJM which includes mainly orifice abrasive mixer, focusing tube, and nozzle.

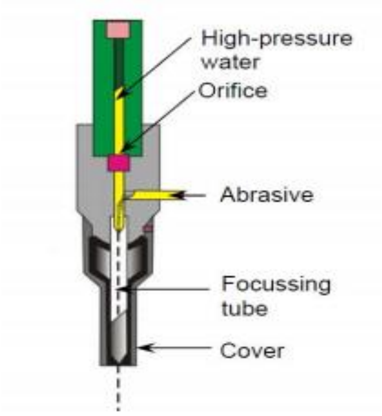

Figure.1 Cutting head of AWJM

II. LITERATURE REVIEW

M. Dittricha et al(2014) have investigated the influence of the process parameters on Ceramic surface via Design of Experiment on the material removal rate (MRR) with the objective of good surface conditions. **Mohamed Arezki et al (2014)** have worked on two modern optimization algorithms named hoopoe heuristic‖ and cuckoo optimization‖ algorithm on AWJM and some other processes. **M. Chithirai Pon Selvan et al (2012)** have investigated the effects of Parameters on surface roughness of aluminium on AWJC by Taguchi. It has been found that water pressure has the most effect on the surface roughness. **Mehdi Zohooret al (2012)** has used ANOVA to determine the effect of process parameters with different levels in AWJM on hardox steel material. **AzlanMohd Zain et al(2011)** applied two computational approaches, Genetic Algorithm and Simulated Annealing on AA 7075 aluminium alloy in AWJM. **Izzet karakurt et al(2011)** have studied experimentally the effects of process parameters on granites on the kerf angle are investigated via DOE and ANOVA. Also three different garnet Baltic brown, aksarayyaylak, Bergama grey was used to experiments. **SoodabehDarzi et al (2013)** have given brief introduction to the PSO algorithm. Particle Swarm Optimization (PSO) is heuristic robust stochastic optimization technique works in field of Artificial Intelligence (AI). the PSO is a useful and valuable technique with goal of maximizing or minimizing of certain value that has been used in wide area and different fields such as large field of engineering, physics, mathematics, chemistry and etc. **Neelesh K. Jain et al(2007)** have described optimization of process parameters of four AMPs namely USM, AJM, WJM, and AWJM processes using genetic algorithms (GA) giving the details of formulation of optimization models, solution methodology used, and optimization results. **AzlanMohd Zain (2011) et al** have applied integrated techniques of Simulated Annealing (SA) and Genetic Algorithm (GA) soft computing techniques to estimate optimal process parameters that lead to a minimum value of machining performance while machining on AWJM. **UshastaAich et al(2014)** have done experiments to analyze the effect of machining parameter on cutting of borosilicate glass by AWJM for depth of cut. Optimum condition of control parameter setting is also searched through particle swarm optimization (PSO).**C. Cui et al(2013)**have used particle swarm optimization (PSO) to evaluate the straightness and flatness errors using the Least Squares Method (LSM).**Vinay Sharma et al (2011)**worked on Taguchi–Fuzzy decision method has been used to determine the effective process parameters for improving the productivity of coal cutting on AWJM. **Pankaj Balkrishna Tambe et al (2011)** optimized MRR using Genetic Algorithm (GA) for the carbon/epoxy reinforced composite with a constraint on surface roughness. **Metin Kök et al(2011)** have studied the influence of input process parameters on the mean surface roughness, maximum roughness of profile height, and mean spacing of profile irregularity of AWJ cut surfaces on Particle-reinforced aluminum alloy metal matrix composites (MMCs) such as 7075 Al alloy composites reinforced with Al2O3 particles using genetic expression programming (GEP).

In optimizing the machining process parameters, the selection of machining process parameters is a very crucial part in order for the machine operations to be successful. Particle swarm optimization is based on a social psychological model of social influence and social learning, inspired by the social behavior of bird flocking or fish schooling. A Particle swarm optimization algorithm maintains a swarm of particles, where each particle represents a potential solution. A swarm is similar to a population, while a particle is similar to an individual. In simple terms, the particles are flown through a multidimensional search space, where the position of each particle is adjusted according to its own experience and that of its neighbor‘s.

III. SOLUTION METHODOLOGY

In many industries of manufacturing, the parameter setting is made based on the skill and experience of the machinist or based on the handbook recommendations. However, due to this, optimum parameter setting is not achieved which leads towards poor quality, reduced production, and increased cost of product.

Control Parameter of AWJM considered in this study such as water jet pressure at the nozzle exit ‘P_{water}’ (MPa); diameter of abrasive-water jet nozzle ‘d_{awnoz}’ (mm); traverse or feed rate of the nozzle ‘f_{noz}’(mm/s); mass flow rate of water ‘M_{water}’ (kg/s) and mass flow rate of abrasives ‘M_{abr}’ (kg/s).

Objective functions:

$$MRR = h_t * w * f_n \qquad (1)$$

Where,

h_t = depth of penetration = $(h_c + h_d)$

w= width of the kerf = (wtop+ w bottom) / 2

≈ d_{awnoz} , the diameter of the focussing tube or nozzle or the insert

f_n= traverse speed of the AWJ or cutting speed

Whereindentation depth due to deformation wear ‘h_d’ and indentation depth due to cutting wear ‘h_c’ are calculated using the equations mentioned in theAppendix A.

Power consumption constraint:

$$1 - \frac{p_{water} M_{water}}{P_{max}} \geq 0.0 \qquad (2)$$

Particle swarm Optimization

The Particle swarm optimization algorithm is population-based and a set of potential solutions evolve to approach a suitable solution for a problem. Being an optimization method, the aim is finding the global optimum of fitness function defined in a given search space. In the Particle swarm optimization algorithm, each individual is called a "particle" and is subject to a movement in a multidimensional space that represents the belief space. Particles have memory, thus retaining part of their previous state. There is no restraint for particles to share the same point in belief space, but in any case their individuality is preserved. Each particle's movement is the composition of an initial random velocity and two randomly weighted influences.

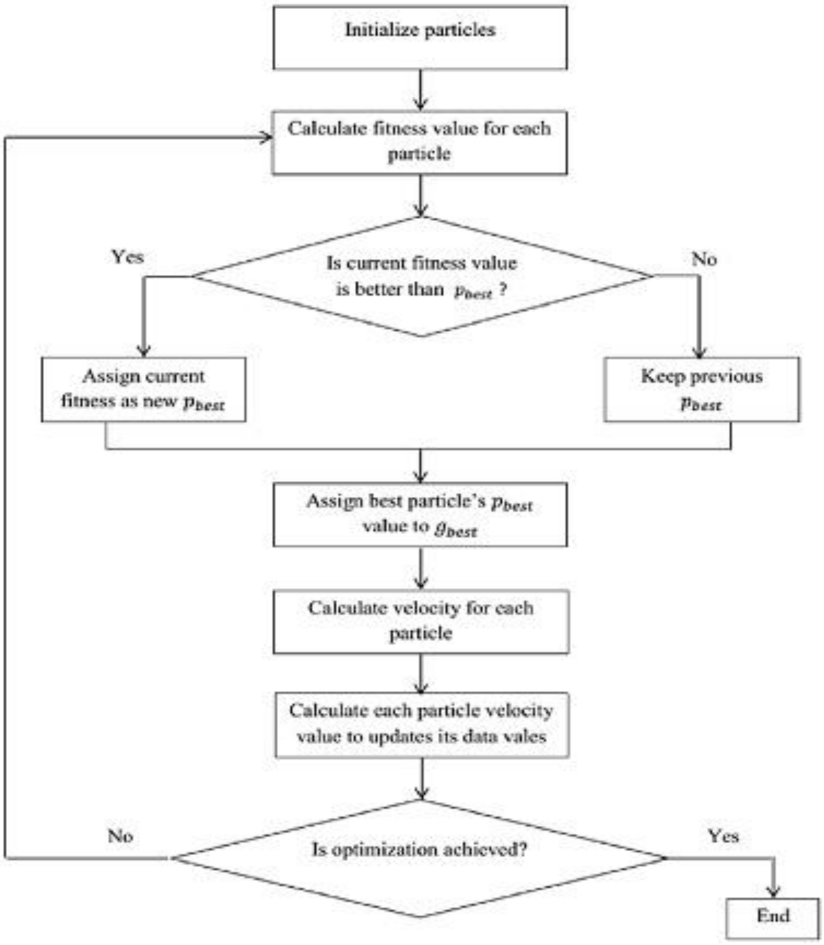

Figure 2: Flow chart of PSO

The particle updates its velocity and positions according to equation 3 and equation 4 respectively

$$V_{new} = w \times V_{old} + C_1 \times (rand_1) \times (p_{best} - p_{old}) + C_2 \times (rand_2) \times (g_{best} - p_{old}) \qquad (3)$$

$$p_{new} = p_{old} + v_{new} \qquad (4)$$

Where

W - Inertia weight

V_{new}- New velocity calculated for each particle

V_{old} - Velocity of the particle from the previous iteration

P_{new}- New position calculated for each particle

p_{old}- Position of the particle from the previous iteration

C_1 & C_2- Cognitive and social acceleration constants

rand- Generates random value in the range [0 1]

p_{best}- Personal best position stored

g_{best} - best position of particle in the population.

And C_1 and C_2 are generated in the range 0.4 to 2

P_{new} should be in upper and lower limits so different methods are used to handle these.

IV. PROBLEM DEFINITION

Material removal rate maximization in AWJM with power consumptions constraints. Process parameters such as water pressure, nozzle transverse speed, and diameter of nozzle, mass flow rate of water and mass flow rate of abrasive are to be used for this work. Titanium is work material and abrasive particle is Al_2O_3.

Table I shows the titanium Material Specification and Properties and Table II shows the abrasive particle AL_2O_3 specification.

Table I: Work Material Specification

SR NO.	PROPERTIES	SYMBOL	UNIT	VALUE
1	Flow Stress of Work Material	σ_{fwork}	MPa	8142
2	Elastic Limit of Work Material	σ_{ework}	MPa	883
3	Poisson's Ratio of work Material	ν_{work}	-	0.20
4	Young's modulas of elasticity of Work Material	E_{ywork}	MPa	1,14,000
5	Drag or Skin Fraction Coefficient for Work Material	C_{fwork}	-	0.002

Table II: Abrasive Particle Specification

SR NO.	PROPERTIES	SYMBOL	UNIT	VALUE
1	Density of abrasive Particle	ϱ_{abr}	Kg/mm^3	$3.95 * 10^{-6}$
2	Poisson Ratio of Abrasive particle	ϑ_{abr}	--	0.25
3	Young Modulus of Elasticity of abrasive particle	E_{Yabr}	MPa	3,50,000
4	Roundness factor of the abrasive Particle	f_{r-abr}	-	0.35
5	Sphericity factor of the abrasive particle	f_{s-abr}	-	0.78
6	Proportion of abrasive Grains effectively	η_{abr}	-	0.7
7	Moment of Inertia of abrasive Particle about C.G	I_{pabr}	-	$=0.5 \times m_p r_m^2$
8	Mean Radius of abrasive particle	r_m	-	$7.62 \times M_a^{-1}$
9	Abrasive Mesh Size	M_a	-	# 80
11	Mixing Efficiency between abrasive and Water	ξ	Nil	0.8
12	Proportion of abrasive grains effectively Participating in Machining	n_{abr}	Nil	0.7

Table III shows different parameters which are to be considered as control parameters with its ranges.

Table III: Parameters with range

SR NO.	NOTATION	PARAMETER	UNIT	RANGE
1	M_{abr}	Mass flow rate of Abrasive	kg/s	$0.0003 \leq M_{abr} \leq 0.08$
2	M_{water}	Mass flow rate of Water	kg/s	$0.02 \leq M_{water} \leq 0.2$
3	P_{water}	Water jet Pressure at Nozzle Exit	MPa	$50.0 \leq P_{water} \leq 400.0$
4	d_{awnoz}	Diameter of abrasive Water jet Nozzle	mm	$0.5 \leq d_{awnoz} \leq 5.0$
5	f_{noz}	Traverse or feed rate of nozzle	mm/s	$0.2 \leq f_{noz} \leq 25.0$

V. RESULT AND DISCUSSION

Following optimum solution was obtained from total 55 run for the population size ‘Ps’ = 30; No of iteration Ns=80

Table IV: Obtained results from PSO

Parameter	Value Obtained
Water jet pressure at nozzle exit (MPa)	388.20
Diameter of abrasive-water jet nozzle (mm)	4.9537
Traverse or feed rate of the nozzle (mm/s)	18.92
Mass flow rate of water (kg/s)	0.1370
Mass flow rate of abrasive particles (kg/s)	0.0714
Optimum value of MRR (mm3/s)	1083.4
Power consumption achieved	52.40kW (Allowable56kW)
Value of normalized constraints	0.064

Figure 3 representing variation in water jet pressure at nozzle exit with respect to iterations, in the present case an optimum value of 388.20 MPa has been obtained. Figure 4 representing variation in the Diameter of nozzle with respect to iterations in PSO. Figure 5 representing variation in Traverse rate ofnozzle exit with respect to iterations, Figure 6 and Figure 7 show the variation in Mass flow rate of water and mass flow rate of abrasive respect to number of iterations respectively.Figure 8 show the variation of the objective function (i.e. MRR, Eq. (1)) with no. of iteration in PSO. A power consumption constraint is satisfied in all parameter selections. With respect to all constraints and all control parameters it is found that MRR is 1083.4 mm^3/sec.

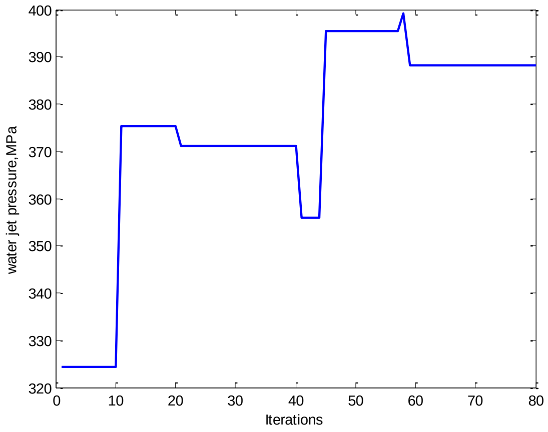

Figure 3 Effect in water jet pressure Vs iterations of PSO

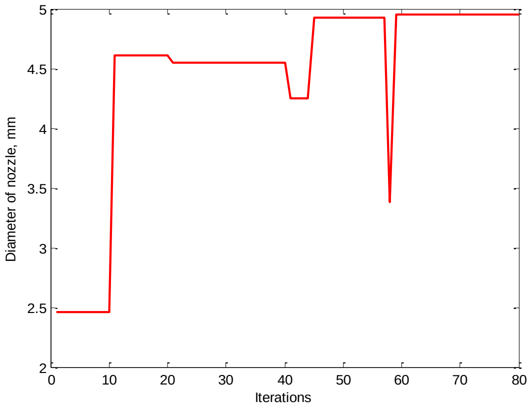

Figure 4 Effect in Diameter of Nozzle Vs iterations of PSO

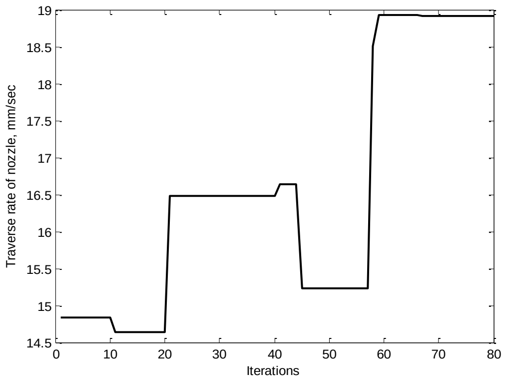

Figure 5 Effect in Traverse Rate of nozzle Vs iteration of PSO

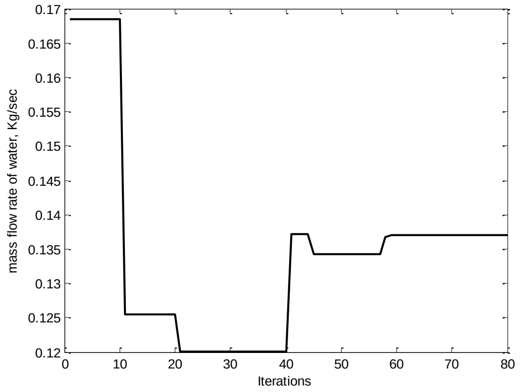

Figure 6 Effect in Mass flow rate of Water Vs iteration of PSO

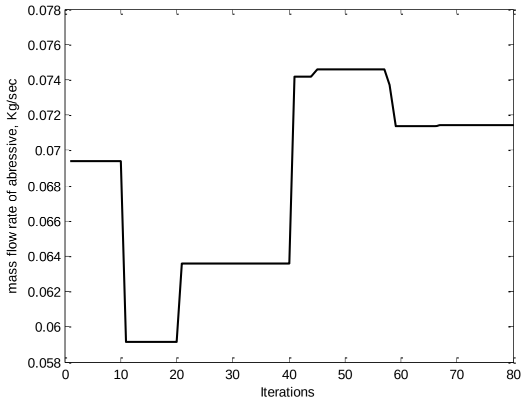

Figure 7 Effect in Mass flow rate of abrasive Rate Vs iteration of PSO

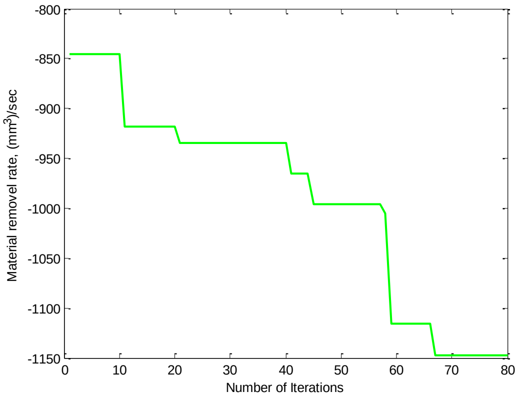

Figure 8 Effect in Material Removal Vs iteration of PSO

VI. COMPARISION

Table V shows the comparison of optimization results.

Table V: Comparison of PSO results

Method	P_{water} (MPa)	d_{awnoz} (mm)	M_{abr} (kg/s)	M_{water} (kg/s)	f_{noz} (mm/s)	MRR (mm^3/s)	Power Consumptions (kW)	Value of normalized constraints
PSO	388.2	4.953	0.071	0.137	18.92	1083.4	52.40	0.064
GA [10]	398.3	3.726	0.079	0.141	23.17	900.23	55.97	0.0005

In above table V we can see that MRR is higher in PSO results than GA results. Also there is change in abrasive water jet nozzle diameter which leads to higher MRR. Mass flow rate of water and abrasive are approximately same in both PSO and GA. Traverse rate is decrease in PSO results which also leads to Good Surface Roughness. Also power consumption is low in PSO results

VII. CONCLUSION

1. Particle Swarm optimization is powerful nontraditional optimization technique, used for optimizing the MRR of Abrasive water jet machining.
2. In particle swarm optimization, Velocity of particle helps to generate new solution.
3. It has been found that introduction of velocity clamping and inertia weight is helpful to find better solution in each iteration and optimal solution in last.
4. Better solution was found in each iteration and after no. of iteration it’s become steady.
5. Results obtained by particle swarm optimization are better than genetic algorithm**.**

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APPENDIX - A

Indentation depth due to deformation wear h_d is given by

$$\frac{\eta_{abr}d_{awnoz}M_{abr}\left[\sqrt{2}\times10^{4.5}\xi M_{water}P_{water}^{0.5}-(M_{abr}+M_{water})\left(\frac{5\pi^2\sigma_{ework}^{2.5}}{\varrho_{abr}^{0.5}}\left[\frac{1-\nu_{abr}^2}{E_{yabr}}+\frac{1-\nu_{work}^2}{E_{ywork}}\right]^2\right)\right]^2}{(1570.8\,\sigma_{fwork})\,d_{awnoz}^2f_{noz}(M_{abr}+M_{water})^2+(\sqrt{2}\times10^{4.5}\xi\,C_{fwork}\eta_{abr})[\sqrt{2}\times10^{4.5}\xi M_{water}P_{water}^{0.5}]-(M_{abr}+M_{water})\left(\frac{5\pi^2\sigma_{ework}^{2.5}}{\varrho_{abr}^{0.5}}\left[\frac{1-\nu_{abr}^2}{E_{yabr}}+\frac{1-\nu_{work}^2}{E_{ywork}}\right]\right)(M_{abr}M_{water}P_{water}^{0.5})} \quad (5)$$

Indentation depth due to cutting wear h_c is given by

$$\left[\frac{1.028\times10^{4.5}\xi}{\sqrt{\frac{3000\sigma_{\mathrm{fwork}}f_{rabr}}{\varrho_{\mathrm{abr}}}}^{0.6}}\frac{1}{\varrho_{\mathrm{abr}}{}^{0.4}}\frac{d_{awnoz}{}^{2}M_{abr}{}^{0.4}}{f_{noz}{}^{0.4}}\frac{M_{water}P_{water}{}^{0.5}}{M_{abr}+M_{water}}-\frac{18.48\left(1+\frac{m_{p}r_{m}{}^{2}}{I_{p}}\right)^{\frac{2}{3}}\xi^{\frac{1}{3}}}{\sqrt{\frac{3000\sigma_{\mathrm{fwork}}fr^{0.6}}{\varrho_{\mathrm{abr}}}}^{\frac{1}{3}}f_{rabr}{}^{0.4}}\left(\frac{M_{water}P_{water}{}^{0.5}}{M_{abr}+M_{water}}\right)^{\frac{1}{3}}\right] \tag{6}$$

If $\alpha_t \leq \alpha_o$

h_c = 0 otherwise;

here angle of impingement at which max erosion occureα_o is found using

$$\alpha_o=\left(\frac{0.02164\,(\sqrt{\frac{3000\sigma_{\mathrm{fwork}}f_{rabr}{}^{0.6}}{\varrho_{\mathrm{abr}}}})^{\frac{1}{3}}\,f\_r\hat{}0.4)}{k_a{}^{\frac{2}{3}}\xi^{\frac{1}{3}}}\right)\left(\frac{M_{abr}+M_{water}}{M_{water}P_{water}{}^{0.5}}\right)^{\frac{1}{3}}\text{(degrees)} \tag{7}$$

Angle of impingement at top of machined surface, which is given by

$$\alpha_t=\left(\frac{0.389\times10^{-4.5}\rho_a{}^{0.4}(\sqrt{\frac{3000\sigma_{\mathrm{fwork}}f_{rabr}{}^{0.6}}{\varrho_{\mathrm{abr}}}})}{\xi}\right)\left(\frac{d_{awnoz}{}^{0.8}f_{noz}{}^{0.4}(M_{abr}+M_{water})}{M_{water}\,M_{abr}{}^{0.4}P_{water}{}^{0.5}}\right)\quad\text{(degrees)} \tag{8}$$