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Mohammad Imtiyaz Ahmad
National Institute of Technology, Durgapur, imtiyazahmed230@gmail.com

Dilip Kumar Biswas
National Institute of Technology, Durgapur, dilipkr_biswas@yahoo.co.in

S. S ROY
Technology Innovation Centre, CMERI, Durgapur, S.SROY@gmail.com

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Gait Analysis of Eight Legged Robot

Mohammad Imtiyaz Ahmad[1], Dilip Kumar Biswas[2] & S. S ROY[3]

[1&2]Department of Mechanical Engineering, National Institute of Technology, Durgapur
[2]Technology Innovation Centre, CMERI, Durgapur
E-mail: imtiyazahmed230@gmail.com, dilipkr_biswas@yahoo.co.in

Abstract - For any legged mobile machine, gait is the methodical, logical and scientific lifting and placement of foot to follow desired path on the desired terrain. To run a walking machine on any terrain, selection and analysis of gait is must. To meet the locomotion characteristics of an eight-legged robot in this paper we describe gait analysis of eight legged spider like robot. The longitudinal gait stability margin of the robot changes with change in duty factor. We analyze the wave gait and equal phase gait for this legged robot and found that there is a jump in stability margin of full cycle equal phase gait to that of wave gait at duty factor 3/4, and stability margin of half cycle equal phase gait jumps to wave gait at duty factor 7/8. We try to verify our result through graphical and simulation analysis.

Keywords - *Duty factor, wave gait, equal phase gait.*

I. INTRODUCTION

Wheeled vehicles are very familiar in modern system and at present it is the main means of transportation. However it requires smooth terrain and paved road. They cannot move on rough terrain. To overcome of this difficulty walking machines were developed, because they are more suitable to move on irregular terrain. Therefore in past few years walking machine form an important area of study, however controlling legs of walking machine is a difficult task. Hence there is a need to develop a method for generation and control of the sequence of placing and lifting of legs such that at any instant body should be stable and capable of moving from one position to other. The generation and sequence of such leg motion is called gait.

At first for gait analysis Muybridge [1] used photography to study the locomotion of animals. Authors of [2] used mathematics to analyze gait. While [3] developed gait formula. Later McGhee and Frank [4], defines duty factor, phase difference, gait matrix. In [5] regular and symmetric periodic gait with phase difference maximizes the gait stability margin for hexapod was defined. Later Song and Waldron [6] developed analytical method for gait study and derive longitudinal gait stability margin of wave gait. Some [7,8] proposed general and distributed method to define gait.

In this paper we use analytical method to define wave gait and equal phase gait for eight-legged robot. We find a relation between stability margin and duty factor for eight legged wave gait and equal phase gait which are discussed in the later section.

II. DEFINITION AND TERMINOLOGY

To understand gait analysis some definitions are need to know which are described here, [4,9]

Transfer Phase:-It is the period in which foot is not on the ground.

Support phase:-It is the period in which foot is on the ground.

Cycle time:-It is time for complete cycle of leg locomotion of periodic gait.

Duty factor (β):-It is the time fraction of cycle time in which foot is in support state.

Leg phase (ϕ):-It is the fraction of cycle period by which contact of particular leg lags behind contact of leg 1.

Leg stroke (R):-Distance through which foot is translate relative to body during support phase..

Stroke pitch (P):-Distance between centers of stroke of adjacent legs on one side.

Stability margin (*S*):-Shortest distance between vertical projection of centre of gravity to the boundary of support pattern in horizontal plane.

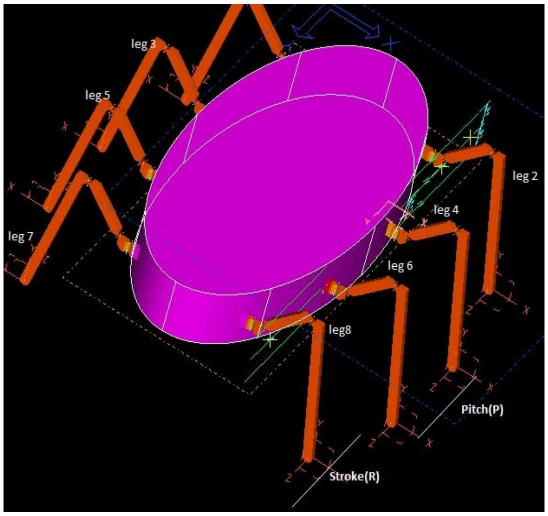

Fig. 1: CAD Model of eight legged robot

"Fig.1"shows a model of eight legged robot, where leg numbers 1, 3, 5, 7 are assigned for left side of legs and leg numbers 2, 4, 6, 8 are assigned for right side legs.

III. ANALYSIS OF WAVE GAIT

Gait is defined as the time and location of placing and lifting of each foot coordinated with the motion of the body in its six degree of freedom in order to move the body from one place to other.

In a wave gait motion, the placement of each foot runs from the rear leg to the front on either side as a wave, and the placement of a leg occurs concurrently with the lift of the leg which is ahead of it, and each pair of legs is 180º out of phase (symmetric) and all legs have the same duty factor.

From [10,11], for 2n-legged machine, the leg phase difference is given as,

$$\phi_{2m+1}=F(m\beta), m=1,2,3.....,n-1 \text{ and } 3/(2n)\leq\beta<1 \qquad (1)$$

Where *F(X)* is fractional part of real number *X* and *m* denotes leg number starting from left and numbered from front to rear, and *2n* is number of legs. So, in case of eight leg

$$2n=8 \quad \phi_3=\beta, \phi_5=F(2\beta), \phi_7=F(3\beta), \beta\geq 3/8 \qquad (2)$$

Where, ϕ =phase difference, β =duty factor.

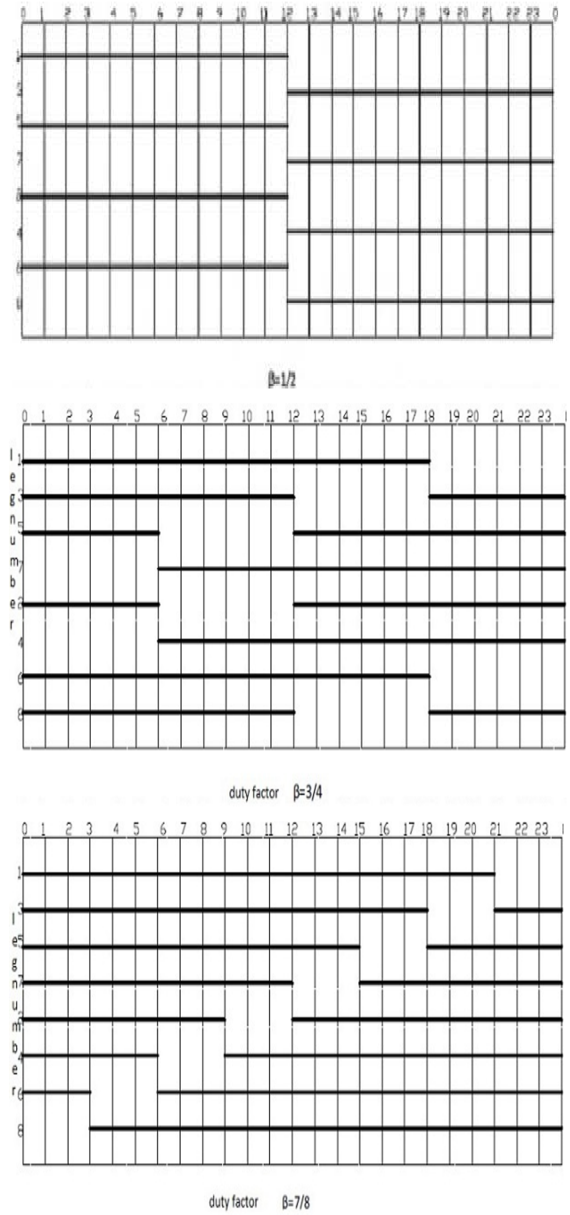

Fig. 2: Gait diagram of wave gait with different duty factors

"Fig. 2" shows gait diagram of wave gait with different duty factors. Solid horizontal line shows that foot is on the ground and empty space for foot is in transfer phase.

From [12], some useful theorems to find stability margin of wave gaits are

Theorem1:-For a *2n*-legged wave gait [11] with duty factor in the range 1□≤ β □1the longitudinal gait stability margin (S) can be determined from following equation.

If β > 3/2 and R ≤ R_b

$$S_1 = \left(\frac{n}{2}-1\right).P + \left[1-\frac{3}{4\beta}\right].R \tag{3}$$

Where *P* is pitch and *R* is stroke and

$$R_b = \left[\frac{\beta}{(3\beta-2)}\right].P \tag{4}$$

If β > 3/2 and R ≥ R_b,

$$S_2 = \left(\frac{n}{2}-\frac{1}{2}\right).P + \left[\frac{1}{4\beta}-\frac{1}{2}\right].R$$

The definitions' which are used here were defined in [4, 12] and [13].

In (3) the second term is negative for β < *3/4* .Reducing *R* would increase stability and maximum value is

$$S_{1\max} = \left(\frac{n}{2}-1\right).P \tag{5}$$

For β >3/4

$$S_{1\max} = \left(\frac{n}{2}-1\right).P + \left[1-\frac{3}{4\beta}\right].R_m \tag{6}$$

Where R_m is maximum value of R. For R =0, vehicle cannot move.

In (4) second term negative for range1/2<β<1.Reducing R would increaseS2.

$$S_{2\max} = \left(\frac{n}{2}-\frac{1}{2}\right).P \tag{7}$$

From (1) and (2),

For eight legged robot, the longitudinal gait stability margin normalized to stroke pitch is

$$S_1 = 1 + \left[1-\frac{3}{4\beta}\right].\frac{R}{P} \tag{8}$$

$$S_2 = \frac{3}{2} + \left[\frac{1}{4\beta}-\frac{1}{2}\right].\frac{R}{P} \tag{9}$$

(8) and (9) is plotted for wide range of 'R/P' and β which is shown in "Fig.3", where we can see that longitudinal front stability margin(S) increases with increase in duty factor and it reaches a maximum value at R/P=1.2 for duty factor 11/12, and maximum value at R/P=1.5 for duty factor 5/6.Thus as ratio of stroke by pitch increases longitudinal stability margin first increases at certain value then decreases.

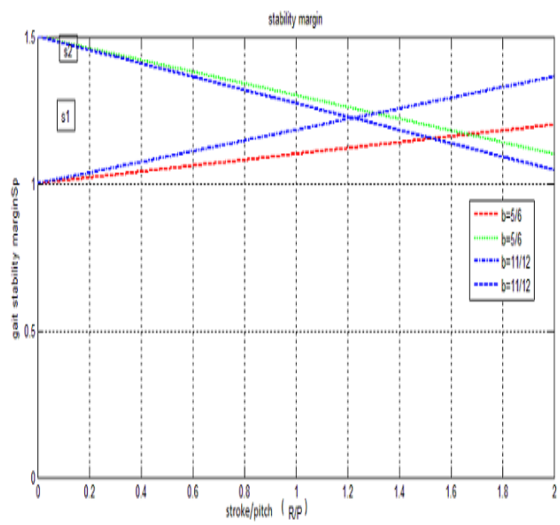

Fig.3: Stability margin(S) vs (stroke/pitch) ratio

IV. ANALYSIS OF EQUAL PHASE GAIT

Equal phase gait equally distribute the placing events over the locomotion cycle. Therefore it is sufficient the placing events on the left side only. There are two methods to distribute the placing events of the locomotion cycle.

4.1 *Half cycle equal phase gait*

In half cycle equal phase gait the placing event on one side are equally distributed in a half cycle. Due to symmetry the placing event on other side would be equally distributed in other half cycle.

For *2n-legged* machine, leg phase for half cycle described as,

$$\phi_{2m+1} = 1 - \frac{m}{2n}, m = 1, 2, \ldots n-1 \tag{10}$$

Therefore, in case of eight leg,

$$\phi_3 = \frac{7}{8}, \phi_5 = \frac{3}{4}, \phi_7 = \frac{5}{8}$$

By using these phase differences we can analyze the gait diagram for half cycle equal which are shown in "Fig.4",

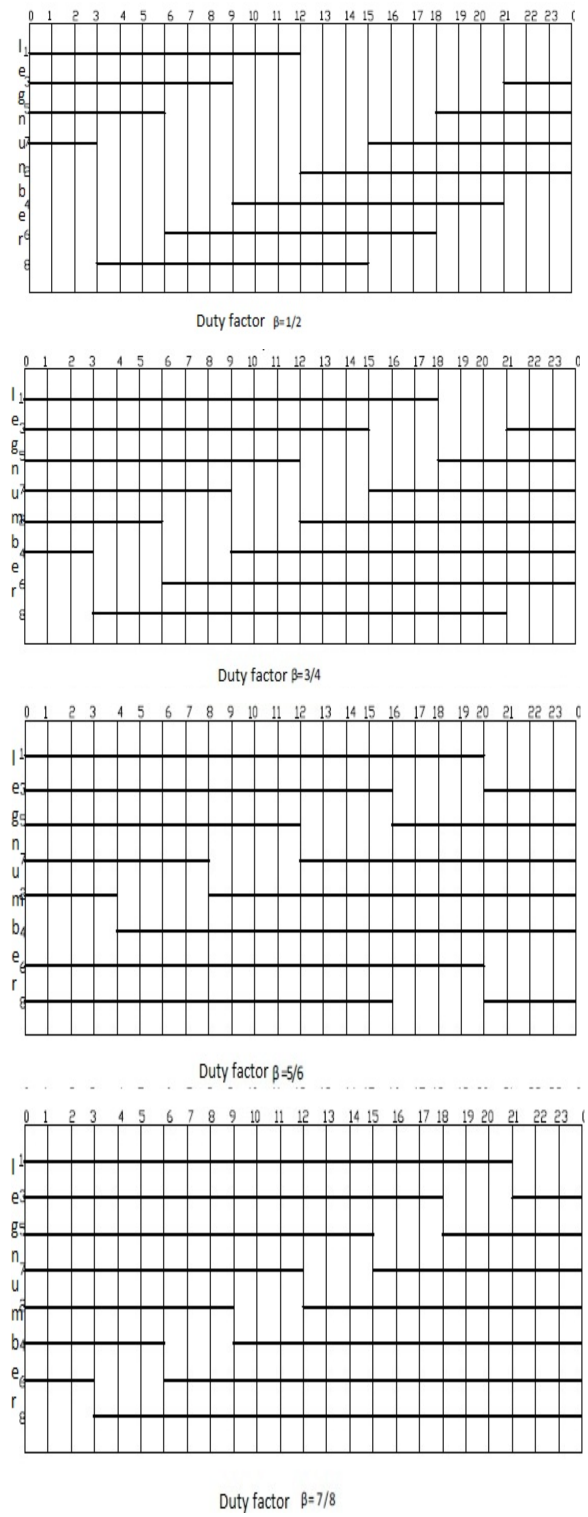

Fig. 4: Gait diagram for half cycle equal phase gait

Where we observed that for $\beta \le 1/2$ gait is unstable, because no feet on the other side are on ground.

Phase increment for half cycle gait is 1-1/(2n),which is 7/8 for Eight legged. Now, when foot 1 is lifted, local phase of foot 3, 5, 7 are

$$\psi_3 = \beta - \frac{7}{8}, \psi_5 = \beta - \frac{3}{4}, \psi_7 = \beta - \frac{5}{8}$$

For $1/2 \le \beta < 5/8$, ψ_3, ψ_5, ψ_7 are greater than β, so foot 3, 5 and 7 are in transfer phase. This is critical time since all foots on left side are in transfer phase. Hence gait is unstable for $\beta \le 5/8$ .When foot 5 is lifted, Local phase of foot 1, 3 and 7 are $\psi_1 = \beta - \frac{1}{4}, \psi_3 = \beta - \frac{1}{8}, \psi_7 = \beta - \frac{7}{8}$

Foot 1 is always on ground since $\beta - 1/4$ for β >1/2, and Foot7 is in transfer phase when $F(\beta - 7/8) > \beta$.

This is to be true when $(\beta - 7/8) < 0, or \beta < 7/8$. Hence, $5/8 \le \beta < 7/8$

So, phase of foot 8 relative to foot 5 is

$$\psi_8 = \beta - \frac{3}{8}$$

This is always less than duty factor β .Therefore foot 8 is on the ground. Position of Rear boundary is defined by foot 3 and 8 are,

$$P_3 = P + \frac{R}{2} - \left[\beta - \frac{1}{8}\right] \cdot \frac{R}{\beta}$$

$$P_8 = -P + \frac{R}{2} - \left[\beta - \frac{3}{8}\right] \cdot \frac{R}{\beta}$$

So, rear longitudinal stability margin when foot 5 is lifted is, $S_{l5} = -\frac{P_3 + P_8}{2}$

By putting values of $P3$ and $P8$ in this equation we get,

$$S_{l5} = \left[\frac{1}{2} - \frac{1}{4\beta}\right] . R \qquad (11)$$

When foot 7 is lifted, local phase of foot 5 and 8 are

$$\psi_5 = \beta - \frac{1}{8}, \psi_8 = \beta - \frac{1}{2}$$

Both $\psi_5 and \psi_8$ are less than duty factor β for all values of β lies between ½ and 1.Therefore foot 5 and 8 are on ground.

So, Position of foot 5 and 8 are,

$$P_5 = \frac{R}{2} - \left(\beta - \frac{1}{8}\right) . \frac{R}{\beta}$$

$$P_8 = -P + \frac{R}{2} - \left(\beta - \frac{1}{2}\right) . \frac{R}{\beta}$$

Hence rear stability margin S_{l7} when foot 7 is lifted is,

$$S_{l5} = -\frac{P_5 + P_8}{2} .$$

By putting values of $P5$ and $P8$ in this equation we get,

$$S_{l7} = \frac{P}{2} + \left[\frac{1}{2} - \frac{5}{16\beta}\right] .R \qquad (12)$$

Compare (11) and (12), by subtracting both, so

$$S_{l5} - S_{l7} = -\frac{P}{2} + \frac{R}{16\beta}$$

Since, pitch (P)>stroke (R) and for $\beta \le 5/8, S_{l5} < S_{l7}$

Therefore gait stability margin

$$S = \left[\frac{1}{2} - \frac{1}{4\beta}\right] .R \quad \text{for} \quad 5/6 \le \beta < 7/8 \qquad (13)$$

When $7/8 \le \beta < 1$, only critical time is when foot 7 is lifted. So gait stability margin for this case

$$S = \frac{P}{2} + \left[\frac{1}{2} - \frac{5}{16\beta}\right] .R \quad \text{for} \quad 7/8 \le \beta < 1 \qquad (14)$$

4.2 Full cycle equal phase gait

In full cycle equal phase gait the placing event on one side are equally distributed in a full cycle. Due to symmetry the placing event on other side would be equally distributed in other half cycle.

For *2n-legged* machine, leg phase for full cycle described as $\phi_{2m+1} = 1 - m/(n), m = 1,2,...n-1$

Therefore, in case of eight legs, phase increment is

$1 - 1/n = 1 - 1/4 = 3/4$ and phase differences of foot 3, 5 and 7 with respect to foot 1 are,

$\phi_3 = 3/4, \phi_5 = 1/2, \phi_7 = 1/4$

By using these phase difference we drawn gait diagram for eight legged full cycle equal phase gait which is shown in “Fig.5”.

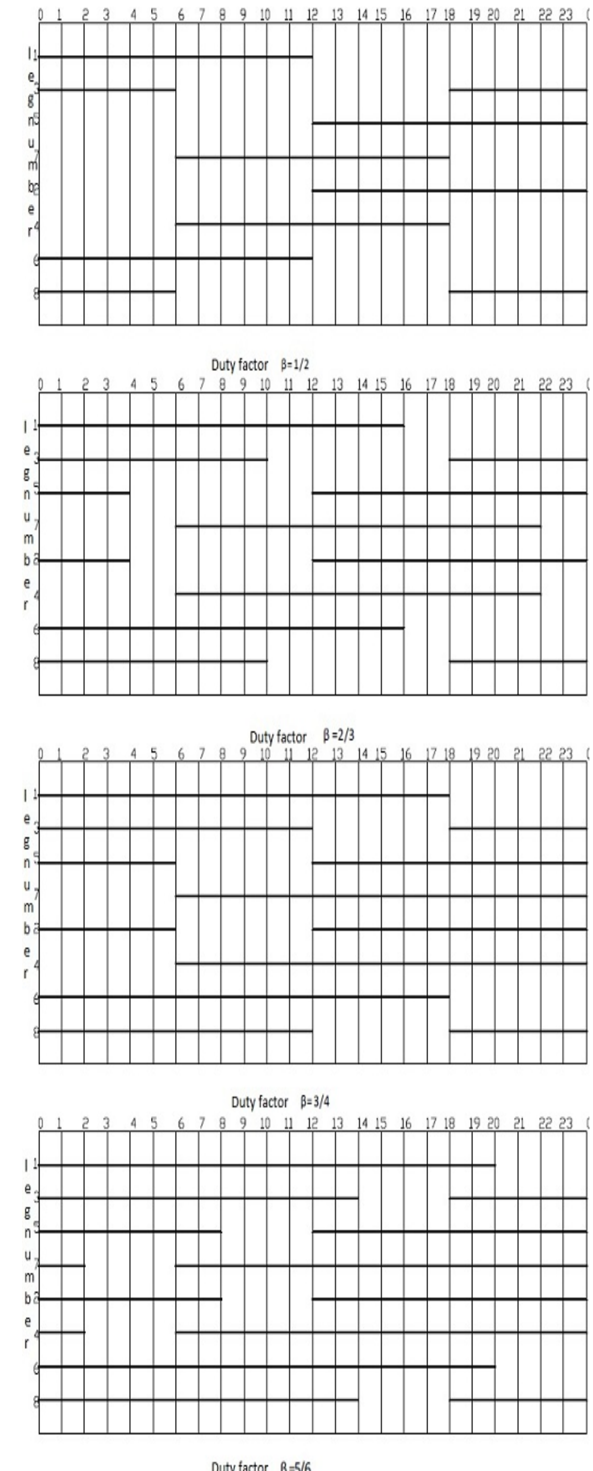

Fig. 5: Gait diagram for full cycle equal phase gait
In case of eight legged full cycle equal phase gait
Phase difference is 3/4 or 90º

Now, when foot 1 is lifted,

Local phase of foot 3, 5, and 7 are,

$$\psi_3 = \left(\beta - \frac{3}{4}\right), \psi_5 = \left(\beta - \frac{1}{2}\right), \psi_7 = \left(\beta - \frac{1}{4}\right)$$

Consider the case, when $\beta < 2/3$, local phase of foot7 ($\psi_7 = \beta - 1/4$) is less than duty factor β. Hence foot 7 is on the ground, and $\psi_5 = \beta - 1/2$ is also less than duty factor β. Therefore foot 5 is also on ground. In this case both foot 5 and foot 7 are on ground. Hence this is not a critical time.

Now, when foot 3 is lifted,

Local phase of foot 1, 5 and 7 are $\psi_1 = \beta - \frac{1}{4}, \psi_5 = \beta - \frac{3}{4}, \psi_7 = \beta - \frac{1}{2}$

Here, ψ_1, ψ_5, ψ_7 are greater than duty factor β for all values of $\beta \geq 1/2$. So, this is not a critical time.

When foot 5 is lifted,

Local phase of foot 1, 5 and 7 are,

$$\psi_1 = \beta - \frac{1}{2}, \psi_3 = \beta - \frac{1}{4}, \psi_7 = \beta - \frac{3}{4}$$

Foot 7 is in transfer phase when $F(\beta - 3/4) > \beta$. This is only true for $\beta - 3/4 < 0$, or $\beta < 3/4$

Therefore, for $\beta < 3/4$ foot 7 is always in transfer phase.

This is a critical time. Local phase of foot 8 relative to foot 5 is $\psi_8 = \beta - 1/4$. The position for foot 3 and 8 at this phase are,

$$P_3 = P + \frac{R}{2} - \left[\beta - \frac{1}{4}\right] \cdot \frac{R}{\beta}$$

$$P_8 = -P + \frac{R}{2} - \left[\beta - \frac{1}{4}\right] \cdot \frac{R}{\beta}$$

So, rear longitudinal stability margin when foot 5 is lifted is,

$$S_{l5} = -\frac{P_3 + P_8}{2}$$

By putting values of $P3$ and $P8$ in this equation we get,

$$S_{l5} = \left[\frac{1}{2} - \frac{1}{4\beta}\right] .R \quad \text{for} \quad 1/2 \leq \beta < 3/4 \qquad (15)$$

Now, when foot 7 is lifted, local phase of foot 5 and foot 8 with respect to foot 7 are $\psi_5 = \beta - 1/4, \psi_8 = \beta - 1/2$

Therefore, positions of foot 5 and foot 8 at this instant are

$$P_5 = \frac{R}{2} - \left[\beta - \frac{1}{4}\right] \cdot \frac{R}{\beta}$$

$$P_8 = -P + \frac{R}{2} - \left[\beta - \frac{1}{2}\right] \cdot \frac{R}{\beta}$$

So, rear longitudinal stability margin for leg 7 is

$$S_{l7} = -\frac{P_5 + P_8}{2}.$$

By putting values of $P3$ and $P8$ in this equation we get,

$$S_{l7} = \frac{P}{2} + \left[\frac{1}{2} - \frac{3}{8\beta}\right] .R \quad \text{for} \quad 3/4 \leq \beta < 1 \qquad (16)$$

Compare (15) and (16), by subtracting both, so

$$S_{l5} - S_{l7} = -\frac{P}{2} + \frac{R}{16\beta}$$

Since, pitch (P)>stroke (R) and for $\beta \leq 3/4, S_{l5} < S_{l7}$

Therefore gait stability margin

$$S = \left[\frac{1}{2} - \frac{1}{4\beta}\right] .R \quad \text{for} \quad 1/2 \leq \beta < 3/4 \qquad (17)$$

When $3/4 \leq \beta < 1$, only critical time is when foot 7 is lifted. So gait stability margin for this case

$$S = \frac{P}{2} + \left[\frac{1}{2} - \frac{5}{16\beta}\right] .R \quad \text{for} \quad 3/4 \leq \beta < 1 \qquad (18)$$

From "Fig.2", and "Fig.4" we observe that for eight legged robot, gait diagram of half cycle equal phase gait at duty factor $\beta = 7/8$ is identical to that of wave gait for same duty factor, and from "Fig.3" and "Fig.5", the gait diagram for full cycle equal phase gait at duty factor $\beta = 3/4$ is identical to that of wave gait at duty factor $\beta = 3/4$. longitudinal stability margin of eight legged half cycle equal phase gait and full cycle equal phase gait against different values of duty factors, which is shown in "Fig.6".

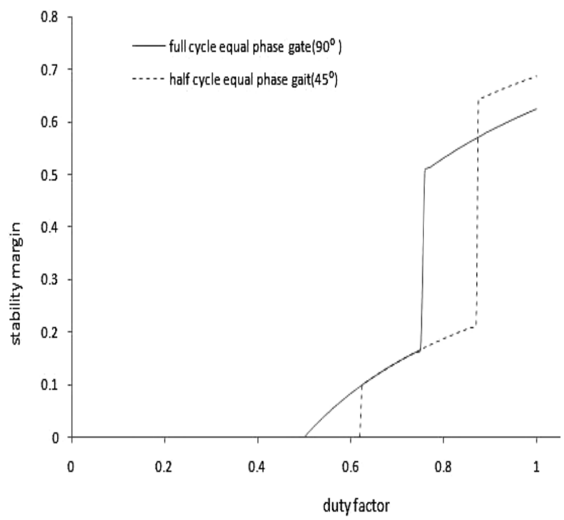

Fig. 6: Graph of stability margin Vs Duty factor

By using (13),(14) and (17),(18) we plot a graph for stability margin versus duty factor.

In "Fig.6" solid line shows the gait stability margin for full cycle equal phase gait and dotted lines shows gait stability margin of half cycle equal phase gait.

From "Fig.6" we can see that there are two discontinuities in stability margin of half cycle equal phase gait at duty factor $\beta = 5/8$ and $\beta = 7/8$. At $\beta = 5/8$ the longitudinal rear stability margin jumps from unstable value to $S_l = 0.1$ and at duty factor $\beta = 7/8$ the longitudinal rear stability margin jumps from 0.213 to 0.643, these changes can be analyzed by gait diagram of half cycle equal phase gait shown in "Fig.4". For duty factor $\beta = 1/2$, there is no foot on left side are on the ground between lifting of foot 1 and placing of foot 7. So it is unstable, it becomes stable when duty factor β reaches to 7/8. At duty factor $\beta = 7/8$, half cycle equal phase gait jumps to that of wave gait since gait diagram of both wave gait and half cycle equal phase gait at this duty factor are equal. For full cycle equal phase gait there is discontinuity at duty factor $\beta \leq 3/4$, where stability margin S_l jumps from 0.16 to 0.50. For duty factor $\beta \leq 1/2$ gait is unstable, since between lifting of foot 1 and placing of foot 7 there is no foot on left side are on ground. For duty factor $\beta = 3/4$ the stability margin of full cycle equal phase gait jumps to that of wave gait, this jump can be seen by observing "Fig.6".

V. CONCLUSION

For eight-legged half cycle equal phase gait, the gait stability margin is $S = [1/2 - 1/(4\beta)].R$ for $5/6 \leq \beta < 7/8$, and

$S = P/2 + [1/2 - 5/(16\beta)].R$ for $7/8 \leq \beta < 1$.

For eight-legged full cycle equal phase gait, the gait stability margin is $S = [1/2 - 1/(4\beta)].R$ for $1/2 \leq \beta < 3/4$, and

$S = P/2 + [1/2 - 5/(16\beta)].R$ for $3/4 \leq \beta < 1$. Half cycle equal phase gait at duty factor $\beta = 7/8$ jumps to wave gait, and full cycle equal phase gait jumps to wave gait at duty factor $\beta = 3/4$.Hence wave gait is more stable than equal phase gait for duty factor $\beta \geq 3/4$.

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