# Jacobian Integral of the Equations of Motion of The System in the Case of Circular Orbit of the Centre of Mass

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**Abstract:** A Study of the effect of earth's oblateness and magnetic force on the motion and stability of the system of two cable connected satellites for the circular orbit of the centre of mass. We have got a set of non-linear, non-homogenous and non-autonomous equation. The general solution of these equations can not be obtained even for the circular orbit of the centre of mass of the system. So, we have analysed the effected of the earth's oblateness and magnetic force on the existence and behaviour of different equilibrium positions of the system. Also discuss about Hooke's modulus of elasticity and concluded that its equilibrium position is stable in the Liapunov.

**Key words:** Hooke's modulus of elasticity, Non-Linear and Non-Homogenous, Equilibrium positions of the system, Jacobian integral

## I. INTRODCUTION:

The Jacobi integral is a formula of incorporating various parameters of the system with some variants for particular cases. An approach of describing the effect of earth's oblateness and magnetic force on the motion and stability of the system of two cable connected satellites for the circular orbit of the centre of mass. We have got a set of non-linear, non-homogenous and non-autonomous equation. In this approach, the general solution of these equations can not be obtained even for the circular orbit of the centre of mass of the system. So, we have analysed the effected of the earth's oblateness and magnetic force on the existence and behaviour of different equilibrium positions of the system. Also discuss about Hooke's modulus of elasticity and concluded that its equilibrium position is stable in the Liapunov.

Here, we assume that the centre of mass of the system moves along a circular orbit.

Thus, e = 0

$$\therefore \rho = \frac{1}{1+ecosv} = 1$$

$$\therefore \rho' = 0 \quad \ldots (1.1.1)$$

Hence, the equation of motion takes the following form:

$$x'' - 2y' - 3x - 4\beta x = -\bar{\lambda}_\alpha [1 - \frac{I_0}{r}]x + A\, cosi$$

$$y'' + 2x' + \beta y = -\bar{\lambda}_\alpha [1 - \frac{I_0}{r}]y \quad \ldots (1.1.2)$$

Where $A = \frac{\left(\frac{m_2}{m_1 + m_2}\right)\left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)\mu_E}{\sqrt{\mu p}}$

$$\bar{\lambda}_\alpha = \left(\frac{P^3 \lambda}{\mu I_0}\right) . \left(\frac{m_1 + m_2}{m_1 m_2}\right)$$

$$\beta = \frac{3k_2}{P^2} \; and \; r = \sqrt{x^2 + y^2}$$

In case of circular orbit, dashes will represent differentiation with respect to $\tau$ where (v is replaced by $\tau$ )

$$\therefore \tau = \omega t \quad \ldots (1.1.3)$$

$\omega$ being the angular velocity of the centre of mass of the system.

The condition of the constrained will assumes the form.

$$x_2^2 + y_2^2 \le I_0^2 \quad \ldots (1.1.4)$$

The motion will be described by the system of equations (1.1.2) in which $\bar{\lambda}_\alpha\,(t) \neq 0$, we have from (1.1.2)

$$x'' - 2y' - (3 + 4\beta)x = -\bar{\lambda}_\alpha [1 - \frac{I_0}{r}]x + A\, cosi$$

$$y'' + 2x' + \beta y = -\bar{\lambda}_\alpha [1 - \frac{I_0}{r}]y \quad \ldots (1.1.5)$$

The condition for constraint will assume the form

$$x^2 + y^2 \le I_0^2 \quad \ldots (1.1.6)$$

For the critical value of $\bar{\lambda}_{\alpha 0} = \bar{\lambda}_{\alpha 0}(t_0)$, the system will be moving like a dumbbell satellite and hence the new set of equations (1.1.5) does not contain time explicitly and therefore, there must exist Jacobian integral of the problem.

Multiplying the two equations of (1.1.5) by $2x'$ and $2y'$ respectively and adding, we get after integration of Jacobian integral of the form:

$$x'^2 + y'^2 = (3 + 4\beta)x^2 - \beta y^2 - \tilde{\lambda}_\alpha (x^2 + y^2) + 2\tilde{\lambda}_\alpha I_0 (x^2 + y^2)^{1/2} + 2Axcosi + h \quad \ldots (1.1.7)$$

Where h is the constant of integration. The curve of zero velocity can be written in the form:

$$(3 + 4\beta)x^2 - \beta y^2 - \tilde{\lambda}_\alpha (x^2 + y^2) + 2\tilde{\lambda}_\alpha I_0 (x^2 + y^2)^{1/2} + 2A\, x\, cosi + h = 0 \quad \ldots (1.1.8)$$

$\therefore$ we conclude that the satellite $m_1$ will move inside the boundary of different curves of zero velocity represented by (1.1.8) for different values of Jacobian constant h.

## II. EQUILIBRIUM SOLUTION OF THE PROBLEM:

If the system is moving with effective constraint and the cable remains tight, we have obtained the differential equations

$$x'' - 2y' - 3x - 4\beta x = -\tilde{\lambda}_\alpha \left(1 - \frac{I_0}{r}\right) x + A\, cosi$$

$$y'' + 2x' + 4\beta y = -\tilde{\lambda}_\alpha \left(1 - \frac{I_0}{r}\right) y \qquad \ldots (1.2.1)$$

The equilibrium positions of the system are given by the constant values of the co-ordinate in rotating frame of reference.

Let $x = x_0$

$y = y_0$

Where $x_0$ and $y_0$ are constants, give equilibrium position of the system.

$\therefore \quad x' = x_0' = 0 = x''$

$y' = y_0' = 0 = y''$

Putting these values in (1.2.1) we get

$$-3x_0 - 4\beta x_0 = -\bar{\lambda}_\alpha \left(1 - \frac{I_0}{r}\right) x_0 + A\, cosi$$

$$\beta y_0 = -\bar{\lambda}_\alpha \left(1 - \frac{I_0}{r}\right) y_0 \qquad \ldots (1.2.2)$$

Where $r_0 = \sqrt{x_0^2 + y_0^2}$

Now, we discuss two particular solutions to the system of equations (1.2.2) which will be obtained as follows:

From the two equations of (1.2.2) we observe that

$x_0 = 0$

$y_0 = 0$

Hence, there will be two positions of equilibrium:

(i) **The First Equilibrium Condition**: -
The system may be wholly extended along x – axis. Let this position be (a , 0).

In this case,

$x_0 = \neq ,0, y_0 = 0, r = x_0.$

$$-3x_0 - 4\beta x_0 = -\bar{\lambda}_\alpha \left(1 - \frac{I_0}{x_0}\right) x_0 + A\, cosi$$

$$= -\bar{\lambda}_\alpha x_0 + \bar{\lambda}_\alpha I_0 + A\, cosi$$

or, $\quad x_0(\bar{\lambda}_\alpha - 4\beta - 3) = \bar{\lambda}_\alpha I_0 + A\, cosi$

$\therefore x_0 = \dfrac{\bar{\lambda}_\alpha I_0 + A\, cosi}{\bar{\lambda}_\alpha - 4\beta - 3}$

Here, $x_0$ is positive and hence, $\bar{\lambda}_\alpha I_0 + A\, cosi$ will be taken positive throughout our discussion.

$\therefore$ the first equilibrium condition is given by

$$\left[\frac{\bar{\lambda}_\alpha I_0 + A\, cosi}{\bar{\lambda}_\alpha - 4\beta - 3}, 0\right] \qquad \ldots (1.2.3)$$

(ii) **Second equilibrium condition:-**

The system may be extended along y – axis, $y \neq 0$. We get from the second equation of (1.2.2)

$\beta y_0 = -\bar{\lambda}_\alpha \left(1 - \frac{I_0}{r_0}\right) y_0$

$or, y_0 \left[\beta + \bar{\lambda}_\alpha \left(1 - \frac{I_0}{r_0}\right)\right] = 0$

But $y_0 \neq 0$

$\therefore\ \beta + \bar{\lambda}_\alpha \left(1 - \frac{I_0}{r_0}\right) = 0$

$or, \bar{\lambda}_\alpha \left(1 - \frac{I_0}{r_0}\right) = -\beta$

or, $\bar{\lambda}_\alpha + \beta = \bar{\lambda}_\alpha \frac{I_0}{r_0}$

$or, r_0 = \dfrac{\bar{\lambda}_\alpha I_0}{\bar{\lambda}_\alpha + \beta}$

$or, \quad x_0^2 + y_0^2 = \left[\dfrac{\bar{\lambda}_\alpha I_0}{\bar{\lambda}_\alpha + \beta}\right]^2$

$$y_0^2 = \left[\frac{\bar{\lambda}_\alpha I_0}{\bar{\lambda}_\alpha + \beta}\right]^2 - x_0^2 \qquad \ldots (1.2.4)$$

Now, from 2nd equation of (1.2.2), we get

$$or,\ \bar{\lambda}_\alpha \left(1 - \frac{I_0}{r_0}\right) = -\beta \qquad \ldots (1.2.5)$$

$\therefore$ from the first equation of (1.2.2) by using (1.2.5),

We have,

$-3x_0 - 4\beta x_0 = \beta x_0 + A\, cosi$

or, $\quad x_0(5\beta + 3) = -A\, cosi$

$$\therefore x_0 = (-A\, cosi)/(5\beta + 3) \qquad \ldots (1.2.6)$$

Using equation (1.2.6) in (1.2.4), we get

$$y_0^2 = \left\{\frac{\bar{\lambda}_\alpha I_0}{\bar{\lambda}_\alpha + \beta}\right\}^2 - \left\{\frac{A\, cosi}{5\beta + 3}\right\}^2$$

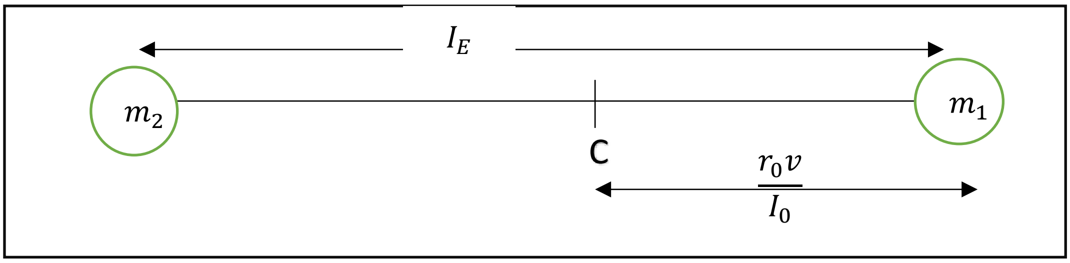
$$y_0 = \pm[\{\frac{\tilde{\lambda}_\alpha I_0}{(\tilde{\lambda}_\alpha + \beta)}\}^2 - \left\{\frac{A\, cosi}{5\beta + 3}\right\}^2]^{1/2}$$

∴ The 2nd equilibrium position is given by

$$\left[\left\{\frac{-A\ cosi}{(5\beta+3)}\right\}, \pm\left[\left\{\frac{\bar{\lambda}_\alpha I_0}{\bar{\lambda}_\alpha+\beta}\right\}^2 - \left\{\frac{A\ cosi}{5\beta+3}\right\}^2\right]^{1/2}\right] \quad \text{... (1.2.7)}$$

Thus, we have obtained the co-ordinates of the points of two equilibrium positions of the system as given in (1.2.3) and (1.2.7).

## III. THE VALUE OF THE MODULUS OF ELASTICITY:




We suppose that the extended length of the cable connecting the two satellites is $I_E$ at any equilibrium position and $r_0$ i.e; the length of normalized extended cable between the centre of mass of the system and the satellite $m_1$. Hence, actual extended length of the cable between $m_1$ and the centre of mass will be $\frac{r_0 v}{I_0}$ where v is given by $v = I_0 \frac{m_2}{M}$.

Now, taking moments of different masses about the satellite $m_1$ in equilibrium position,

$$m_2 I_E = (m_1+m_2)\left(\frac{r_0 v}{I_0}\right)$$

$$or, \quad m_2 I_E = (m_1+m_2)\left(\frac{r_0}{I_0}\right).\left(\frac{I_0 m_2}{M}\right) \quad \left[\therefore v = \frac{I_0 m_2}{M}\right]$$

$$or, \ I_E = r_0 \quad \text{... (1.3.1)}$$

We consider the two equilibrium positions of the system separately for obtaining the value of Hooke's modulus of elasticity.

(i) **First Equilibrium Positiion**;
In this case;

$$r_0 = a = x_0 = \frac{\bar{\lambda}_\alpha I_0 + A\ cosi}{\bar{\lambda}_\alpha - 4\beta - 3} \quad \text{... (1.3.2)}$$

Comparing equations (1.3.1) and (1.3.2), we get,

$$I'_E = \frac{\bar{\lambda}_\alpha I_0 + A\ cosi}{\bar{\lambda}_\alpha - 4\beta - 3} \quad \text{... (1.3.3)}$$

Where $I'_E$ is the stretched length of the cable in the first equilibrium position
Since,

$$\bar{\lambda}_\alpha = \left(\frac{P^3 \lambda}{\mu I_0}\right).\left\{\frac{m_1+m_2}{m_1.m_2}\right\}$$

$$\lambda = \left(\frac{\mu I_0}{P^3}\right).\left\{\frac{m_1.m_2}{m_1+m_2}\right\}\bar{\lambda}_\alpha$$

Finding the value of $\bar{\lambda}_\alpha$ from (1.3.3) and putting this value of $\bar{\lambda}_\alpha$ in the above, we get,

$$\lambda = \left(\frac{\mu m_1 m_2 I_0}{P^3(m_1+m_2)}\right).\frac{\{3I'_E + 4\beta I'_E + A\,cosi\}}{(I'_E - I_0)} > 0 \qquad \text{... (1.3.4)}$$

The relation (1.3.4) gives a meaningful value of $\lambda$ in the case of the first equilibrium position.

In this case, we may also obtain the length of the stretched cable $I'_E$ from (1.3.4) in the form

$$I'_E = \frac{-A\,cosi\,.\mu m_1 m_2 - \lambda P^3(m_1+m_2)I_0}{3\mu m_1.m_2 I_0 - \lambda P^3(m_1+m_2) + 4\beta\mu m_1.m_2 I_0} \qquad \text{... (1.3.5)}$$

**(ii) Second Equilibrium Position**

In this case

$$r_0 = \sqrt{x_0^2+y_0^2} = \sqrt{\left(\frac{A\,Cosi}{5\beta+3}\right)^2 + \left(\frac{\bar{\lambda}_\alpha I_0}{\bar{\lambda}_\alpha+\beta}\right)^2 - \left(\frac{A\,cosi}{5\beta+3}\right)^2}$$

$$= \sqrt{\frac{(\bar{\lambda}_\alpha+\beta)^2(A\,cosi)^2 + \bar{\lambda}_\alpha{}^2 I_\alpha{}^2(5\beta+3)^2 - (A\,cosi)^2.(\bar{\lambda}_\alpha+\beta)^2}{(5\beta+3)^2.(\bar{\lambda}_\alpha+\beta)^2}}$$

$$= \sqrt{\frac{\bar{\lambda}_\alpha{}^2 I_\alpha{}^2(5\beta+3)^2}{(5\beta+3)^2.(\bar{\lambda}_\alpha+\beta)^2}}$$

$$i.e.;\ r_0 = b = \frac{\bar{\lambda}_\alpha I_0}{(\bar{\lambda}_\alpha+\beta)} \qquad \text{... (1.3.6)}$$

*comparing* (1.3.1) and (1.3.6), we get

$$I'_E = r_0 = b = \frac{\bar{\lambda}_\alpha I_0}{(\bar{\lambda}_\alpha+\beta)} \qquad \text{... (1.3.7)}$$

Where $I'_E$ being the extended length of the cable in the second equilibrium position.

Equation (1.3.7) relates to motion of the system with unextended string or loose string. In this case $\lambda$, the Hooke's modulus of elasticity, is not positive and hence it does not give the meaningful value of $\lambda$. therefore, the second position of equilibrium is untenable.

In this way, we conclude that only the first position of equilibrium provides a significant value of $\lambda$. And the other position gives meaningless value of $\lambda$.

Therefore, we shall establish the stability for the system in the first position of equilibrium (a, 0) only.

## IV. STABILITY OF THE SYSTEM:

We shall study the stability of the first equilibrium position of the system in the liapunov's sense. The first equilibrium position is given as

x = a, y = 0

Let us suppose that there are small variations in the co-ordinates at the given equilibrium position.

Let $\delta_1 \, and \, \delta_2$ be small variations in the $x_0 \, and \, y_0$ co-ordinates respectively for a given position of equilibrium.

$$\therefore \; x = a + \delta_1, \qquad y = 0 + \delta_2$$

$$\therefore \; x' = \delta_1' \quad , \; y' = \delta_2'$$

$$x'' = \delta_1'' \quad , \; y'' = \delta_2''$$

Putting these values in the set of equations (1.2.1) we get

$$\delta_1'' - 2\delta_2' - 3(a + \delta_1) - 4\beta(a + \delta_1) = -\bar{\lambda}_\alpha \left(I - \frac{I_0}{r_1}\right)(a + \delta_1) + A \, cosi$$

$$\delta_2'' + 2\delta_1' + \beta\delta_2 = -\bar{\lambda}_\alpha \left(I - \frac{I_0}{r_1}\right).\delta_2 \qquad \dots (1.4.1)$$

Where, $r_1^2 = (a + \delta_1)^2 + \delta_2^2$ ... (1.4.2)

The variational equations of (1.4.1) will have the same Jacobi's integral as the original set of equations given by (1.3.1)

This will take the form

$$(\delta_1')^2 + (\delta_2')^2 = (3 + 4\beta)(a + \delta_1)^2 - \beta\,\delta_2^2 - \bar{\lambda}_\alpha\{(a + \delta_1)^2 + \delta_2^2\} + 2\,\bar{\lambda}_\alpha I_0\{(a + \delta_1)^2 + \delta_2^2\}^{1/2} + 2A(a + \delta_1)cosi + h_1 \qquad \dots (1.4.3)$$

Where $h_1$ is the constant of integration.

In this way we have obtained the equation (1.4.3) as the Jacobi's integral for the system of variational equations.

Expanding the terms, the equation (1.4.3) can be written as –

$$V(\delta_1, \delta_2, \delta_1', \delta_2') = (\delta_1')^2 + (\delta_2')^2 + (\delta_1)^2\left[-(3 + +4\beta) + \bar{\lambda}_\alpha\right] + (\delta_2)^2\left[\bar{\lambda}_\alpha - \left(\frac{I_\alpha \bar{\lambda}_\alpha}{a}\right) + \beta\right]$$
$$+ \delta_1\left[-2(3 + 4\beta)a + 2a\bar{\lambda}_\alpha - 2\bar{\lambda}_\alpha I_0 - 2A\,cosi\right]$$
$$+ \left[a^2\bar{\lambda}_\alpha - (3 + 4\beta)a^2 - 2a\bar{\lambda}_\alpha I_0 - 2a\,A\,cosi\right] + 0(3) = h_1 \qquad \dots (1.4.4)$$

Where 0(3) stands for the third and higher order terms in the small quantities $\delta_1 \, and \, \delta_2$.

Now, we shall take with the help of Liapunov's theorem on stability for obtaining the sufficient conditions for stability. The Jacobian integral V is the integral of the system for the variational equatioins (1.4.1), its differential equation taken along the trajectory of the system must vanish identically.

Therefore, the only condition that the unilateral position be stable in the Liapunov's sense is that V must be positive definite. For making the function a positive definite function it is necessary that the function (1.4.4) does not have the term of the first order in the variables shown in its argument and the terms of the second order must satisfy, Sylvester's conditions for positive definite form. The third and higher order terms will have no effect on the sign of the function V. Hence. We conclude that the sufficient conditions for the stability of the system at the equilibrium position in the Laipunov's sense are

(i) $-2(3 + 4\beta)a + 2a\bar{\lambda}_\alpha - 2\bar{\lambda}_\alpha I_0 - 2A\,cosi = 0$

(ii) $\bar{\lambda}_\alpha - (3 + 4\beta) > 0$

(iii) $\bar{\lambda}_\alpha - \left(\frac{\bar{\lambda}_\alpha I_0}{a}\right) + \beta > 0$ ... (1.4.5)

We now analyse the several conditions of (1.4.5) for stability of the system at the given equilibrium position separately.

**Condition (i)**

$$L.H.S. = -2(3+4\beta)a + 2a\bar{\lambda}_\alpha - 2\bar{\lambda}_\alpha I_0 - 2A\, cosi$$

$$= 2a(\bar{\lambda}_\alpha - 3 - 4\beta) - 2\bar{\lambda}_\alpha I_0 - 2A\, cosi$$

$$= 2\left[\frac{\bar{\lambda}_\alpha I_0 + A\, cosi}{\bar{\lambda}_\alpha - 3 - 4\beta}\right](\bar{\lambda}_\alpha - 3 - 4\beta) - 2\bar{\lambda}_\alpha I_0 - 2A\, cosi$$

$$= 2\bar{\lambda}_\alpha I_0 + 2A\, cosi - 2\bar{\lambda}_\alpha I_0 - 2A\, cosi = 0$$

∴ The first condition is satisfied identically

**Condition (ii)**

$$L.H.S = \bar{\lambda}_\alpha - (3+4\beta)$$

$$= (\bar{\lambda}_\alpha I_0 + A\, cosi)/a > 0$$

$$\left[\because a = \frac{\bar{\lambda}_\alpha I_0 + A\, cosi}{\bar{\lambda}_\alpha - 3 - 4\beta} > 0\right]$$

$$= positive$$

∴ the second condition is also satisfied identically.

**Condition (iii)**

$$L.H.S = \bar{\lambda}_\alpha - \bar{\lambda}_\alpha I_0/a + \beta$$

$$= \bar{\lambda}_\alpha - \bar{\lambda}_\alpha I_0.\left[\frac{\bar{\lambda}_\alpha - 4\beta - 3}{\bar{\lambda}_\alpha I_0 + A\, cosi}\right] + \beta$$

$$= \frac{\bar{\lambda}_\alpha(I_0\bar{\lambda}_\alpha + A\, cosi) - \bar{\lambda}_\alpha I_0(\bar{\lambda}_\alpha - 4\beta - 3) + \beta(\bar{\lambda}_\alpha I_0 + A\, cosi)}{\bar{\lambda}_\alpha I_0 + A\, cosi}$$

$$= \frac{\bar{\lambda}_\alpha{}^2 I_0 + \bar{\lambda}_\alpha A\, cosi - \bar{\lambda}_\alpha{}^2 I_0 + 4\bar{\lambda}_\alpha I_0\beta + 3(\bar{\lambda}_\alpha I_0) + \bar{\lambda}_\alpha \beta I_0 + \beta\, A\, cosi}{\bar{\lambda}_\alpha I_0 + A\, cosi}$$

$$= \frac{\bar{\lambda}_\alpha(5I_0\beta + 3\, I_0 + A\, cosi) + \beta(A\, cosi)}{\bar{\lambda}_\alpha I_0 + A\, cosi}$$

$$= \frac{\bar{\lambda}_\alpha(3\, I_0 + 5\beta\, I_0 + A\, cosi) + \beta(A\, cosi)}{a(\bar{\lambda}_\alpha - 4\beta - 3)} \qquad \therefore a = \frac{\bar{\lambda}_\alpha I_0 + A\, cosi}{\bar{\lambda}_\alpha - 4\beta - 3} > 0$$

$$= positive$$

Hence, the third condition is also satisfied identically.

Thus, we see that all the three conditions of (1.4.5) for stability are satisfied identically.

Hence, we conclude that the equilibrium is stable at (a, 0) in the Liapunov's sense.

## V. CONCLUSION:

The equilibrium solution of the problem and their stability in case of the circular orbit of the centre of mass of the system. On the basis of the analysis of the free motion of the system it has been proved that all the motions of the system are bound to be converted into constrained one and hence the Jacobi's integral has been deduced for the motion. Only one equilibrium position has been obtained and meaningful value of the Hooke's modulus of elasticity $\lambda$ for the connecting cable has been obtained at the equilibrium position. Moreover, it has been concluded that only this equilibrium position is stable in the Liapunov's sense.

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