Effect of Shadow of the Earth Due to Solar Radiation Pressure, Magnetic Force and Earth's Oblateness on the Non-Linear Oscillation of the System in a Circular Orbit of the Centre of Mass of the System.

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ABSTRACT

We have studied the non-linear oscillation of the system of the satellites connected by light, flexible and extensible cable under the influence of magnetic force, the shadow of the earth due to solar radiation pressure and earth oblateness in the case of circular orbit of the Centre of mass of the system. The non-linear terms present in the equations of motion of the system are taken into consideration. First of all we have derived equations of motion for non-linear oscillations of the system having almost periodic oscillations due to Malkin. An attempt has been made to analyse the motion and stability of the system analytically. As there is no periodic terms in the equation of motion, so only non-resonant solution have been obtained and shown to be stable.

KEYWORDS: Stability, Solar radiation pressure, Earth Magnetic force, Satellites, Circular orbit, Oblateness of earth.

1. INTRODUCTION

This paper is devoted to study the effect of shadow of the earth due to solar radiation pressure, magnetic force and earth's oblateness on the non-linear oscillation and stability of two satellites connected by light, flexible and extensible cable in the central gravitational force in a circular orbit of the Centre of mass of the system in case of two dimensional motion**.** Beletsky, V.V. is the pioneer worker in this field. This paper is an attempt towards the generalisation of works done by him.

2. EQUATIONS OF MOTION FOR NON-LINEAR OSCILLATION.

The equation of motion of one of the two satellites when the centre of mass moves along a circular orbit in Nechvill's coordinates can be obtained by exploiting Lagrange's equation of motion of first kind in the form:

$$x'' - 2y' - (3+4B)x - \frac{A\cos\epsilon\,\sin v}{\pi} = -\overline{\lambda}_\alpha\left[1-\frac{l_0}{r}\right]x - C\text{Cosi}$$

and $$y'' + 2x' + By = -\overline{\lambda}_\alpha\left[1-\frac{l_0}{r}\right]y$$

……..……. (2.1)

Where, $A = \frac{p^3}{\mu}\left[\frac{B_1}{m_1} - \frac{B_2}{m_2}\right]$, $B = \frac{3K_2}{p^2}$, $C = \left(\frac{Q_1}{m_1} - \frac{Q_2}{m_2}\right)\sqrt{\frac{\mu_E}{\mu p}}$, $\overline{\lambda_\alpha} = \frac{p^3}{\mu}\lambda_\alpha = \frac{p^3}{\mu}\left(\frac{m_1+m_2}{m_1 m_2 l_0}\right)\lambda$

and $r^2 = x^2 + y^2$

Here, dashes denote differentiations with respect to T and T = wt where w is the angular velocity in case of circular orbit of the centre of mass and t is the time.

The condition of constraint is given by

$$x^2 + y^2 \le l_o^2 \qquad \text{……..…… (2.2)}$$

It has been found in the previous chapter that there exits an equilibrium position (a,0,0) and has been seen to be stable in the sense of Liyapunov.

Now we want to discuss the effect of the shadow of the earth due to solar radiation pressure, magnetic force and oblateness of the earth on the equilibrium position (a,0) for non-linear oscillation of the system.

For this, Let η_1 and η_2 be small variations in x and y coordinates at the given equilibrium point (a, 0) of the system.

Then, we have

$$x = a + \eta_1 \quad \text{and} \quad y = \eta_2$$
$$x' = \eta_1' \quad \text{and} \quad y' = \eta_2' \qquad \text{………….. (2.3)}$$
$$x'' = \eta_1'' \quad \text{and} \quad y'' = \eta_2''$$

Now,

$$r^2 = (a + \eta_1)^2 + \eta_2^2 = a^2 + 2a\eta_1 + \eta_1^2 + \eta_2^2 = a^2\left[1 + \frac{2a\eta_1 + \eta_1^2 + \eta_2^2}{a^2}\right]$$

$$r = a\left[1 + \frac{2a\eta_1 + \eta_1^2 + \eta_2^2}{a^2}\right]^{1/2} \qquad \text{………….. (2.4)}$$

But at the equilibrium position, we have

$$r_0 = a \qquad \text{……………. (2.5)}$$

Using (2.5) in (2.4), we get

$$r = r_0\left[1 + \frac{2r_0\eta_1 + \eta_1^2 + \eta_2^2}{r_0^2}\right]^{\frac{1}{2}}, \quad \frac{1}{r} = \frac{1}{r_0}\left[1 + \frac{2r_0\eta_1 + \eta_1^2 + \eta_2^2}{r_0^2}\right]^{-\frac{1}{2}} \qquad \text{…………… (2.6)}$$

Now expanding the right hand side of (2.6) and retaining terms only up to third order in infinitesimals η_1 and η_2, we get after some simplifications

$$\frac{1}{r} = \frac{1}{r_0} - \frac{\eta_1}{r_0^2} + \frac{\eta_1^2}{r_0^3} - \frac{\eta_2^2}{2r_0^3} + \frac{3}{2}\frac{\eta_1^2}{r_0^4} + \frac{3}{2}\frac{\eta_1\eta_2^2}{r_0^4} \qquad \text{………….. (2.7)}$$

Putting the values from (2.3), due to small variations, in the system of equations (2.1), we get a new, set of variational equations of motion for the non-linear oscillations of the system in the form:

$$\eta_1'' - 2\eta_2' - (3 + 4B)(r_0 + \eta_1) - \frac{A\cos\epsilon\,\sin v}{\Pi} = -\bar{\lambda}_\alpha\left[1 - \frac{l_0}{r}\right](r_0 + \eta_1) - C\cos i$$

and

$$\eta_2'' + 2\eta_1' + B\eta_2 = -\bar{\lambda}_\alpha\left[1 - \frac{l_0}{r}\right]\eta_2 \qquad \text{……………. (2.8)}$$

Now substituting the values $\frac{1}{r}$ of from (2.6) in (2.8), we get after neglecting fourth and higher order terms in infinitesimals η_1 and η_2 as:

$$\eta_1'' - 2\eta_2' - (3 + 4B)(r_0 + \eta_1) = -C\cos i - \bar{\lambda}_\alpha\left[1 - l_0\left\{\frac{1}{r_0} - \frac{\eta_1}{r_0^2} + \frac{\eta_1^2}{r_0^3} - \frac{\eta_2^2}{2r_0^3} + \frac{3}{2}\frac{\eta_1^2}{r_0^4} + \frac{3}{2}\frac{\eta_1\eta_2^2}{r_0^4}\right\}\right](r_0 + \eta_1)$$

and $$\eta_2'' + 2\eta_1' + B\eta_2 = -\bar{\lambda}_\alpha\left[1 - l_0\left\{\frac{1}{r_0} - \frac{\eta_1}{r_0^2} + \frac{\eta_1^2}{r_0^3} - \frac{\eta_2^2}{2r_0^3} + \frac{3}{2}\frac{\eta_1^2}{r_0^4} + \frac{3}{2}\frac{\eta_1\eta_2^2}{r_0^4}\right\}\right]\eta_2$$

Or, $$\eta_1'' - 2\eta_2' - (3 + 4B - \bar{\lambda}_\alpha)\eta_1 = (3 + 4B - \bar{\lambda}_\alpha)r_0 - C\cos i + \bar{\lambda}_\alpha l_0\left(1 - \frac{\eta_2^2}{2r_0^2} + \frac{5}{2}\frac{\eta_1^3}{r_0^3} + \frac{\eta_1\eta_2^2}{r_0^3}\right)$$

and $$\eta_2'' + 2\eta_1' - \left(\frac{\bar{\lambda}_\alpha l_0}{r_0} - B - \bar{\lambda}_\alpha\right)\eta_2 = \bar{\lambda}_\alpha l_0\left(\frac{\eta_1^2\eta_2}{r_0^3} - \frac{\eta_1\eta_2}{r_0^2} - \frac{\eta_2^3}{2r_0^3}\right)$$

i.e. $$\left.\begin{aligned}&\eta_1'' - 2\eta_2' - m_1^2\eta_1 = G\\ &\eta_2'' + 2\eta_1' - m_2^2\eta_2 = H\end{aligned}\right\} \qquad \text{…………..(2.9)}$$

Where, $m_1^2 = (3 + 4B - \bar{\lambda}_\alpha)$, $m_2^2 = \left(\frac{\bar{\lambda}_\alpha l_0}{r_0} - B - \bar{\lambda}_\alpha\right)$, $H = \bar{\lambda}_\alpha l_0\left(\frac{\eta_1^2\eta_2}{r_0^3} - \frac{\eta_1\eta_2}{r_0^2} - \frac{\eta_2^3}{2r_0^3}\right)$

and $$G = (3 + 4B - \bar{\lambda}_\alpha)r_0 - C\cos i + \bar{\lambda}_\alpha l_0\left(1 - \frac{\eta_2^2}{2r_0^2} + \frac{5}{2}\frac{\eta_1^3}{r_0^3} + \frac{\eta_1\eta_2^2}{r_0^3}\right) \qquad \text{… … … … … . . (2.10)}$$

Thus, the system of equations (2.9) represents an almost periodic oscillator due to Malkin.

3. SOLUTION OF THE EQUATION AND ITS STABILITY.

The solution of the linear part is obtained by putting G=0 and H=0 in [2.9] and are given by

$$\eta_1 = a_1\sin(w_1T + \beta_1) + a_2\sin(w_2T + \beta_2)$$

and , $$\eta_2 = a_1K_1\cos(w_1T + \beta_1) + a_2K_2\cos(w_2T + \beta_2)$$

This can be written as:

$$\eta_1 = a_1\sin\phi_1 + a_2\sin\phi_2$$

and $$\eta_2 = a_1K_1\cos\phi_1 + a_2K_2\cos\phi_2 \qquad \text{………….. (3.1)}$$

Where , $$\phi_1 = w_1T + \beta_1$$

$$\phi_2 = w_2 T + \beta_2$$

Where a_1, a_2, β_1 and β_2 are arbitrary constants and w_1, w_2 are the frequencies of the free oscillations of the linearised system of equations.

Also w_1 and w_2 satisfy the characteristic equation

$$w^4 + (m_1^2 + m_2^2 - 4)w^2 + m_1^2 m_2^2 = 0 \qquad \text{……………..(3.2)}$$

Differentiating (3.1), we have

$$\eta_1' = a_1 w_1 \cos\phi_1 + a_2 w_2 \cos\phi_2$$
$$\eta_2' = -a_1 K_1 w_1 \sin\phi_1 - a_2 K_2 w_2 \sin\phi_2$$
$$\eta_1'' = -a_1 w_1^2 \sin\phi_1 - a_2 w_2^2 \text{ sins } \phi_2$$
$$\eta_2'' = -a_1 K_1 w_1^2 \cos\phi_1 - a_2 K_2 w_2^2 \cos\phi_2 \qquad \text{……………. (3.3)}$$

Putting the values of η_1, η_2, η_1', η_2', η_1'' and η_2'' from (3.1) and (3.3) in (2.1), we get

$$\sin\phi_1 [a_1(w_1^2 - 2k_1 w_1 + m_1^2)] + \sin\phi_2 [a_2(w_2^2 - 2k_2 w_2 + m_1^2)] = 0$$

and $$\cos\phi_1 [a_1(k_1 w_1^2 - 2w_1 + m_1^2 k_1)] + \cos\phi_2 [a_2(k_2 w_2^2 - 2w_2 + m_2^2 k_2)]$$

… ….…….... (3.4)

Equation given in (3.4) will be satisfied identically if the coefficients of $\sin\phi_1$, $\sin\phi_2$, $\cos\phi_1$ and $\cos\phi_2$ must vanish separately.

Hence we get

$$w_1^2 - 2k_1 w_1 + m_1^2 = 0$$
$$w_2^2 - 2k_2 w_2 + m_1^2 = 0$$

……….. (3.5)

$$k_1 w_1^2 - 2w_1 + m_1^2 k_1$$
$$k_2 w_2^2 - 2w_2 + m_2^2 k_2 = 0 \qquad \text{…..……… (3.6)}$$

From [3.5] and [3.6], we get

$$\left.\begin{aligned} k_1 &= \frac{w_1^2 + m_1^2}{2w_1} = \frac{2w_1}{w_1^2 + m_2^2} \\ k_2 &= \frac{w_2^2 + m_1^2}{2w_2} = \frac{2w_2}{w_2^2 + m_1^2} \end{aligned}\right\} \qquad \text{..………. (3.7)}$$

Now, we shall study the general solutions of the entire non-linear equations [2.9] with the supposition that G ≠0 and H ≠0.

For this, the variation of arbitrary constants will be taken into consideration and the method of parameters will be exploited for our further studies.

Therefore, let us assume that a_1,a_2,ϕ_1 and ϕ_2 are now variables instead of constants in the linear case

Since,

$$\eta_1 = a_1 \sin\phi_1 + a_2 \sin\phi_2$$
$$\eta_2 = a_1 K_1 \cos\phi_1 + a_2 K_2 \cos\phi_2$$
$$\eta_1' = a_1' \sin\phi_1 + a_1 \phi_1' \cos\phi_1 + a_2' \sin\phi_2 + a_2 \phi_2' \cos\phi_2$$
$$\eta_2' = a_1' K_1 \cos\phi_1 - a_1 K_1 \phi_1'' \sin\phi_1 + a_2' K_2 \cos\phi_2 - a_2 K_2' \phi_2' \sin\phi_2$$
$$\eta_1'' = a_1' w_1 \cos\phi_1 - a_1 w_1 \phi_1'' \sin\phi_1 + a_2' w_2 \cos\phi_2 - a_2 w_2 \phi_2'' \sin\phi_2$$
$$\eta_2'' = -a_1' K_1 w_1 \sin\phi_1 - a_1 K_1 \phi_1' \sin\phi_1 - a_2' K_2 w_2 \sin\phi_2 - K_2 w_2 \phi_2' \cos\phi_2$$

……………...(3.8)

Comparing the values of η_1' and η_2' in the system of equation [3.8] and [3.3], we have by subtracting

$$a_1' \sin\phi_1 + a_1 \phi_1' \cos\phi_1 - a_1 w_1 \cos\phi_1 + a_2' \sin\phi_2 + a_2 \phi_2' \cos\phi_2 - a_2' w_2 \cos\phi_2 = 0$$
$$a_1' K_1 \cos\phi_1 - a_1 K_1 \phi_1'' \sin\phi_1 + a_1 K_1 w_1 \sin\phi_1 + a_2' K_2 \cos\phi_2 - a_2 K_2 \phi_2' sin\phi_2 + a_2 K_2 w_2 sin\phi_2 = 0$$

………….. (3.9)

Therefore, in two cases, when G≠ 0, H ≠0 and G=0 and H=0, substituting the values of and their derivatives from [3.1], [3.3] and [3.8] and using relations [3.5] and [3.6], the system of equations [2.9] reduces to the form:

$$a_1' w_1 \cos\phi_1 - a_1 w_1 \phi_1' \sin\phi_1 + a_1 w_1^2 \sin\phi_1 + a_2' w_2 \cos\phi_2 - a_2 w_2 \phi_2' \sin\phi_2 + a_2' w_2^2 \sin\phi_2 = G$$

$$and \; - a_1' K_1 w_1 \sin\phi_1 - a_1 K_1 w_1 \phi_1'' \cos\phi_1 + a_1 K_1 w_1^2 \cos\phi_1 - a_2 K_2 w_2 \sin\phi_2 - a_2 K_2 w_2' \phi_2' cos\phi_2 + a_2 K_2 w_2^2 cos\phi_2 = H$$

………….. (3.10)

Multiplying the first equations of [3.9] by K_1w_1 and adding it to the second equation of [3.10], we get

$$a_2'\sin\phi_2\,[w_1K_1 - w_2K_2] + a_2[\phi_2' - w_2](w_1K_1 - w_2K_2)\cos\phi_2 = H \quad \ldots\ldots\ldots\ (3.11)$$

Again, multiplying the first equation of [3.9] by K_2w_2 and adding it to the 2nd equation of [3.10], we get,

$$a_1'[w_1K_1 - w_2K_2]\sin\phi_1 + a_1(\phi_1' - w_2)(w_2K_2 - w_1K_1)\cos\phi_1 = H \quad \ldots\ldots\ldots\ (3.12)$$

Again, multiplying the 2nd equation of [3.9] by w_1 and then subtracting it from K_1 times the first equation of [3.10], we get

$$a_2'[w_2K_1 - w_1K_2]\cos\phi_2 - a_2(\phi_2' - w_2)(w_2K_1 - w_1K_2)\sin\phi_2 = K_1G \quad \ldots\ldots\ldots\ (3.13)$$

Lastly, multiplying the 2nd equation of [3.9] by w_2 and then subtracting it from K_2 times the first equation of [3.10], we get

$$a_1'[w_1K_2 - w_2K_1]\cos\phi_1 - a_1(\phi_1' - w_1)(w_1K_2 - w_2K_1)\sin\phi_1 = K_2G \quad \ldots\ldots\ldots\ (3.14)$$

Now substituting the values of K_1 and K_2 from [3.7] in the system of equations [3.11], [3.3] and [3.14], we get

$$a_1'\left(\frac{w_2^2 - w_1^2}{2}\right)\sin\phi_1 + a_1(\phi_1' - w_1)\left(\frac{w_2^2 - w_1^2}{2}\right)\cos\phi_1 = H$$

$$a_1'\left[\frac{m_1^2(w_1^2 - w_2^2)}{2w_1w_2}\right]\cos\phi_1 - a_1(\phi_1' - w_1)\left[\frac{m_1^2(w_1^2 - w_2^2)}{2w_1w_2}\right]\sin\phi_1 = K_2G$$

$$a_1'\left(\frac{w_1^2 - w_2^2}{2}\right)\sin\phi_2 + a_2(\phi_2' - w_2)\left(\frac{w_1^2 - w_2^2}{2}\right)\cos\phi_2 = H$$

$$\text{and}\,a_2'\left[\frac{m_1^2(w_2^2 - w_1^2)}{2w_1w_2}\right]\cos\phi_2 - a_2(\phi_2' - w_2)\left[\frac{m_1^2(w_2^2 - w_1^2)}{2w_1w_2}\right]\sin\phi_2 = K_1G \quad \ldots\ldots\ldots\ (3.15)$$

After solving these equations for a_1', a_2', ϕ_1', and ϕ_2' we get them in the form:

$$a_1' = -\left[\left(\frac{-2H}{w_2^2 - w_1^2}\right)\sin\phi_1 + K_2\frac{w_1w_2}{m_1^2}\left(\frac{2G}{w_2^2 - w_1^2}\right)\cos\phi_1\right]$$

$$a_2' = -\left[\left(\frac{-2H}{w_2^2 - w_1^2}\right)\sin\phi_2 + K_2\frac{w_1w_2}{m_1^2}\left(\frac{2G}{w_2^2 - w_1^2}\right)\cos\phi_2\right]$$

$$\phi_1' = w_1 + \frac{1}{a_1}\left[-\left(\frac{-2H}{w_2^2 - w_1^2}\right)\cos\phi_1 + K_2\frac{w_1w_2}{m_1^2}\left(\frac{2G}{w_2^2 - w_1^2}\right)\cos\phi_2\right]$$

$$\text{and}\,\phi_2' = w_2 + \frac{1}{a_2}\left[-\left(\frac{2H}{w_2^2 - w_1^2}\right)\cos\phi_1 - K_1\frac{w_1w_2}{m_1^2}\left(\frac{2G}{w_2^2 - w_1^2}\right)\sin\phi_2\right] \quad \ldots\ldots\ldots\ (3.16)$$

From [3.2], we have

$$w^4 + (m_1^2 + m_2^2 - 4)w^2 + m_1^2m_2^2 = 0$$

Which is a quadratic equation in w^2

Let w_1 and w_2 be its two roots.

Then

$$w_1^2w_2^2 = m_1^2m_2^2$$

$$\therefore \frac{w_1w_2}{m_1^2} = \frac{m_2}{m_1} \quad \ldots\ldots\ldots\ (3.17)$$

Substituting the value from (3.17) in the system of equations [3.16], we get

$$\left.\begin{aligned} a_1' &= -[H^*\sin\phi_1 + K_2G^*\cos\phi_1] \\ a_2' &= -[H^*\sin\phi_2 + K_2G^*\cos\phi_2] \\ \phi_1' &= w_1 + \frac{1}{a_1}[-H^*\cos\phi_1 + K_2G^*\sin\phi_1] \\ \phi_2' &= w_2 + \frac{1}{a_2}[-H^*\cos\phi_2 + K_2G^*\sin\phi_2] \end{aligned}\right\} \quad \ldots\ldots\ldots\ (3.18)$$

$$\left.\begin{aligned} \text{Where, } H^* &= \frac{-2H}{w_2^2 - w_1^2} \\ G^* &= \frac{2m_2G}{m_1(w_2^2 - w_1^2)} \end{aligned}\right\} \quad \ldots\ldots\ldots\ (3.19)$$

Thus, we get new system of four variation equations given by [3.18] considering a_1, a_2, ϕ_1 and ϕ_2 as variables.

Now in the system equation [3.18], we put right hand side of the value of H and G from [3.11] and there after the values of η_1 and η_2 from [3.1]. Then the right hand side terms of the expression are expanded into trigonometrical sums and the averaged values of the variables are taken. In this way, all the terms in the system of equations [3.18] may be dropped except the free terms,We get a system of equation for the first approximation as

$$a_1' = 0, a_2' = 0, \phi_1' = w_1^* \text{ and } \phi_2' = w_2^* \qquad \dots\dots\dots\dots\dots\dots (3.20)$$

Where,

$$w_1^* = w_1 - \frac{1}{4(w_1^2 w_2^2)}\left[a_1^2\left(-K_1 + \frac{3}{2}K_1^3 - \frac{3K_2m_2}{m_1} + \frac{K_1^2K_2m_2}{2m_1}\right) + a_2^2\left(-2K_2 + 3K_2^2K_1 - \frac{6K_1m_2}{m_1} + \frac{K_1^3m_2}{m_1}\right)\right]$$

= a constant quantity

$$and,\ w_2^* = w_2 - \frac{1}{4(w_1^2 - w_2^2)}\left[a_1^2\left(-2K_2 + 3K_1^2K_2 - \frac{6K_1m_2}{m_1} + \frac{K_1^3m_2}{m_1}\right) + a_2^2\left(-K_2 + \frac{3}{2}K_2^3 - \frac{3K_1m_2}{m_1} + \frac{K_1K_2^2m_2}{m_1}\right)\right] =$$

a constant quantity

…………… (3.21)

Integrating [3.20], we get

$$a_1 = constant = a_1^*,\ a_2 = constant = a_2^*, \phi_1 = w_2^*T + m_2 \text{ and } \phi_1 = w_1^*T + m_1$$

……………… (3.22)

Where m_1 and m_2 are constants.

Hence, we see that in the equations [3.22], a_1 and a_2 remain constants where as the values of ϕ_1 and ϕ_2 are slightly changed in the first approximation with the change in the frequencies. But it has no effect on stability. Therefore, w the first approximation of the equations of non-linear oscillations given by [2.9] can be expressed as

$$\eta_1 = a_1^* \sin(w_1^*T + m_1) + a_2^* \sin(w_2^*T + m_2)\ and\quad \eta_2 = a_1^*K_1\cos(w_1^*T + m_1) + a_2^*K_2\cos(w_2^*T + m_2)$$

……………(3.23)

Where, a_1^*, a_2^*, m_1 and m_1 are arbitrary constants and w_1^*, w_2^* will be the new frequencies.

Finally, we conclude that the solutions given in [3.23] for the system of equations [2.9] will be stable.

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