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AN ALGORITHM FOR COMBINE HARVESTER REEL STAGGER DETERMINATION BASED ON REEL KINEMATICS AND CROP STEM DEFLECTION

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ABSTRACT

A principle for the determination of reel stagger, based on reel kinematics and crop stem deflection, is proposed. Equations derived theoretically and information obtained empirically are combined to obtain an algorithm for the determination of reel stagger. The algorithm has yet to be evaluated on actual combine harvesters in the harvesting mode.

INTRODUCTION

One operational parameter of the combine harvester reel is reel stagger, denoted X_R in **Fig. 1**. It's value should vary with the type of crop and the condition of the crop at the time of harvest. Hence, current combine harvester designs allow for its variation.

The rational determination of reel stagger has rarely been addressed. Klenin et. al. (1985) presented an analysis involving crop stem deflection and reel stagger. In essence; they assumed the stem to behave as a straight and rigid rod hinged at the base, and then sought to determine the temporal point of the commencement of cutting of the bunch of crop being handled by a single reel slat or tine bar. In reality, unless the stems, in being deflected by the reel, break at the base, their actual behavior would be substantially different from that of a rigid rod hinged at the base. The analysis presented here assumes the stem to be a deformable vertical cantilever, fixed at the base. Furthermore, it is thought to be more convenient to determine the temporal point of the completion of cutting of the bunch of crop being handled by a single reel slat or tine bar.

REEL AND CUTTER BAR KINEMATICS

Reel and cutter bar kinematics have been dealt with in detail elsewhere (Oduori et. al. (1992)). Generally, the following assumptions are made;

1. The reel rotates about its lateral axis at a uniform angular velocity, denoted ω (rad/s) and taken to be positive in the clockwise sense.
2. The whole header advances in the positive X-direction (see **Fig. 1**) at uniform advance velocity, denoted V (m/s).

3. There is no motion in the lateral direction. The motion of the reel can therefore be considered two-dimensional.

The coordinate reference frame is fixed to the ground and, at time t=0, is located as illustrated in **Fig. 2**. Under these conditions, the trajectories of the tip, T, and hinge, H, of a tine on a conventional tined reel design would be as shown in in **Fig. 2**. These trajectories are geometrically similar looped trochoids. The cutter bar assembly moves at the advance velocity. Equations of position, velocity, and acceleration of the hinge and tip, at an arbitrary time, t, are readily obtained.

REEL KINEMATICS AND CROP STEM DEFLECTION

A model of crop stem deflection by the reel has been proposed by Sakai et. al. (1993) in which the following assumptions were made;

1. A bunch of deflected stems can be considered to behave as a single vertical cantilever fixed at the base.

2. The resultant force, F, acting to deflect the stems, is always perpendicular to the curvature of the deflected stem, at the point of contact between the reel and the stems.

So far, assumptions concerning the mechanical properties of the stems appear to be unnecessary. The resultant model is illustrated in **Fig. 3.**

It is postulated that for proper synchronization of reel and cutter bar operation, the uncut stems deflected by the reel should be cut while the reel still tends to increase their deflection. Thus, the stem should be cut before or just at the moment in time, denoted t_m, when the velocity vector of the point in the reel that contacts the stems becomes tangent to the curvature of the deflected stems. With this condition satisfied, the effectiveness of the reel's delivery of cut crop onto the gathering table (also known as platform) should be assured. This limiting condition is illustrated in **Fig. 4**. Accordingly it follows that;

$$\phi_m = \phi(t_m) - 2\pi \qquad (1)$$

where ϕ_m and $\phi(t_m)$ are defined as shown in **Figs. 3** and **4**, respectively, and measured in radians, and π is the circular constant equal to 3.14159. All angles are taken to be positive in the clockwise sense. The relationship involving crop stem deflection and reel stagger is as follows (Sakai et. al. (1993));

$$X_R = \left[R^2 - (Y_R - Y_m)^2\right]^{1/2} + \Delta X_m \qquad (2)$$

where R is the radius from the reel's centre of rotation to the tine's hinge axis, Y_R is the pernpendicular distance from the ground to the reel's axis of rotation (see **Figs. 1** and **2**), Y_m and ΔX_m are as defined in **Fig. 3**. All distances are in metres. Considering the timing of entry of a reel slat or tine bar into the crop, as expounded in detail by Sakai et. al. (1993), one finds;

$$Y_R = Y_C + AR_O\,; \qquad R/R_O > A \geq 1 \tag{3}$$

where Y_C is the representative height of the crop in metres, A is a dimensional factor whose value is limited as shown in equation (3) but is usually taken to be unity, and R_O is the rate of header advance in metres per radian of reel rotation. R_O (alternatively V/ω) is an important parameter of motion along a trochoidal trajectory. Furthermore it can be shown, as was done by Sakai et. al. (1993), that;

$$\omega t_2 = \pi - \cos^{-1}\left(AR_O/R\right) \tag{4}$$

where ωt_2 is the value of ωt at which the reel slat or tine bar first enters the crop. By considering the direction of the velocity vector at the tine's hinge axis, denoted $\phi(t)$, and using equation (1), it was also shown by Sakai et. al. (1993), that the following relationship holds true;

$$\omega t_m = \cos^{-1}\left(R_O \cos\phi_m/R\right) + \pi + \phi_m \tag{5}$$

where ωt_m is illustrated in **Fig. 4**. The quantity denoted Y_m in **Fig. 3** may alternatively be denoted $Y(t_m)$ and, by using the equations of position, it can be readily shown, as was done by Sakai et. al. (1993), that the following relationship holds true;

$$Y_m = Y_R + R\cos\omega t_m \tag{6}$$

The quantity denoted ΔX_m may be represented as $[X(t_m) - X(t_2)]$ and by using the equations of position, one readily obtains;

$$\Delta X_m = R_O\left(\omega t_m - \omega t_2\right) + R\sin\omega t_m - R\sin\omega t_2 \tag{7}$$

In the above equations, the variables denoted, A, R, and R_O are expected to be determined on the basis of constraints such as allowable grain loss levels and feasible combine harvester advance velocity. The representative height of the crop, denoted Y_C, is not in the control of the combine harvester engineer. Thus, assuming Y_C, A, R, and R_O to be known, equations (2), (5), (6), and (7), contain five unknowns among them, namely, X_R, Y_m, ΔX_m, ωt_m, and ϕ_m. It is therefore necessary to seek further information in order to be able to solve for a unique value of X_R. Considering that ωt_m could be determined by using equation (5), if ϕ_m were known, and that X_R is the quantity to be ultimately determined, the additional information should involve Y_m, ΔX_m, and ϕ_m. An empirical study was undertaken in order to determine the relationship, or relationships, involving these three variables.

EMPIRICAL STUDY ON CROP STEM DEFLECTION

Measurements were taken, in the field, on a ready-to-harvest *japonica* rice variety grown at the Kyushu University Farm in Fukuoka, Japan, during October, 1991. Among the objectives of the study was to determine the following functional relationship;

$$\phi_m = \phi(\Delta X_m, Y_m)$$

The apparatus used in the study is described in detail by Oduori et. al. (1993). The rate of deflection was controllable. The deflecting force was sensed by a home-made L-shaped force sensor. Uniformly spaced reflector tape pieces, together with an ultra-violet light source and sensor were used to measure the speed of deflection. Before actual measurement, a bunch of crop would be selected, more or less randomly and isolated by manually cutting the crop in its immediate vicinity. The only criterion applied in selecting the bunch of crop was that it should be reasonably upright. The complete block factorial experiment with three levels of loading speed, denoted U_D, three levels of height, Y_m, and three replicates of each combination of treatments was adopted. The data acquisition system and relevant data processing are illustrated in **Figs. 5** and **6** respectively. A linear relationship of the following form;

$$\phi_m = \alpha + \beta(\Delta X_m/Y_m)$$

was found to fit well to the data as can be seen in **Fig. 7** and from the regression results in **Table 1**. A two-tailed Student's *t* -test indicated that the mean value of α was not significantly different from zero, which conforms to the assumption of an initially vertical cantilever. A correlation analysis indicated that β was almost uncorrelated to deflection speed, U_D, but fairly positively correlated to Y_m. However, a one-way ANOVA for the effect of Y_m on β revealed that the variation in β attributable to variation in Y_m was no more than what might be expected of chance variation at the 95% significance level. Thus for the particular rice variety studied in this work, the following relationship is thought to be acceptable;

$$\phi_m = 1.4848(\Delta X_m/Y_m) \qquad (8)$$

where the number 1.4848 is the mean value of α as obtained by regression and tabled in **Table 1**, and ϕ_m is measured in radians. For practical purposes, α may be approximated to 1.5.

DETERMINATION OF REEL STAGGER

The flowchart in **Fig. 8** illustrates the algorithm for the determination of reel stagger. All the equations used in the algorithm, excepting equation (8), are based entirely on reel kinematics and the proposed model of crop stem deflection. Therefore, they are not dependent on the crop to be harvested. Equation (8), however, is derived from empirical data and is therefore specific to the *japonica* rice variety which was studied in this work.

CONCLUSIONS

The following conclusions were reached in this work;

1. A model of stem deflection was proposed. In subsequent analysis of empirical data, not reported here, actual crop stem deflection compared well with the implications of the proposed model.

2. Six methematical expressions relevant to reel stagger determination were derived based on reel kinematics and the crop stem deflection model. However, these equations were not sufficient for the determination of reel stagger.

3. An empirical study on crop stem deflection yielded an additional expresson that is relevant to reel stagger determination but dependent on the type and condition of the crop. The *japonica* rice variety was used as the test crop.

4. The theoretically derived equations and empirical results were combined to obtain an algorithm for the determination of reel stagger. The algorithm has yet to be validated on an actual combine in the harvesting mode.

5. It is envisaged that the validation of an algorithm for reel stagger determination should make possible the real-time automatic control of reel stagger to conform to varying crop conditions, given the high level of sensing and control technologies available today.

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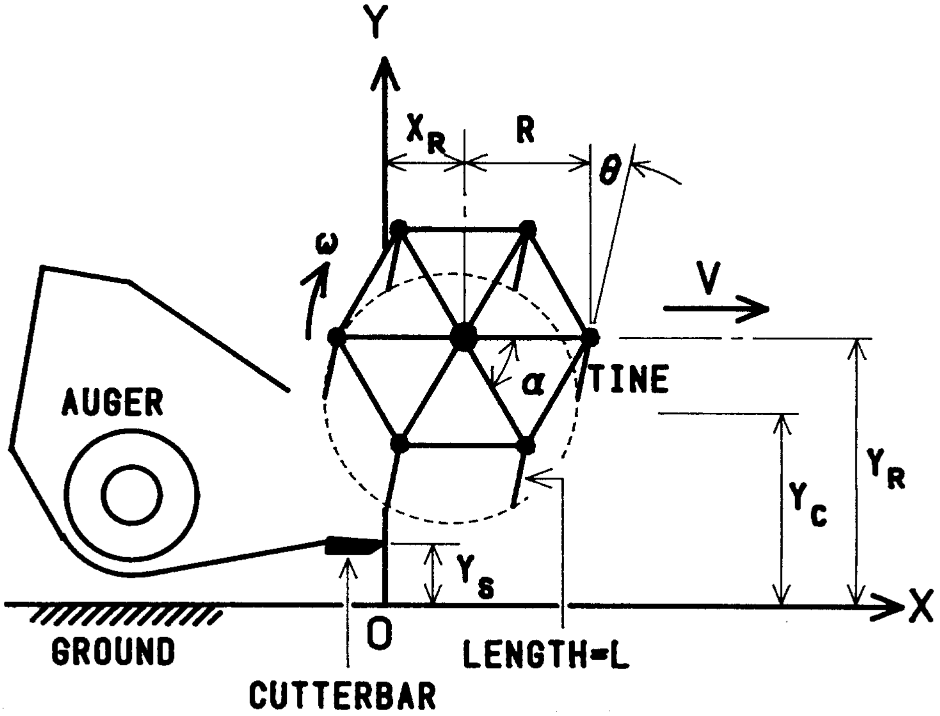

Fig. 1 - Tined Reel with Relevant Parameters

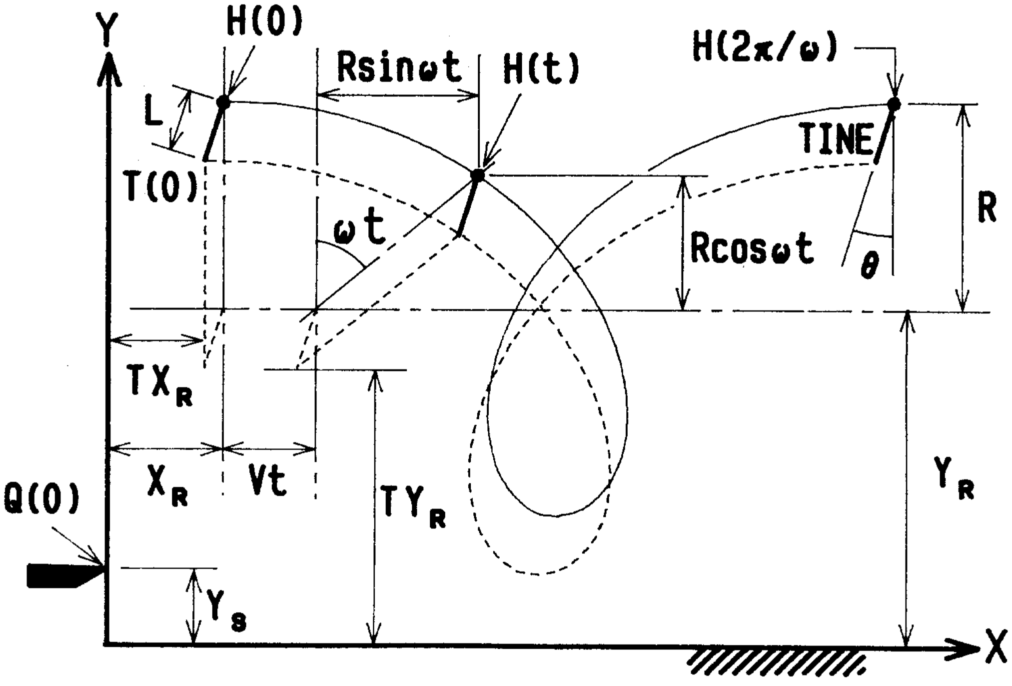

Fig. 2 - Trajectories of a Tine's Hinge and Tip

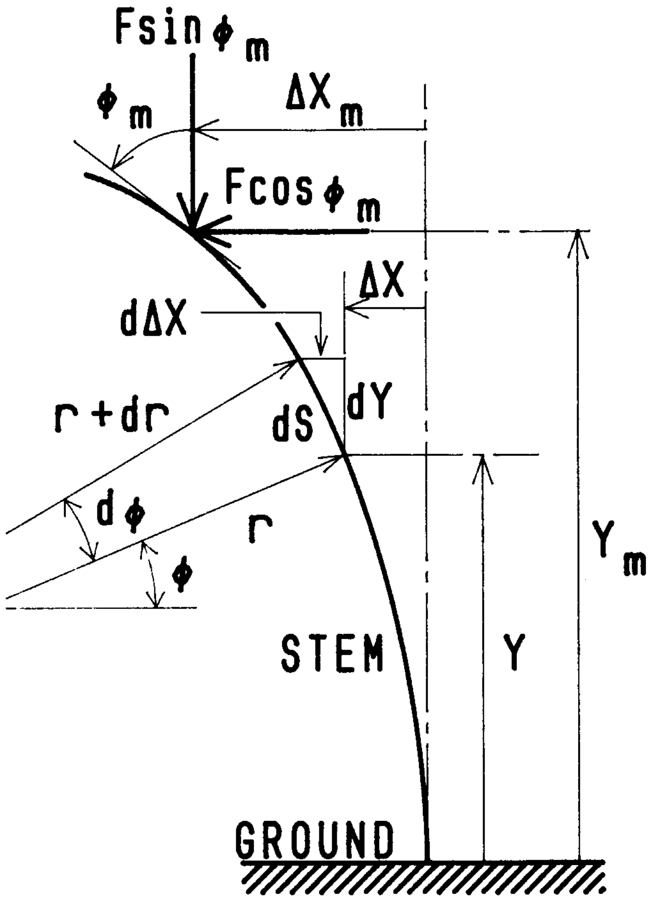

Fig.3 - Stem deflection model

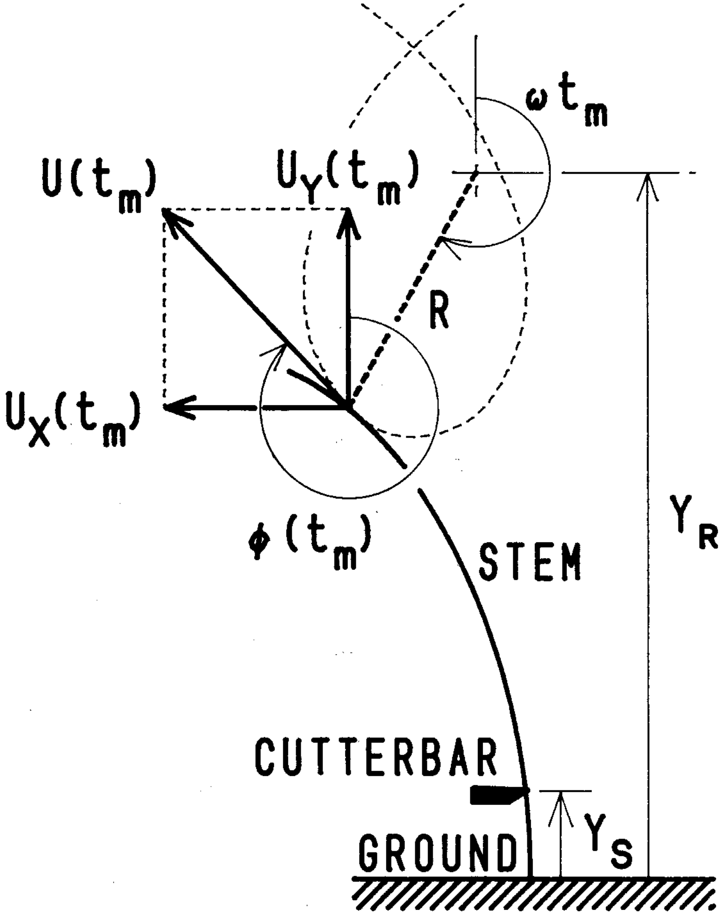

Fig.4 - Timing of Stem Cutting

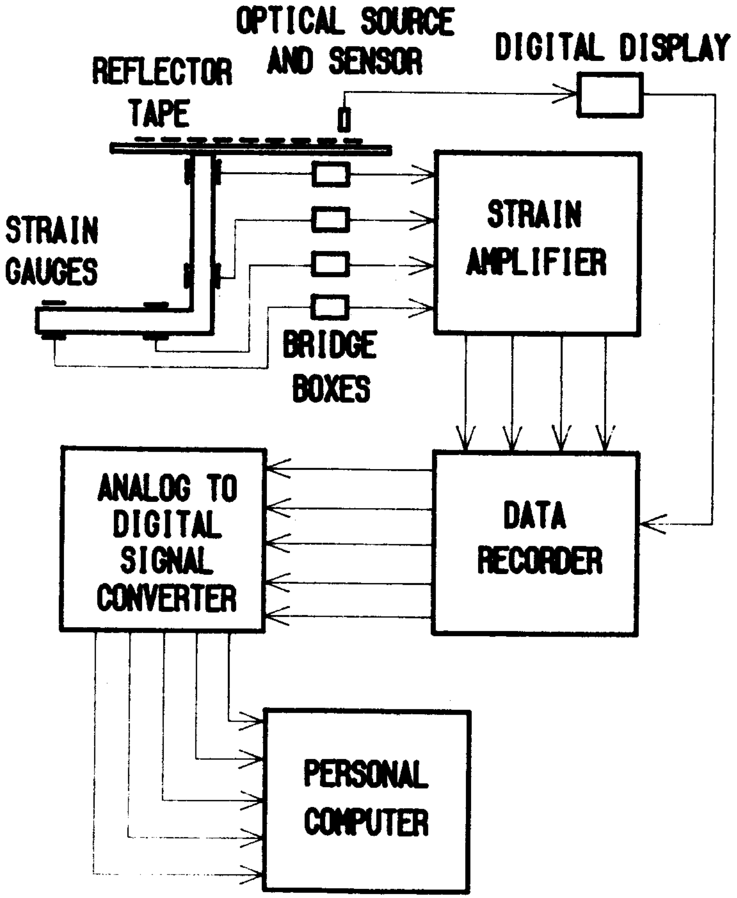

Fig. 5 - Data acquisition system

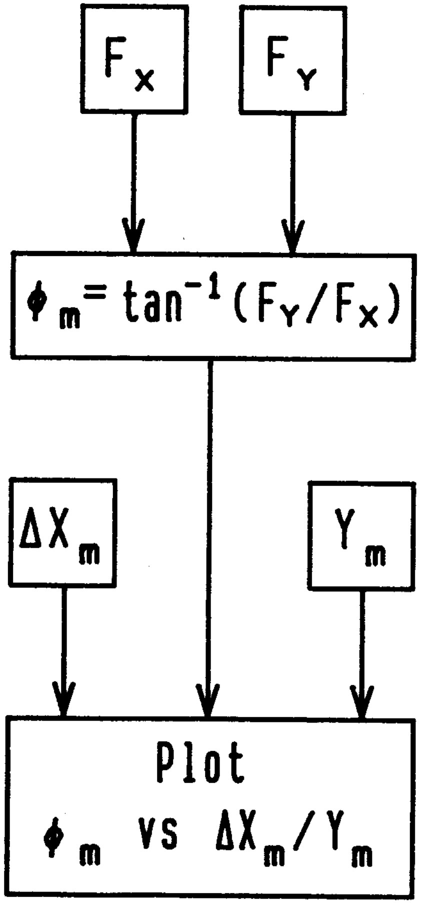

Fig. 6 - Data processing

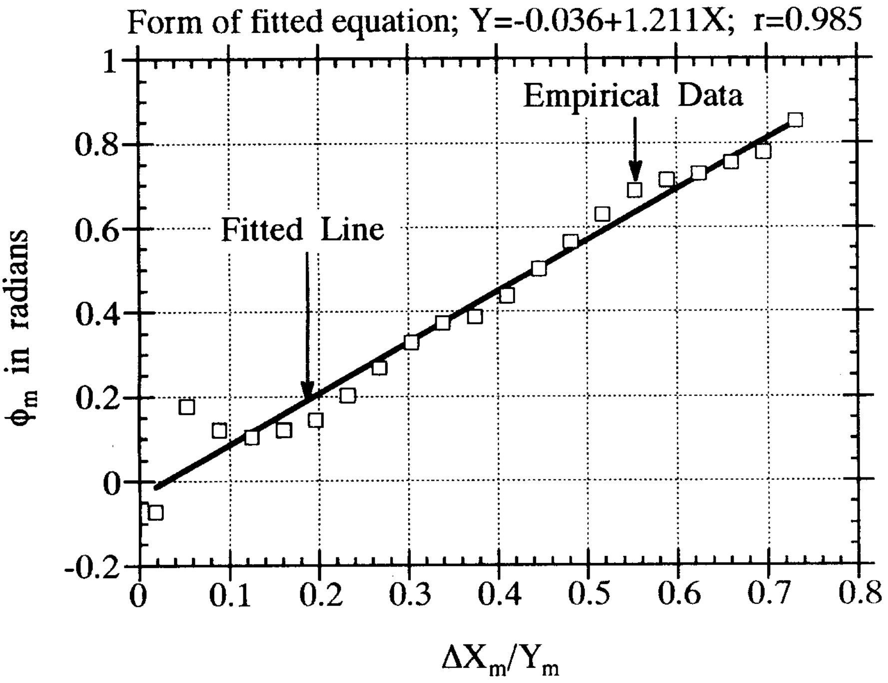

Fig. 7 - Data plot for Y_m=0.35m, U_D=0.005m/s

Table 1 - Regression of ϕ_m on $\Delta X_m/Y_m$

Y_m (m)	U_D (m/s)	REGRESSION RESULTS		
		α	β	r
0.35	0.005	-0.036	1.211	0.985
	0.010	-0.023	1.003	0.991
	0.015	-0.195	1.372	0.997
0.40	0.005	-0.282	1.910	0.989
	0.010	-0.084	1.419	0.982
	0.015	-0.108	1.610	0.996
0.45	0.005	0.009	1.425	0.985
	0.010	-0.304	1.747	0.990
	0.015	-0.285	1.666	0.993

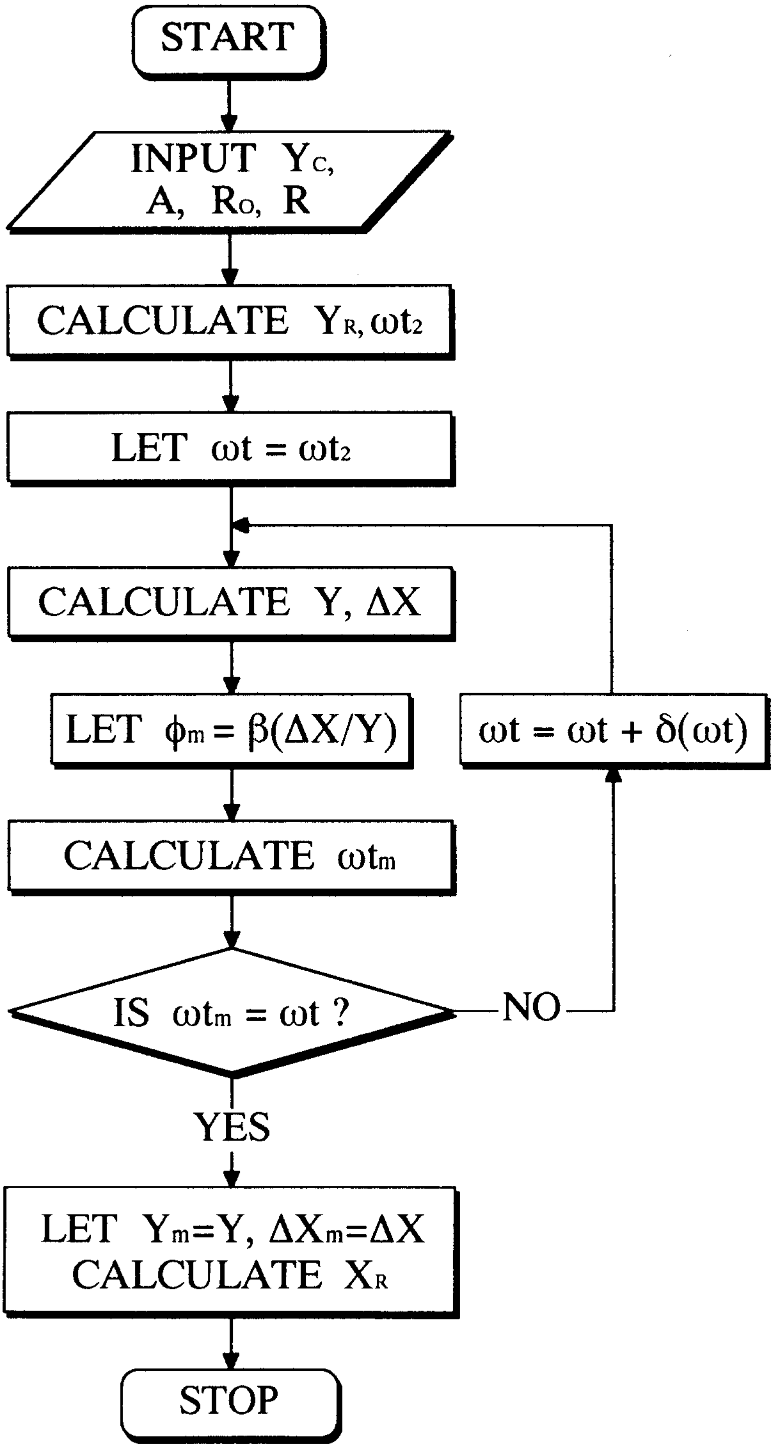

Fig. 8 - The determination of reel stagger