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Davidson Laboratory

Stevens Institute of Technology

A SURVEY OF CYCLOIDAL PROPULSION

by

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DAVIDSON LABORATORY
STEVENS INSTITUTE OF TECHNOLOGY
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ABSTRACT

This report presents a brief history of cycloidal propulsion and a description of the kinematics of the flow through a cycloidal propeller. The various types of cycloidal propellers are discussed and a description of several installations is presented. A survey is presented of the literature pertaining to theoretical design procedures used for cycloidal propellers. A comparison of cycloidal and screw propulsion shows that cycloidal propeller efficiency is in the range 0.45 to 0.58 as compared to 0.66 to 0.76 for screw propellers. Some advantages of cycloidal propulsion are discussed. In order to insure optimum efficiency in designs of the future, it is recommended that research be carried out to find the influence of: Kramer's effect, a lifting surface passing through a vortex sheet, wake contraction, blade motion, wake adaption and blade proportions.

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INTRODUCTION

A cycloidal propeller is a combined propulsion and steering device that produces a useful thrust (which may be controlled in magnitude and direction) while absorbing power. The thrust is produced by several blades which revolve in a circular orbit about a common axis, while each blade rotates about a separate spanwise axis.

The use of the cycloidal propeller principle is not new. For centuries the Chinese have used windmills with vertical feathering sails. Inventors in the United States have attempted to use this device for more than 130 years. United States patent records show that in 1824 an inventor applied for a patent on a feathering vane windmill. Experiments involving cycloidal propulsion in the marine field can be found scattered throughout the 19th century.

The first successful application of cycloidal propulsion to ships occurred in 1922 as a result of the work of Kirsten[1] who presented the mathematics describing its operation in 1928. Also, in 1928, Schneider[2] developed the variable pitch cycloidal propeller in Germany. This type of cycloidal propeller, with improvements made through the years, is the type which today is found in most applications.

In the United States, Eastman[3] continued the investigations initiated by Kirsten's successful experiments. Plans for a cyclogiro aircraft propeller were developed, and experiments proved the advantages of this type of combined aircraft sustentation and propulsion.

Interest in cycloidal propellers subsided in the United States during World War II only to be revived again in 1945 by reports of the accomplishments of German vessels equipped with Voith-Schneider propellers. During the post war period and up to the present time, the U.S. Army and Navy have designed and built several experimental craft utilizing cycloidal propulsion. Notable among these is the LTI 2194, a United States Army Transportation Corps towboat equipped with two 1000 cycloidal propellers[4]. Cycloidal propeller design and construction in this country has been performed by the Pacific Car and Foundry Company, Renton, Washington.

In the future, it will be necessary for cycloidal propulsion to compete with other means of ship propulsion. In order to insure optimum efficiencies of future designs, it is first necessary to find information on the theory used in design procedures for cycloidal propellers and then to disclose areas in which further research may provide means of increasing cycloidal propulsion efficiency. The information contained herein attempts to fulfill these needs. A survey of the pertinent literature was made, and the articles containing useful theoretical design information are summarized. On the basis of the information found during the literatue survey, suggestions are presented for needed research.

There is some controversy in the literature about the proper name for a propulsion device in which the blades rotate and revolve in a manner similar to the motions of a planet relative to the sun. The term cycloidal propeller has been chosen here since this term is most descriptive. This is so because the path of the blade axis through a fluid is a cycloid no matter what particular blade motion or orientation is used. The terms "vertical axis propeller", "Voith-Schneider propeller" and "Kirsten-Boeing propeller" are all less representative of the entire field of cycloidal propellers.

The study described herein was conducted at the Davidson Laboratory, Stevens Institute of Technology under Office of Naval Research Contract No. 263-27 and Davidson Laboratory Project No. KK-2117.

NOMENCLATURE

a distance between S and P (see Sketch 1)

a_o distance between S_o and P (see Sketch 1)

A_o slope of the curve of lift versus angle of attack

C chord length of section

C_T load coefficient based on velocity

D blade orbit circle diameter

D_s diameter of screw propeller

e_b blade efficiency

e_p propeller efficiency

F_d drag force

J advance coefficient, $J = V/nD$

K a constant

K_q torque coefficient based on rpm, $K_q = Q_o/\rho\, n^2 D^4 \ell$

K_t thrust coefficient based on rpm, $K_t = T/\rho\, n^2 D^3 \ell$

L lift force

ℓ blade length

N resultant force on propeller blade

n revolutions per second

O origin of axes

P generating point

p pitch ratio = advance of propeller in one revolution at zero slip divided by propeller diameter

Q_o torque required by propeller in open water

R radius of blade orbit circle of cycloidal propeller or ship resistance in smooth water

r radial distance of control point of cycloidal propeller from axis of rotation

r' distance between O and S' (see Sketch 1)

s slip ratio, $s = (V_o - V)/V_o$

S' control point

S, S_o auxillary points defined in Sketch 1

T thrust developed by propeller

U	tangential velocity
V	velocity of fluid approaching the propeller
V_o	speed of advance of propeller with no slip
w	resultant kinematic velocity

Greek Letters

α	kinematic angle of attack
β	blade angle
β_o	amplitude of sinusoidal blade motion
γ	angle between resultant velocity and tangential velocity
ϵ	$\epsilon = \tan^{-1} F_d/L$
η	$\eta = r/R$
θ	polar coordinate, measured from negative y-axis to $\overline{OP}$
λ	advance ratio, $\lambda = V/R\omega = J/\pi$
ρ	density of fluid
ω	angular velocity of propeller

Subscripts

R, T	denote components parallel to radius and tangent lines, respectively
x, y	denote components parallel to x and y-axes, respectively

KINEMATICS OF CYCLOIDAL PROPELLERS

Unfortunately, there are contradictions in literature concerning the terms "prolate cycloid" and "curtate cycloid". The term "trochoid" is sometimes used to mean curtate cycloid and sometimes refers to the whole family of cycloidal curves. The terminology adopted here is that which may be found in most analytic geometry text books. (For example, see Wilson and Tracy[5])

When a circle rolls without slipping along a straight line, the path traced by any point P, in the plane of the circle, is a cycloid. Let R be the radial distance from the center of the circle to the point P. Let r be the radius of the generating circle. If $R > r$, then P traces a prolate cycloid, as shown by curve "A" in Fig. 1. If $R = r$, the P traces an ordinary cycloid, as shown by curve "B" in Fig. 1, and if $R < r$, then P traces a curtate cycloid (curve "C").

The pitch ratio, p, (defined as the ratio of the distance traveled by P in the direction of advance of the circle during one complete revolution to twice R) determines which type of cycloid is traced by P. The pitch ratio is

$$p = \frac{\pi r}{R} \quad . \tag{1}$$

The advance ratio, λ, is defined as the ratio of the speed of advance of the circle, V, to the circumferential speed of the tracing point P which is $R\omega$, where ω is the angular speed of rotation of the circle. Consequently, the advance ratio is

$$\lambda = \frac{V}{R\omega} \quad . \tag{2}$$

The slip ratio, s, is defined as the ratio of the difference between the speed of advance of the circle at zero slip, V_o, and the actual speed of advance, V, to the speed of advance at zero slip, i.e.,

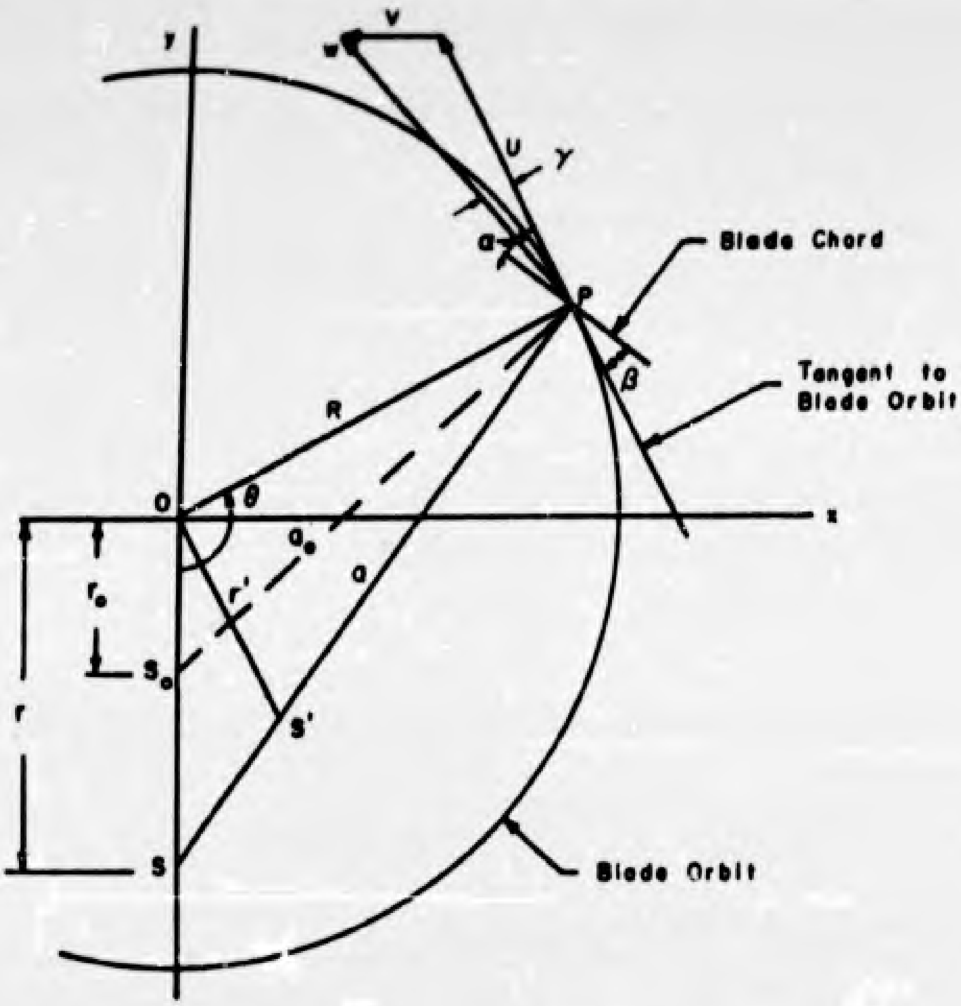
$$s = \frac{V_o - V}{V_o} \quad . \tag{3}$$

Only positive slips will be studied here since propeller operation and not turbine operation is considered. For zero slip it is necessary that

$$V_o = r\omega \quad .$$

Hence, the slip ratio at any slip becomes

$$s = 1 - \frac{V}{V_o} = 1 - \left(\frac{V}{R\omega}\right)\left(\frac{R}{r}\right) = 1 - \frac{\lambda\pi}{P} \quad . \qquad (4)$$



Sketch I

KINEMATICS OF CYCLOIDAL BLADE MOTION

Consider a configuration as shown above in Sketch 1. Point P revolves in a circular orbit having a radius R and center at O. The velocity, V , of the orbit through the fluid is directed in the negative direction along the x-axis of a two-dimensional, rectangular coordinate system. The tangential velocity of P as it revolves about O is

$$U = R\omega \quad . \qquad (5)$$

The advance ratio is then

$$\lambda = \frac{V}{U} \quad . \qquad (6)$$

The square of the resultant velocity of P through the fluid is

$$w^2 = U^2 + V^2 - 2U\,V \cos\theta \quad ,$$

or introducing λ and dividing by U^2 this becomes

$$\frac{w}{U} = \sqrt{1 + \lambda^2 - 2\lambda \cos\theta} \quad , \tag{7}$$

where θ is the angular position of P measured from the negative y-axis in the counter clockwise sense. Let γ be the angle between the resultant velocity w and the tangential velocity U. The relation between γ and θ is such that

$$\sin\gamma = \frac{\lambda \sin\theta}{\frac{w}{U}} \tag{8}$$

and

$$\cos\gamma = \frac{1 - \lambda\cos\theta}{\frac{w}{U}} \quad . \tag{9}$$

Dividing Eq. 8 by Eq. 9, one obtains the relationship:

$$\tan\gamma = \frac{\lambda \sin\theta}{1 - \lambda\cos\theta} \quad . \tag{10}$$

Construct a line through P and perpendicular to w. This line intersects the y-axis at S_o. The line segment $\overline{S_oP}$ is denoted by a_o. From the geometry of Sketch 1, it is evident that the triangle OPS_o is geometrically similar to the triangle composed of the velocities U, V and w. Thus, the side $\overline{OS_o}$ of OPS_o is of constant length, since it is proportional to V.

From Eq. 4, one obtains the relation between pitch and advance ratio:

$$\lambda = \frac{p_o}{\pi} = \frac{r_o}{R} \quad , \tag{11}$$

where the o subscript denotes zero slip. From the similar triangles one obtains:

$$\frac{\overline{OS_o}}{R} = \frac{V}{U} = \lambda \quad , \tag{12}$$

and hence, from Eq. 11 and 12,

$$\overline{OS_o} = r_o \quad . \tag{13}$$

Thus, the point S_o is fixed as P revolves. The distance $\overline{OS_o}$ is the radius of the generating circle, having its center at O, and is used for the construction of the prolate cycloidal path along which P will travel. Thus, the quantity r_o/R is dependent only upon the advance ratio, λ.

In order to produce thrust, a blade is introduced at P, oriented at an angle of attack such that it will develop a lift having a component in the ahead direction. To accomplish this, consider a blade at P such that its chord is at an angle β with respect to the tangent to the blade orbit at P. (See Sketch 2) The angle of attack is

$$\alpha = \beta - \gamma \quad . \tag{14}$$

From this relation and from Sketch 2, it is seen that the condition for ahead thrust is that β be greater than γ. The angle β is called the blade angle and its variation with respect to θ is called the blade motion. If the blade chord is small, the terms involving the rate of change of β with respect to time may be neglected.

Lift will be developed on the blade due to the angle of attack. This lift force, L, is directed perpendicularly to the relative velocity, w, as shown in Sketch 2. Parallel to w there is a drag force F_d. The angle ϵ is defined as

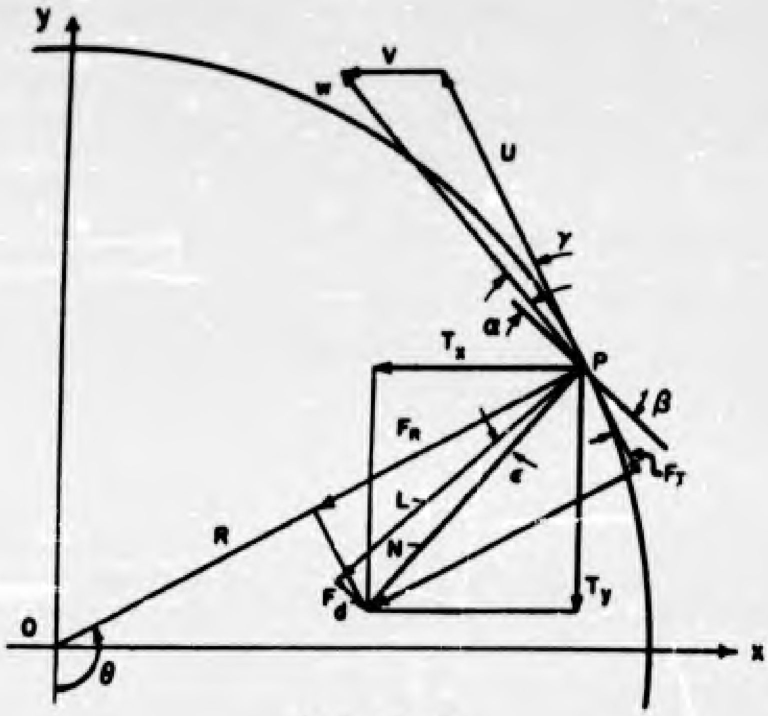
$$\epsilon = \tan^{-1} \frac{F_d}{L} \quad . \tag{15}$$

From airfoil theory for an unstalled airfoil section of unit span, the following relationship is obtained:

$$L = A_o \, \alpha \, \frac{\rho}{2} \, w^2 \, C \quad , \tag{16}$$

where ρ is the density of the fluid, C is the chord length of the section, and A_o is the slope of the curve of the lift versus angle of attack.

The lift and drag force combine to give the resultant, N, of the hydrodynamic forces acting on the blade. (See Sketch 2) This force, N, may be resolved into its x and y components. T_x is the useful thrust acting in the ahead direction. The T_y components of all the blades will nearly cancel each other, resulting in a small oscillatory force (about three percent of the thrust of the propeller) in the athwartships direction. The resultant force on the blade, N , may also be resolved into radial and tangential components, F_R and F_T , respectively. The torque $F_T R$ is that which must be delivered to the blade in order to maintain a constant tangential speed.



Sketch 2

FORCE AND VELOCITY DIAGRAM

One obtains the following relationships from Sketch 2:

$$N = \frac{L}{\cos \epsilon} \quad , \tag{17}$$

$$T_x = N \cos \left(\theta + \gamma + \epsilon - \frac{\pi}{2}\right) = \frac{A_o \ \alpha \sin (\theta + \gamma + \epsilon)}{\cos \epsilon} \left(\frac{\rho}{2} w^2 C\right), \tag{18}$$

$$F_T = N \sin (\gamma + \epsilon) = \frac{A_o \ \alpha \sin (\gamma + \epsilon)}{\cos \epsilon} \left(\frac{\rho}{2} w^2 C\right) \quad , \tag{19}$$

The propeller efficiency is defined as the ratio of the useful propeller thrust times the speed of advance to the torque required times the angular speed of the propeller. For the blade in Sketch 2, considering only the rear half of the orbit ($0 \leq \theta \leq \pi$), the blade efficiency is

$$e_b = \frac{\int_0^{\pi} T_x V \, d\theta}{\int_0^{\pi} F_T U \, d\theta} = \frac{\lambda \int_0^{\pi} \frac{A_o \alpha}{\cos \epsilon} \sin(\theta + \gamma + \epsilon) \frac{W^2}{U^2} d\theta}{\int_0^{\pi} \frac{A_o \alpha}{\cos \epsilon} \sin(\gamma + \epsilon) \frac{W^2}{U^2} d\theta} \qquad .(20)$$

The angle of attack, α, is given by Eq. 14, once the blade motion $\beta(\theta)$ is specified. The velocities induced at the blade due to the bound and shed vorticity of the other blades and the shed vorticity of the blade at Γ have been neglected. If included the effect would be to change α. The lift curve slope A_o is a constant characteristic of the airfoil involved. Once α is known, the drag-lift ratio ϵ may be obtained from the airfoil characteristics. The angle of attack and the drag-lift ratio are functions of θ. Expanding the sine terms in Eq. 20, using Eq. 8 and 9 and canceling A_o, one obtains

$$e_b = \frac{\lambda \int_0^{\pi} \alpha [\sin \theta + (\cos \theta - \lambda) \tan \epsilon] \sqrt{1 + \lambda^2 - 2\lambda \cos \theta} \, d\theta}{\int_0^{\pi} \alpha [\lambda \sin \theta + (1 - \lambda \cos \theta) \tan \epsilon] \sqrt{1 + \lambda^2 - 2\lambda \cos \theta} \, d\theta} \qquad .(21)$$

TYPES OF CYCLOIDAL PROPELLERS AND INSTALLATIONS

True Cycloidal Blade Motion

By specifying different blade motions, several different types of cycloidal propellers may be derived. The first blade motion which will be discussed is that developed by Schneider[2] and applied to the first few Voith-Schneider propellers.

Let the blade angle, β, be controlled so that the blade chord at P is always perpendicular to the line $\overline{SP}$ where S is a point on the y-axis (normal to the flow direction) at a distance r from the origin. (See Sketch 1) From the geometry, one obtains the following:

$$\frac{a}{R} = \sqrt{1 + \eta^2 - 2\eta \cos \theta} \quad , \tag{22}$$

where

$$\eta = \frac{r}{R} \quad ,$$

$$\sin \beta = \frac{\eta \sin \theta}{\frac{a}{R}} \quad , \tag{23}$$

$$\cos \beta = \frac{1 - \eta \cos \theta}{\frac{a}{R}} \tag{24}$$

and

$$\tan \beta = \frac{\eta \sin \theta}{1 - \eta \cos \theta} \quad . \tag{25}$$

Using the trigonometric indentity for a tangent of the sum of two angles, one obtains the following relation for angle of attack from Eq. 10, 14 and 25:

$$\tan \alpha = \tan (\beta - \gamma) = \frac{(\eta - \lambda) \sin \theta}{1 + \eta\lambda - (\eta + \lambda) \cos \theta} \quad . \tag{26}$$

From Eq. 26 and from Sketch 1, it is evident that, for ahead thrust, $\eta > \lambda$ or $r > r_o$. This type of blade motion is known as true cycloidal blade motion.

The magnitude of the total thrust may be increased by moving the point S radially outward. The direction of the total thrust may be controlled by moving S in a circumferential direction. The point S is called the control point for this type of cycloidal propeller.

The pitch ratio of cycloidal propellers having true cycloidal blade motion is limited to about 0.62π due to the large angular accelerations involved in the blade motion near $\theta = 0^{\circ}$. As a result, this type of propeller cannot attain the high efficiencies associated with propeller operation at high pitch ratios. Only the first few Voith-Schneider propellers used true cycloidal blade motion. This type of blade motion does, however, present a simple picture of the principles by which the thrust of a cycloidal propeller is controlled in magnitude and direction.

Other blade motions do not have a single fixed control point as in the case of true blade motion. These motions are more easily described using the following procedure. Through the point O in Sketch 1, draw a line perpendicular to the line $\overline{OP}$. This line intersects the line $\overline{SP}$ at the point S'. The line $\overline{OS'}$ is denoted by r'. The line r' rotates with the line $\overline{OP}$ lagging it by 90°. From the right triangle OPS', one obtains the relation:

$$\frac{r'}{R} = \tan \beta \quad . \tag{27}$$

Different blade motions may now be specified by the path traced by the point S' as r' rotates. This path is called the control path. The shape of the control path is specified for each blade motion by Eq. 27. For each type of blade motion, the magnitude of the total thrust is changed by increasing or decreasing r'/R at each θ, and the direction of the total thrust is controlled by displacing the control path in a circumferential direction without changing its shape. The pitch ratio in each case is still given by

$$p = \frac{\pi r_o}{R} = \pi \lambda_o \quad . \tag{28}$$

The control point, S, is useful for true cycloidal blade motion only. The control path for true cycloidal blade motion is given by

$$\frac{r'}{R} = \frac{\eta \sin \theta}{1 - \eta \cos \theta} \quad , \tag{29}$$

and the shapes of the control paths are shown in Fig. 2.

Kirsten-Boeing Propeller

The Kirsten-Boeing propeller uses a blade motion which is a special type of true cycloidal blade motion. For this propeller the control point is always on the blade orbit and hence the pitch of the propeller is constant and equal to π. This propeller has also been called both a fixed pitch and a π-pitch cycloidal propeller. The control path is given by Eq. 29, with η equal to one.

The Kirsten-Boeing propeller requires the use of doubly symmetric blade profiles which are disadvantageous, since they have poor lift-drag qualities when compared with airfoil profiles. Following a blade traveling along curve "B" in Fig. 1, it is evident that, as a blade passes through a cusp of its ordinary cycloidal path, the edge of profile which had been the leading edge in the previous cycle has become the trailing edge in the next cycle and vice versa. And since it is mechanically impossible for the blade to rotate instantaneously 180° at the cusp, the profile therefore must be doubly symmetric.

Amplified Cycloidal Blade Motion

With a small variation from true cycloidal blade motion the maximum obtainable pitch ratio for variable pitch cycloidal propellers can be increased. To obtain amplified cycloidal blade motion, the blade angle at each position θ is multiplied by a constant k. The Control path for this type of motion is given by

$$\frac{r'}{R} = \tan\left[k \tan^{-1} \frac{\eta \sin\theta}{1 - \eta\cos\theta}\right] , \qquad (30)$$

where η is the pitch of the true cycloidal blade motion divided by π, on which the amplified motion is based. The pitch of the amplified motion is not equal to $\pi\eta$ but is greater than $\pi\eta$ by an amount depending on k.

The maximum obtainable pitch ratio of cycloidal propellers with amplified cycloidal blade motion at the present time is about 0.73π. This limit is due to acceleration stresses as in cycloidal propellers having true cycloidal motion. All of the Voith-Schneider propellers have used amplified motion except the first few which used true cycloidal blade motion.

Sinusoidal Blade Motion

The mechanisms used to produce the aforementioned motions have the disadvantage of mechanical complexity. Sinusoidal blade motion can be produced with a comparatively simple arrangement. The control path for this type of motion is given by

$$\frac{r'}{R} = \tan\left(\beta_o \sin \theta\right) \qquad , \tag{31}$$

where β_o is amplitude of the blade motion, and the blade angle varies sinusoidally with θ .

The efficiency of a cycloidal propeller with sinusoidal blade motion does not compare favorably with other types. While it has been favored for its simple, rugged construction, experience has indicated that more complex mechanical systems are no less dependable.

Cycloidal propellers using curtate cycloidal motion have not been used in the marine field. The lifts on the blades of these propellers have large T_y components. The resulting increased blade loading increases blade stresses and the danger of cavitation becomes more imminent. This type of motion may be good for very high speed craft. Hydrodynamically it has a great resemblance to the operation of a fish tail.

Types of Installations

Most applications of cycloidal propulsion have been to ships which, otherwise, are typical of their respective class of vessel. But, as may be expected, when a radically different component is applied to a device in a given circumstance, the device also will be changed somewhat. This is true of cycloidal propellers. Such a device is the Voith water tractor which is a tug boat fitted with cycloidal propulsion. (See Ref. 6) The propellers are fitted in the forward third of the ship length, and the towing bit is usually all the way aft. Experience has shown that this arrangement gives better maneuveratility under all circumstances than arrangements on conventional tugs.

Table I on the following page gives a description of all installations produced by the Pacific Car and Foundry Company, Renton, Washington. Table II gives a description of several representative installations produced by the J.M. Voith Company, Heidenheim (Brenz) and Bremen, Germany.

TABLE I				
INSTALLATIONS PRODUCED BY PACIFIC CAR AND FOUNDRY COMPANY				
Ship	Type	No. of Props.	Horsepower (U.S.) Per Propeller	Owner
MTL-951	42-ft. Tug	2	70	U.S. Army Trans. Corps
LSM-458	Landing Ship	2	1800	U.S. Navy
MTL-2336	40-ft. Push Boat	1	135	U.S. Army Trans. Corps
Northampton	Ferry	1	900(steering prop.)	Virginia Ferry Corps
PT-8	Exptl. PT Boat	2	1500	U.S. Navy
LTI-2194	Towboat	2	1000	U.S. Army Trans. Corps.

TABLE II					
TYPICAL INSTALLATIONS BY J.M. VOITH COMPANY					
Year	Type	No. of Props.	Horsepower (Metric)	Nationality of Owner	Length-Beam-Draft (feet-inches)
1942	Mine sweeper	2	900	German	122 x 19 x 4-8
1953	Sea-going airplane salvage ship	2	2200	French	215 x 34-10 x 8-6
1955	Trawler	2	600	German	204 x 32-10 x 13
1956	Bow steering propeller for train ferry	1	1000	German	446 x 62-5 x 15-9
1957	Self propelled barge	2	220	Belgium	220 x 27 x 8-3
1957	Double ended vehicle ferry	2	385	Japanese	155 x 34 x 6-6
1957	Water tractors	2	420	German	75 x 20-4 x 9-6
1957	Bow steering prop. for grab and section dredge	1	70	New Zealand	200 x 40 x 11-6
1957	Water tractor	1	750	German	75 x 20-6 x 9-10
1958	Bow steering propeller for tanker	1	180	Canada	160 x 34 x 12
1958	SM boat	2	2000	German	141 x 22 x 6-5
1958	Double ended ferry	2	100	German	78 x 31-6 x 4

SURVEY OF LITERATURE ON HYDRODYNAMICS OF CYCLOIDAL PROPELLERS

The kinematics of the blade motion and ideal flow associated with a cycloidal propeller having true cycloidal blade motion have been studied intensively. Both Kirsten[1] and Schneider[2] have presented papers in which the fundamentals of such propellers are discussed. In these papers the relative motion between the blade and fluid is derived neglecting all induced velocities. Schneider's paper contains an elaborate geometric development of the blade motion and of the flow relative to the blade for a wide variety of conditions which may be realized with a propeller having true cycloidal blade motion. Since aspect ratio, unsteady flow and blade interactions play an important role in the theory of cycloidal propulsion, these papers are only of academic interest.

The first attempt to extend the theoretical investigations to include induced velocity effects was made in 1931 by Krietner[7]. No explicit theoretical results were given, but he discussed the effects of a downwash at each blade equal to one-half of the ultimate wake velocity which is obtained from the application of the momentum theory. Krietner indicated that the results of his investigation were valuable in showing trends due to changes in the propeller characteristics. This approach attempts to correct Kirsten's and Schneider's ideal, two-dimensional results for aspect ratio or induced downwash velocity. Krietner's method is inaccurate since, first of all, it is based on an assumed ultimate wake velocity distribution and, secondly, because the downwash velocity distribution around the orbit is assumed to be one-half of the assumed wake velocity distribution. These assumptions are hard to believe without experimental varification in view of the complicated structure of a wake.

Krietner also discussed several theoretical investigations which were performed. The effect of blade camber was investigated using the empirical results of a series of tests on airfoils performed at Goettingen. He reports that a small camber results in highest efficiencies and that minor changes in camber have a disastrous effect on thrust and efficiency, but no numbers are given. Krietner also investigated optimum blade motion, and found that true cycloidal blade motion was close to being the optimum cycle of those studied. This result is logically explained by the fact that the maximum thrust occurs at the same position in the blade orbit as does the maximum value of instantaneous blade efficiency. Again no numerical results or comparisons are given, nor are the investigated blade motions described.

In addition, Krietner presented several empirical curves describing the operational characteristics of a Voith-Schneider propeller, and compared the effective horsepowers of two comparable designs of a passenger ship, one of which was designed for screw propulsion and the other for a Voith-Schneider propeller. The results show an eight percent to 15 percent lower effective horsepower for the Voith-Schneider propelled design.

Just[8] in 1939 continued the theoretical development of cycloidal propellers with an attempt to include unsteady effects. Momentum theory is applied to an actuator cylinder in two dimensions, i.e., to a cylinder whose axis is perpendicular to the flow direction and which has the property of radially accelerating the fluid which passes through its surface. An expression for thrust is presented as a result of this approach. The efficiencies, as derived by Just for this actuator cylinder, lead to erroneous conclusions since they were based on the projected area of the cylinder. If these efficiencies had been based on the peripheral area $(2\pi RL)$ of the cylinder, then a valid comparison with actuator disc theory could have been made. The assumptions made by Just in setting up the mathematical model for the momentum analysis are not clearly described.

Just[8] then applied an unsteady aerodynamic theory of Glauert to a cycloidal propeller. Velocities induced by tip vortices were also included. It is stated that the results are in good agreement with experiments. This approach is open to doubt on several counts. The interaction between the bound vortex at each blade was not included. Secondly, it was assumed that the angle of attack varies sinusoidally. This assumption is not true of the type of propeller to which Just compared his results. In applying unsteady aerodynamic theory and in Just's representation of the tip vortices, it is assumed that the blade travels in a straight line. Looking at curve "A" of Fig. 1, it is seen that this is not true, especially at the small loop in the path where, in fact, the lift is relatively large.

By far the most complete theoretical treatment of cycloidal propellers is given in two papers by Issay[9,10]. The method presented in these papers, although cumbersome, gives the propeller thrust, torque and efficiency, all of which agree with experiment within 10 percent to 20 percent. Several numerical examples are worked out to illustrate the method of calculation applied to a six-bladed propeller. One example is worked out for a four-bladed propeller as well. This method, however, treats only the two-dimensional problem. Aspect ratio and wake contraction effects would account for a large part of the above indicated discrepancy between Issay's theory and experimental results. Issay begins by expressing the velocities induced at an arbitrary point by the motion of the blade axis through the fluid (kinematic velocities), the bound circulation existing on each blade (bound vorticity and blade interactions), and the vorticity continuously shed in the wake of each blade (unsteady effect). An integral equation involving a double integral is derived from the boundary condition. The equation involves the unknown vorticity distribution, which is a cyclic function of time, on any blade. A solution is obtained by an iteration procedure. Knowing the two-dimensional circulation distribution, the thrust, moment and efficiency can be determined. In this method it is assumed that the propeller is operating at a negligibly small advance ratio. Issay indicates that this assumption is good up to an advance ratio of 0.5. Issay[10] shows that the inclusion of advance ratio in this method, leads to physically unrealistic results. Due to the induced velocities, Issay shows in his numerical examples that it is necessary to rotate the control path through an angle of about five degrees in order to have thrust directly ahead. As a result of this, there is a decrease in efficiency of about five percent.

SCREW VERSUS CYCLOIDAL PROPULSION

The most outstanding advantage of ships equipped with cycloidal propellers, as compared with screw propulsion, is their maneuverability. When operating at a load coefficient equal to one, an athwartships force of over three times the ahead thrust can be developed at the same rpm. At a load coefficient equal to one-half, the available steering force is six times the ahead thrust at the same rpm. At low speeds the ratio of steering force to ahead thrust is equal to one. A cycloidal propeller can develop a steering force of from two to three times the ahead thrust at the same power under most operating conditions. As a result, a ship equipped with cycloidal propulsion is more easily controlled during any ship maneuver.

The range of pitch settings of a variable pitch screw propeller is -0.60 to +1.20. For a cycloidal propeller with amplified cycloidal blade motion the range of pitch is -2.30 to +2.30. The range for ahead thrust with a cycloidal propeller is nearly twice that of a variable pitch screw propeller. Thus, a cycloidal propeller provides a means of realizing the optimum combination of torque, pitch ratio and engine rpm over a wider range of load conditions than does a screw propeller. If a large variety of load conditions is anticipated, then cycloidal propulsion may prove to be more economical in fuel consumption than screw propulsion. The resistance of a ship with appendages such as rudders, struts, and bossings exceeds the bare hull resistance by three to 15 percent. By using a cycloidal propeller the need for these appendages is eliminated, and hence another saving in fuel consumption is accomplished.

When the propeller dimensions for a particular design are chosen on the basis of severe draft limitations, a cycloidal propeller with a greater projected area than that of a screw propeller can be used. For instance, suppose that, due to the draft limitations, the largest screw propeller diameter usable is D_s. Its projected area is $(\pi/4)D_s^2$. In the same design situation, the blade length for a cycloidal propeller would be limited to D_s. The orbit diameter of a cycloidal propeller is between 1.5 and two times the blade length. Its projected area would be at least $1.5(D_s^2)$ or 1.91 times the projected area of the screw propeller. The efficiency of both propellers increases with decreasing load coefficient for the same thrust, and hence a higher efficiency results. (See Fig. 3) A cycloidal propeller, therefore, operates closer to its maximum efficiency than a screw propeller under these conditions. With the larger area, the danger of cavitation is also reduced in the case of cycloidal propellers.

Figure 3 shows a comparison of the propeller efficiency of a cycloidal propeller having amplified cycloidal blade motion and that of the Troost B4.55 screw propeller series. The efficiency of the cycloidal propeller with rotor A linkage was obtained from Fig. 10 of Kingsley[11]. In Kingsley's figure the cycloidal propeller efficiency obtained under operating conditions is plotted against load coefficient based on the projected area. The efficiency of the Troost B4.55 propeller was obtained from K_t , K_q , J curves presented by Van Lammeren, Troost and Koning[12]. Parabolas of constant K_t/J^2 were constructed on the B4.55, K_t - J graph, and the maximum propeller efficiency at each value of K_t/J^2 is plotted here in Fig. 3. When compared in this manner the efficiency of cycloidal propellers with a rotor A linkage is in the range 0.45 to 0.58 as compared to 0.66 to 0.76 for screw propellers.

Summarizing for a vessel requiring good maneuverability or large control forces, a cycloidal propeller will give much better results than a conventional screw propeller. For designs in which the propeller dimensions are limited, the propeller efficiencies of screw propellers and the presently used cycloidal propellers may be comparable. A decrease in fuel consumption may be realized by using cycloidal propulsion in lieu of screw propulsion if a vessel operates under a wide range of load conditions. The propeller efficiency of a cycloidal propeller is about 20 percentage points less than that of a screw propeller when compared at equivalent values of load coefficient.

RESEARCH NEEDED

In surveying current literature on cycloidal propellers, a mathematical model of a cycloidal propeller developed by Issay[9,10] is described. As stated previously, Issay indicates that the results from his theory agree within 20 percent with experimental data. In order to derive more accurate results, a more realistic theoretical model should be developed. The hydrodynamics of cycloidal propulsion are not sufficiently well known so that such a model may be established. In particular, the following topics require further investigation:

1. Kramer's Effect. It is known that the stall angle of a foil section changes with rotational velocity about a spanwise axis. (See Fung[13]) A cycloidal propeller blade experiences periodic changes in rotational velocity of this sort. As a result, the stall angle of the blade is changed. Experiments by the J.M. Voith Company indicate that the thrust of a cycloidal propeller is not reduced by the detrimental effects of stalling of its blade even when high angles of attack are involved. Research is needed to determine the effect of an angle of attack oscillation on the stall angle of a section and whether or not a cycloidal propeller could take advantage of this effect.

2. Traversing a Wake. According to Issay's[10] theory, when a blade passes through a vortex sheet induced by that blade or any other blade, a reversal of thrust occurs. This result does not agree with the experimentally observed variation of the thrust on a blade of a cycloidal propeller. Research is needed to determine the effect on a blade as it passes through a vortex sheet.

3. Wake Contraction. The contraction of the slipstream of an open water screw propeller is axially symmetric. Experiments indicate that the contraction of the wake of a cycloidal propeller in the spanwise direction of the blades is considerable, while that in an athwartships direction is small. In fact, the tip vortex from a blade in the front half of the orbit may pass through the midspan of a blade in the rear half of the orbit. Research is needed to determine the amount of wake contraction at various loads and its effect on the thrust and efficiency of the propeller.

There are several areas in which further research may indicate a means of improving the efficiency of cycloidal propellers. These are

1. Blade Motion, Amplified, true and sinusoidal blade motions have been used in all previous applications and are presently used in all installations of cycloidal propellers because of the relatively simple mechanical systems needed to produce these motions. However, if the blades were positioned by a mechanism which had no such limitations, i.e., hydraulic or electric control, then it is possible to produce a great variety of blade motions. With this possibility arises two questions: What is the optimum blade motion? How much of an increase in efficiency can be obtained by using an optimal blade motion? It is suggested that an experimental program of a fairly simple nature be carried out to find how much of an improvement in efficiency, if any, can be expected with an optimal blade motion. If this program indicates that a substantial improvement can be obtained, then combined theoretical and experimental research should be performed to determine the optimum blade motion under operating conditions. (A rather elementary investigation performed by the author indicates that improvements in efficiency over that of true cycloidal blade motion can be obtained by using one of the following blade motions: a motion such that the angle of attack of the blade is constant and equal to the angle of attack for minimum drag-lift ratio, or a motion such that 100 percent of the thrust is produced at the points of the orbit where the lift on the blade is directed straight ahead.)

2. Wake Adaption. In screw propulsion, it is known that the efficiency of a propeller will be improved if the pitch of each blade section is adapted to a radial variation in the inflow velocity. Similarly, with cycloidal propulsion, an increase in efficiency can be expected if the pitch of each blade section is adapted to an inflow velocity which varies along the axis of revolution of the propeller. If the blade axes are tilted such that, as the propeller revolves, the axes generate a conical surface whose vertex is at some point above the propeller, then the zero slip inflow velocity of each blade section along the span of the blades will increase linearly from the root of the blade to its tip. For an optimum propeller-ship combination, a flat stern is considered best. As a result, the inflow velocity varies from zero to free stream velocity along a line normal to the ship's bottom, but very little in a direction parallel to the bottom. (It should be noted that, in screw propulsion, there is a large circumferential variation in the inflow velocity which cannot be accommodated by a wake-adapted screw propeller whereas there is much less variation in inflow velocity along a circumferential path in a cycloidal propeller design.) Research is needed to determine if sufficiently large increases in efficiency can be obtained by employing a wake-adapted cycloidal propeller to warrant its use in spite of any additional costs.

3. Blade Proportions. High aspect ratio blades would improve the efficiency of cycloidal propellers. For structural reasons, the thickness ratio would have to be increased with increasing aspect ratio. Increasing the thickness ratio has two detrimental effects. It increases the drag-lift ratio and increases the danger of cavitation. It is not clear whether or not optimum proportions for blades have been achieved. A study should be undertaken to determine the best combination of aspect ratio and thickness ratio.

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FIG. 1

PROPERTIES OF CYCLOIDAL PROPELLERS AT ZERO SLIP

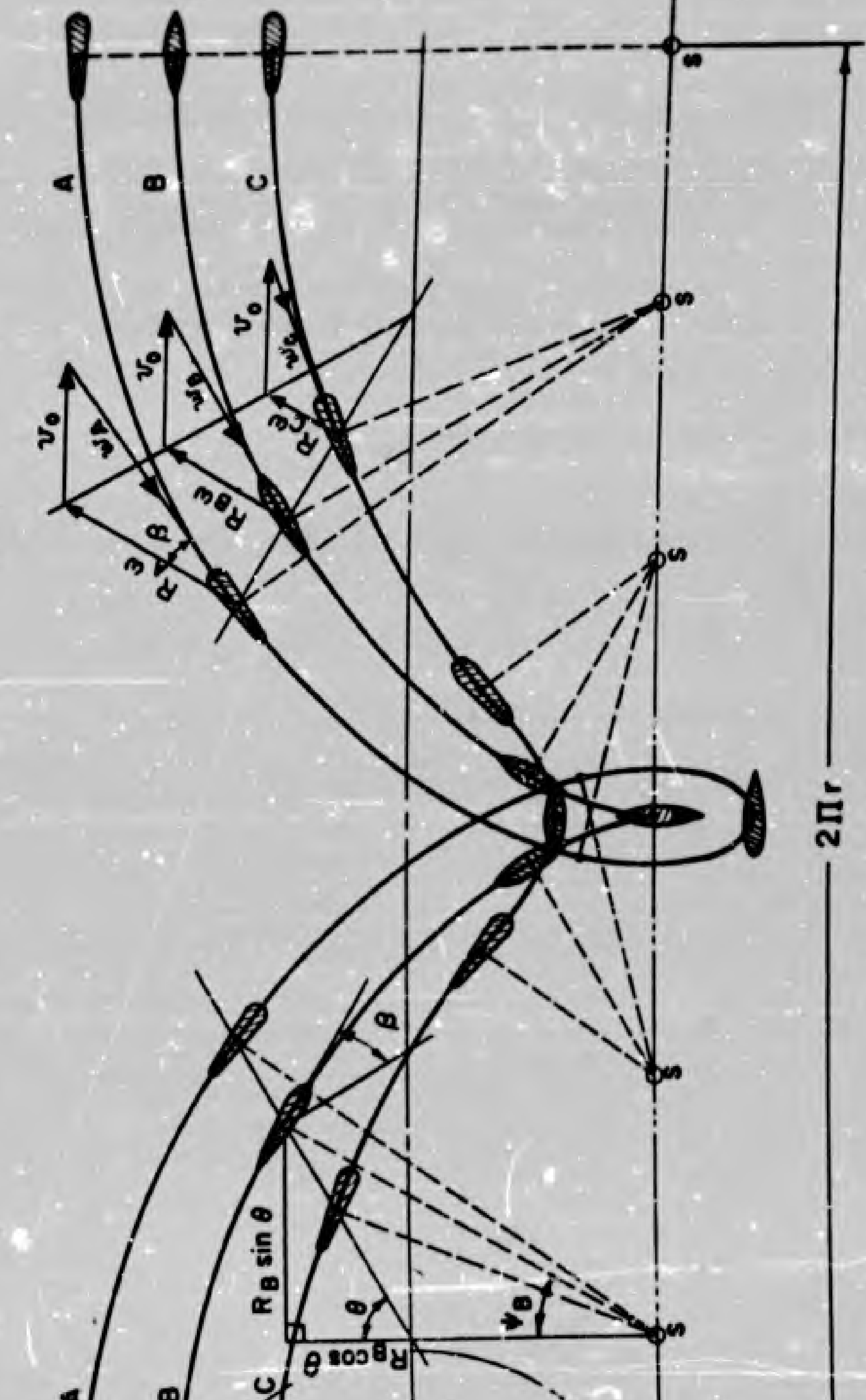

FIG. 2

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RELATIVE SHAPE OF CONTROL PATHS FOR AHEAD OPERATION

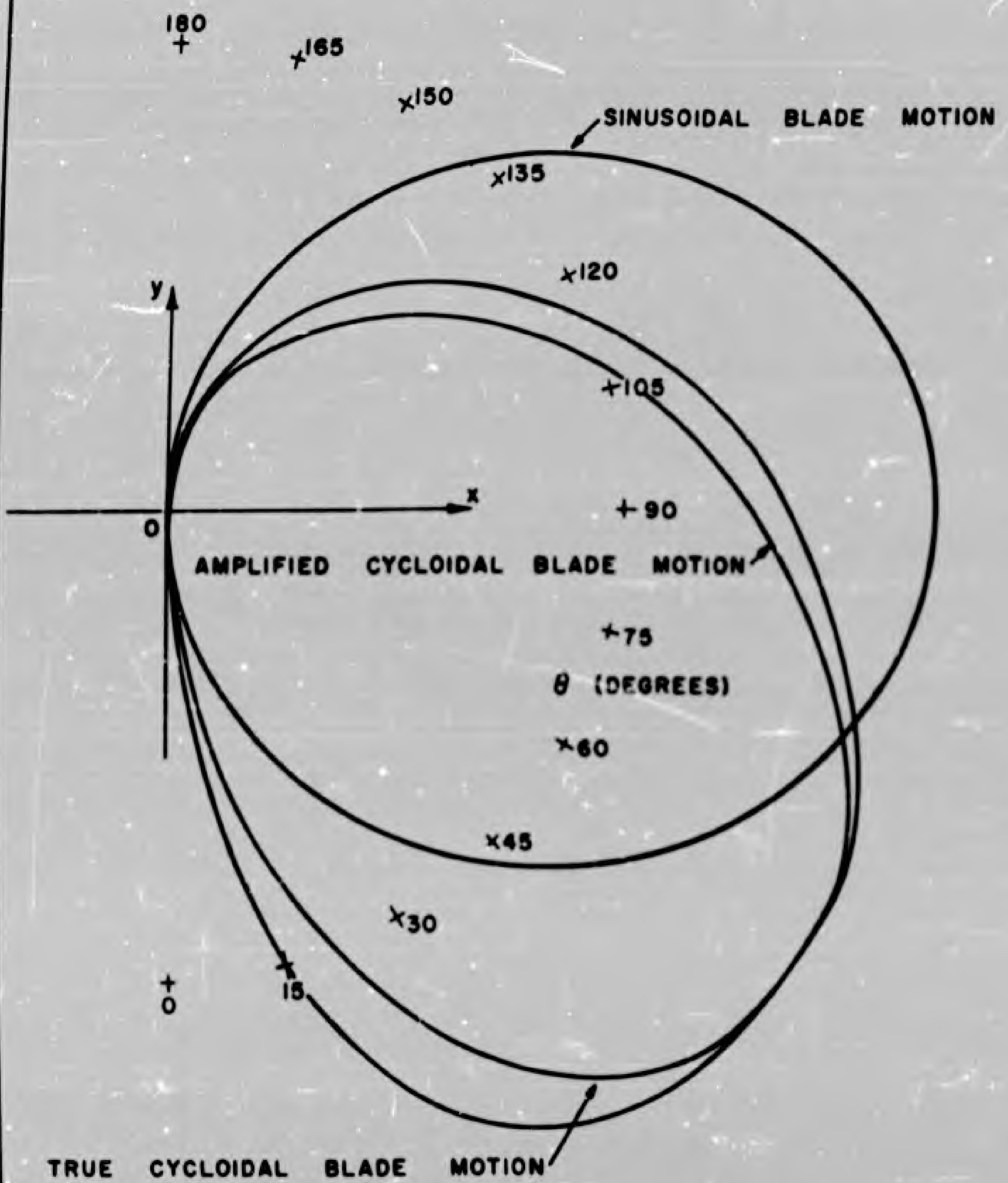

FIG 3

COMPARISON OF PROPELLER EFFICIENCIES