Report 1531

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN

HYDROMECHANICS

○

AERODYNAMICS

○

STRUCTURAL
MECHANICS

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APPLIED
MATHEMATICS

ANALYSIS AND INVESTIGATION OF PROPELLER BLADE STRESSES
PART I

by

E. Venning, Jr., LCDR, USN
and
T. E. Reynolds

[redacted]

HYDROMECHANICS LABORATORY
and
STRUCTURAL MECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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NOTATION

c	Distance from neutral axis to fiber being considered
HP	Horsepower
I	Moment of inertia about neutral axis
M	Local bending moment
RPM	Revolutions per minute
s	Local direct bending stress
σ	Direct stress
τ	Shear stress

ABSTRACT

Failures in service of wide bladed marine propellers indicate that the design stage stress analysis may have engendered a false sense of security in the propeller's strength. The Taylor method of stress analysis is accordingly examined and compared with a newly developed shell theory of stress analysis. The results of certain photoelastic experimental work are also reported as verifying that actual stress distributions in propellers are different from those predicted by the Taylor Method.

INTRODUCTION

Naval architects engaged in marine propeller design have long recognized the inadequacies of the simple cantilever beam stress analysis in its application to certain propeller blades. These shortcomings have been shown to exist by reason of known failures in service of propellers that presumably had been particularly designed for the conditions under which they were operating. During efforts to discover the reason for these failures, suspicion has fallen on the original stress analysis and on the justification for utilizing simple beam theory in this stress analysis.

From study of damaged propellers it has been evident that metallurgical deficiencies and collisons with underwater obstructions usually have not caused the failures. Rather, it has appeared that failure was due to simple overloading in the immediate areas of failure. Since the beam theory stress analysis had indicated there was adequacy of strength it could only be concluded that the actual stress level at time of failure had been higher than predicted.

Further study indicates that failure of propellers designed by beam theory has been more frequent in the case of wide bladed propellers than for narrow blades. These wide bladed propellers may incorporate considerable variation in pitch and employ cross sections that are very thin.

Consequently, they are more nearly like thin shell type structures. For this reason shell type analyses of the stresses caused by hydrodynamic loading would seem to be more in keeping with the geometry of the structure. The desirability of such a shell type analysis has been world-widely recognized by naval architects; however, a search of the literature will indicate that efforts at the development of a truly rigorous, dependable shell analysis applicable to the marine propeller have been singularly few and generally unsuccessful. See references and Appendix I.

This lack of success has not been due to a misunderstanding of the problem, but more because of the mathematical complexity of the calculations associated with the shell analysis. The availability of modern high speed computing machines helps to remove much of the onerousness of the problem, so the real need has reduced to that of development of a suitable and reliable shell theory applicable to marine propellers. The David Taylor Model Basin in cooperation with the Office of Naval Research has therefore initiated an experimental and theoretical program aimed at the development of just such a shell type analysis. Accordingly, this two part report attempts to present information which will indicate:

1. The various shortcomings of the simple beam theory.
2. The more rigorous approach of the proposed shell analysis being developed.
3. The actual distribution of stresses in propeller blades as compared with simple beams.
4. The comparison between stresses predicted by applied shell theory and those actually measured by use of electrical strain gages.
5. The utilization of applied shell theory in actual design work and comparison with results predicted from beam theory.

BEAM THEORY

Practical application of elementary, cantilever beam theory in the design of marine propellers undoubtedly was utilized in the early 1800's by such competent engineers of that period as John Ericsson; however, in modern times, D. W. Taylor is credited with having formally published one of the first papers on such an application[1]. The fact that in 130 years there have been so many successful propellers and comparatively so few failures emphasizes the general validity of this application. Indeed, for narrow bladed propellers of low pitch, it is quite reasonable to treat the structure as a simple, single cantilever beam. However, when the blades become wide and thin, and radially varying pitch is introduced, then the validity of such an application is open to question.

It is to be recognized that in essence Taylor's application of the beam theory reduces the complex effects of hydrodynamic loading on the blades to the more simplified effect of a distributed resultant loading along a single cantilever beam of varying cross-section. Thereafter, the elementary, basic formula

$$s = \pm Mc/I$$

is used to predict the magnitude of the local maximum bending stresses that will occur for a given loading. Inherently, this approach neglects two fundamental facts that become critically important as the geometry of the propeller changes.

First, Taylor's distributed resultant loading is expressed as bending moments acting perpendicular and parallel to the blade face at the center point of each radial section. See Figure 1. As pointed out in Reference 2, such a simplification of the hydrodynamic loading neglects localized reactions to possible peaked pressure loadings. These may arise because of the hydrodynamic pressure distribution across the radial sections of the blades. As shown in Figure 2, these pressure peaks can be quite significant at some points over certain section shapes. Hence, the geometry of the radial section will exercise a governing influence as to whether or not such peaked loadings arise. Thus, it is quite reasonable to expect that these

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[1] References are listed on page 11

peaks in loading may be cause for high concentrations of stress in propeller blades that are relatively very thin as compared with their corresponding chord lengths. It is undoubtedly the presence of these stress concentrations due to hydrodynamic pressure peaks that have been a contributing cause of service failure of some wide, thin bladed propellers. During the design of these propellers, utilization of a modified Taylor beam analysis had been cause for not considering the effect of these peak loadings.

Further, consideration of Reference 1 indicates that the Taylor analysis considers both compressive and tensile bending stresses as well as the normal stresses caused by centrifugal force. However, transverse shear and torsional shear stresses caused by the pressure distribution are not considered. This may not be a shortcoming of any significance, provided this analysis is used for the narrow bladed, parabolic sectioned propellers such as Taylor employed in 1910. But, for modern, wide bladed, thin, airfoil sectioned propellers having peaked pressure loadings, one cannot neglect the definite existence of these shear loadings. It is possible that the presence of combined shear, direct, and bending stresses in thin bladed propellers can give rise to local maximum principal stresses and maximum shear stresses that may be twice as large as the individual direct and shear stresses. This point is best illustrated by the usual Mohr's circle diagram shown in Figure 3. It is probably the presence of these principal stresses that has also contributed to the cause of service failures of some wide, thin bladed propellers. Perhaps this has been the main source of the excessive stress levels that were not revealed by the conventional Taylor method of stress analysis.

Now, in recent experimental work at the Model Basin it has been further established that the distribution of stresses in propeller blades under hydrodynamic loading is not the same as would occur in a simple single cantilever beam. This added discrepancy is discussed more fully in another section of this report.

In summation, the fact that (1) the Taylor method does not consider the presence of certain localized concentrations of loading, (2) that it considers only direct stresses and not combined principal stresses, and (3) that it ignores a stress distribution significantly different from that of a single cantilever beam is considered to be its most unacceptable shortcoming. Frequently, it has been pointed out by others, as Rosingh[3,4] and Hancock[5], that Taylor's consideration of the bending stresses in blade sections cut by a cylinder are different from those occuring in plane sections as is the usual case when using elementary beam theory. This approximation of Taylor's for reasons of simplification is considered to be no worse than his assumption that the propeller acts as a single cantilever beam. As has been stated before, Taylor's method works well with the type of propellers he utilized in 1910; rather, it is encumbent upon the modern naval architect to recognize that Taylor was not concerned with thin, wide bladed propellers. Thus, some shortcomings of his method may arise from improper application rather than from lack of rigorousness on Taylor's part. Significantly, recent work of both an analytical and experimental nature done by Cohen[6] and the Shipbuilding Research Association of Japan[7] has shown that Taylor's method can still be recommended for the practical strength calculations of narrow bladed propellers.

SHELL THEORY

The desirability of applying shell theory to the wide marine propeller blade has been well recognized, but various mathematical difficulties have been an everpresent impediment. Cohen's[6] very notable recent effort to develop a rigorous shell analysis required a number of assumptions and resulting approximations in order to achieve mathematical tractability. As a consequence, Cohen was able to conclude only that his method and Taylor's were equivalent. More recently, Conolly[8] also has been faced by similar mathematical difficulty in an application of shell theory to propeller blades. Thus, it is to be realized that there is no easy road to success in this application of shell theory.

Nevertheless, the need for a workable method of analyzing stresses in wide bladed propellers by shell theory remains. Thus, under Contract

Number Nonr-3072 (00) (x) with the Model Basin, the General Applied Science Laboratories, Inc., of Westbury, L.I., New York, has developed such an analysis[9]. This analysis is programmed for solution on an electronic computer which greatly reduces the time required in its utilization.

The analysis has been specifically developed to permit its use in practical propeller design problems. The effects on blade geometry caused by changes in camber or pitch (as a function of radial position along the blade) are considered. Additionally, not only is section shape an input into the program, but also the particular pressure loading on that section. In this way, the presence of possible pressure peaks is not ignored as in the Taylor method.

In the development of this analysis, use has been made of basic distortion energy theory and accordingly the presence of principal stresses is duly considered. Regarding the distribution of stresses, it does remain necessary to check this new shell analysis against experimental results for various possible loading conditions. The second part of this report, to be issued subsequently, will treat this consideration in more detail.

The fact that this new analysis has been developed around usage of electronic computers has not lessened the basic mathematical difficulties that have plagued others. During development of this analysis, which employs tensor analysis techniques, it was found necessary to increase significantly the number of degrees of freedom in order to improve on the accuracy of the solution. Thus the pioneer efforts of Cohen and Conolly to overcome mathematical difficulties are vindicated by this latest work. Part II of this report subsequently will establish a comparison with the Taylor method so that a conclusion may be reached as to the worth of this new analysis.

STRESS DISTRIBUTION

OBJECTIVES

In anticipation of the eventual need to experimentally prove the validity of the General Applied Science Laboratories' (hereafter referred to as G.A.S.L.) shell theory, the Model Basin has initiated an experimental program having these objectives:

1. To determine the general nature of the stress distribution in typical modern wide bladed propellers.
2. To establish the location of highly stressed areas in some of these typical modern propellers so as to permit intelligent positioning of electrical strain gages.
3. To compare experimentally determined stresses with stresses predicted by the G.A.S.L. shell theory and the Taylor method.

At this time, only the first two objectives have been considered; later, in Part II, the results of consideration of the third objective will be reported.

EXPERIMENTAL METHOD

Having considered the experimental stress measurement work done earlier by Rosingh[4], Biezeno[10], Romsom[11], the Shipbuilding Research Association of Japan[7], and Conolly[8], it was decided to utilize a photoelastic approach in the initial determination of stress distributions in model propellers. Generally, experimental work employing electrical strain gages submerged in a water environment have been beset with electrical continuity problems. Since the qualitative nature of changes in stress distribution was considered to be of primary interest rather than quantitative numerical data, it appeared that photoelastic methods would provide a ready answer to the nature of stress distributions in propellers under hydrodynamic loading.

Using a plastic, bi-refringent material manufactured by the Tatnall Measuring Systems Co., single 0.08 inch thick layers of plastic were molded and attached to the blade contours of four model propellers. These propellers are shown in Figure 4. Some difficulties in achieving satisfactory molded sheets were experienced at the start of the program; however, these problems were solved eventually. The solutions to the various difficulties are presented in Appendix II.

The plastic coated propellers were placed in a water filled tank that was fitted with a heavy glass viewing port. The propellers were then brought up very close to the viewing port where they were driven by a

35 HP propeller dynamometer. In this manner, the nearest possible simulation to actual hydrodynamic loading was achieved.

While the propellers were turning in the otherwise still water, polarized white light, stroboscopically set to flash at a frequency equal to propeller RPM, was directed at the propellers. See Figure 5. The reflected light from the propeller blades was then viewed through a polaroid analyzing lens whose axis was at right angles to the axis of the lens achieving initial polarization of the white light. This arrangement constituted a simple plane polariscope, and it incorporated means to permit the usual rotation of the lens.

RESULTS

By controlling the propeller RPM it was feasible to achieve a variety of thrust loadings, and as these loadings were changed an observer could actually see definite lines of stress distribution in the plastic coatings. These lines were recorded by use of color photography but are presented herein as black and white photographs. See Figure 6.

Because of the manner in which the white light had to be projected onto the propeller blade and then viewed, it was not possible to satisfy the usual photoelastic requirement that the light pass at right angles through the bi-refringent material. Additionally, as the propeller RPM was increased, cavitation began to occur on the propeller blades. This condition, both on the blades and in the wake of the propeller, made viewing of the photoelastic patterns almost impossible.

It was not possible to control the thrust loading on the propeller blades to the fine point where definite tints of passage, or distinct changes in photoelastic fringe order, could be observed. In reality therefore, what was photoelastically observed were lines of stress distribution, that is, colored bands representing constant difference of principal stress. See Figure 7.

From a study of the photographs taken, it is possible to intuitively sense the meaning of these lines in terms of the stresses that result from the known hydrodynamic loading. Realization of the significance of the line orientation also follows from a knowledge of how certain propellers have failed. For example, in Figure 8 will be seen the lines of stress distribution for a model propeller which was tested to destruction as shown in Figure 9. From the arrangement of the stress distribution lines at the blade tips one would suspect that failure could probably occur as it did.

More importantly, from the standpoint of whether or not the Taylor method is properly applicable to wide bladed propellers, these photographs of the actual stress distributions have indicated that the directions of the stresses in propeller blades are not oriented as are the simple direct stresses in a single cantilever beam. See Figures 10 and 11.

Regarding the objective of establishing the location of highly stressed areas in typical modern propeller blades, it is repeated that no attempt was made to determine quantitatively the magnitude of the stress levels in the plastic coated blades. It was not possible to view the material at right angles, and additionally the same blade was not always viewed at the same rotary position. These difficulties plus that of attempting to synchronously photograph the observed photoelastic condition during the period of the stroboscopic flash all introduced considerable doubt as to the reliability of any stress magnitudes that might be inferred. Also, determination of stress levels in photoelastic studies requires a basic knowledge of the fringe order change as a function of applied load. As stated earlier, observance of distinct changes in fringe order was not possible.

Thus, from comparative study of the photographs taken of the propeller blades, it is observed that increases in thrust had the effect of causing an increased number of stress distribution lines to appear in the propellers that were considered. However, the relative spacing of these lines did not significantly change with load. See Figure 6. Accordingly, it was not possible to unequivocally designate certain areas in these blades as being characterized by high concentrations of stress merely from these photographs.

In summary, the objective of gaining some idea of the general nature of propeller stress distribution has been achieved. However, the establishment of the location of highly stressed areas by photoelastic means was not achieved in the propellers considered. This may mean that these particular propellers either did not contain such an undesirable condition or that the plastic coatings were not sensitive to the presence of such concentrations. Due to the previously mentioned difficulties in the use of the photoelastic method, it is not considered worthwhile pursuing the study of these concentrations any further by this approach.

CONCLUSIONS

The fact that wide bladed propellers are periodically failing in service requires that naval architects fully appreciate the limits on application of the Taylor method of propeller stress analysis. Because it ignores local concentrations of loading and does not consider the effect of biaxial principal stresses, it is reasonable to expect that the stress distributions predicted by the Taylor method are different from actual observed stress distributions. Photoelastic experiments have verified this to be the case, and loading tests to destruction have corroborated the significance of the photoelastic studies.

RECOMMENDATIONS

For the work still to be done in Part II of this report it is recommended that primary attention be paid to examining the nature of the static stress levels that arise around the leading and trailing edges of wide bladed propellers. Failures appear to be quite frequent in these outer areas. Since the objective of discovering stress concentrations by photoelastic means has not been successful, it will be necessary to base the location of electrical strain gages on this experience. Knowing that these edges are critical areas, a careful comparison of stresses caused by static point loads (measured in an air environment in the laboratory) with those predicted by the G.A.S.L. shell theory can be made for the same loading conditions.

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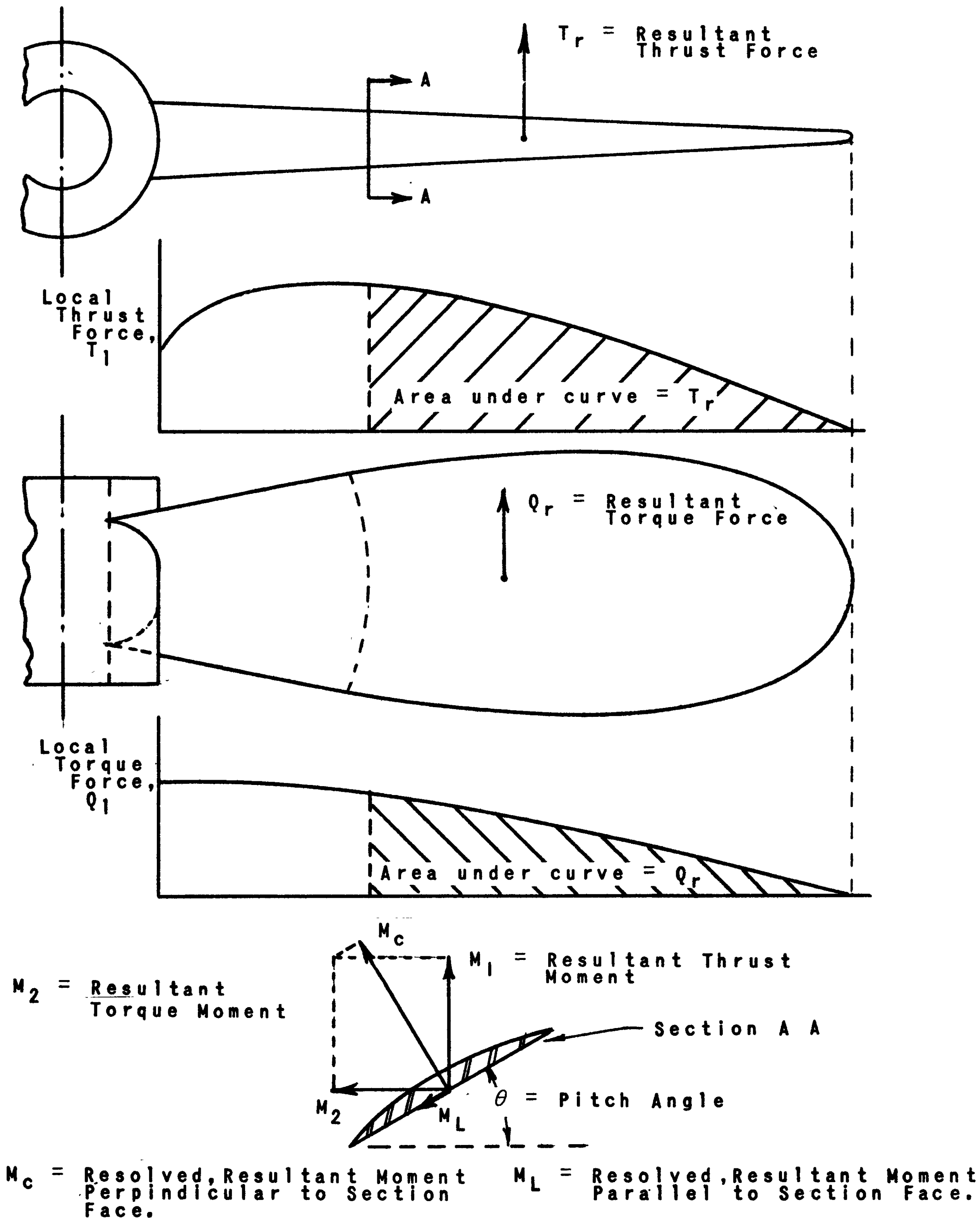


Figure 1 - Taylor's Resolution of Forces on a Propeller Blade

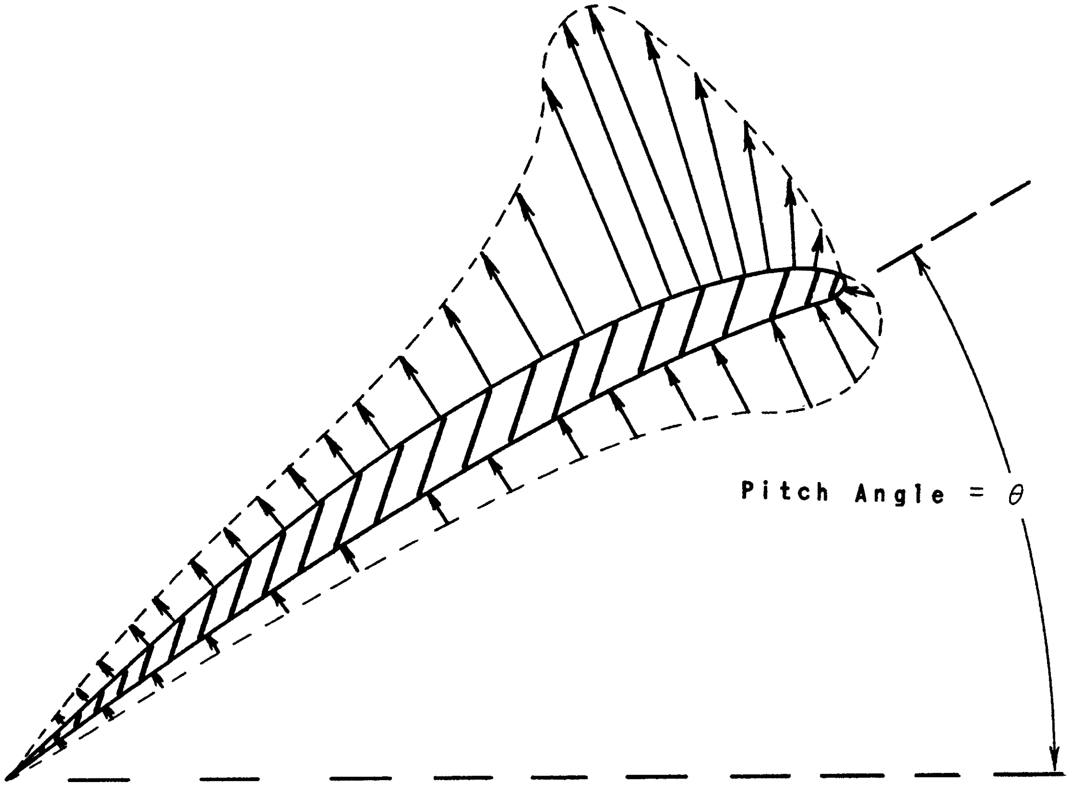


Figure 2 - Possible Peaked Pressure Loading on a Propeller Blade Section

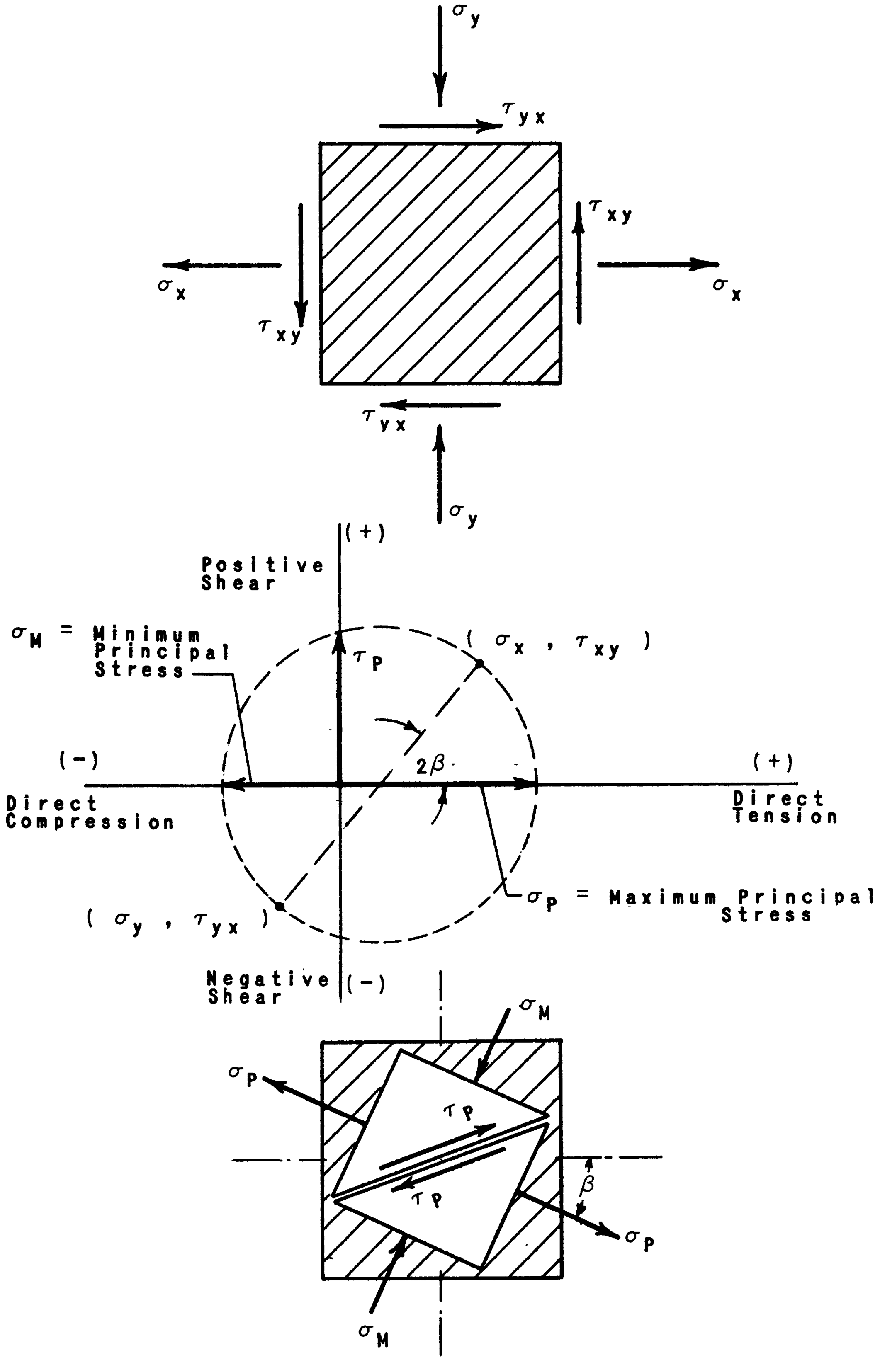
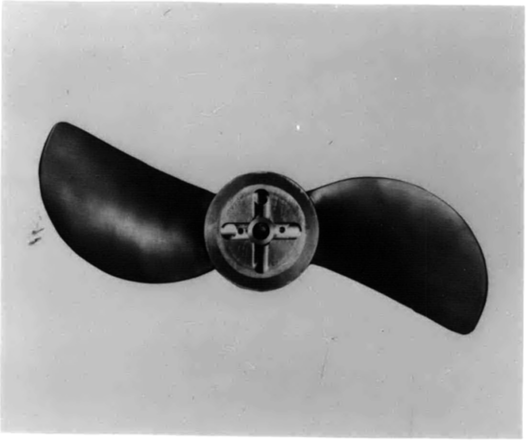


Figure 3 - Typical Mohr's Circle Diagram



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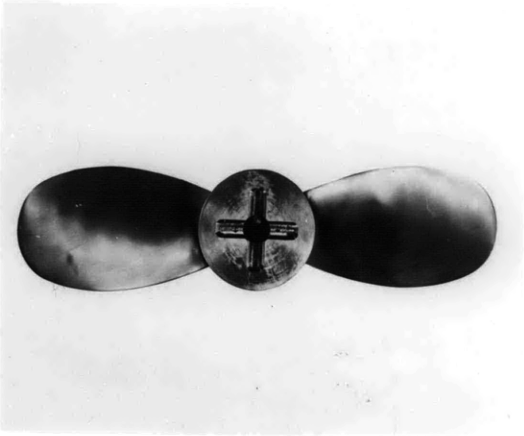
Prop. 3920



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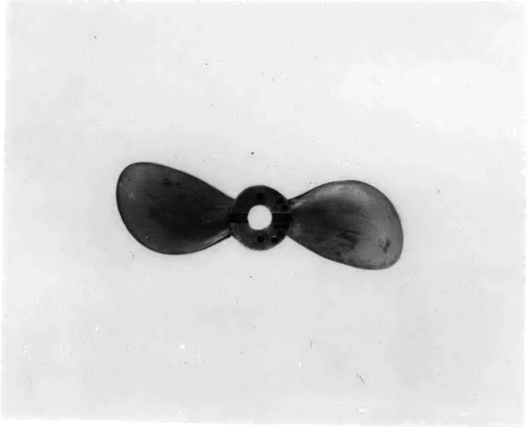

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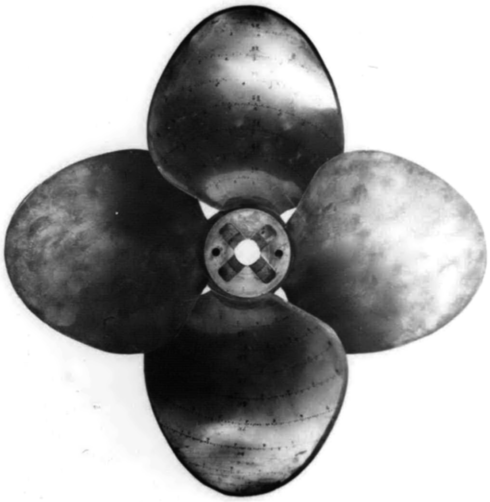


PSD 303019

Prop. 3707

Figure 4 - Photographs of Model Propellers

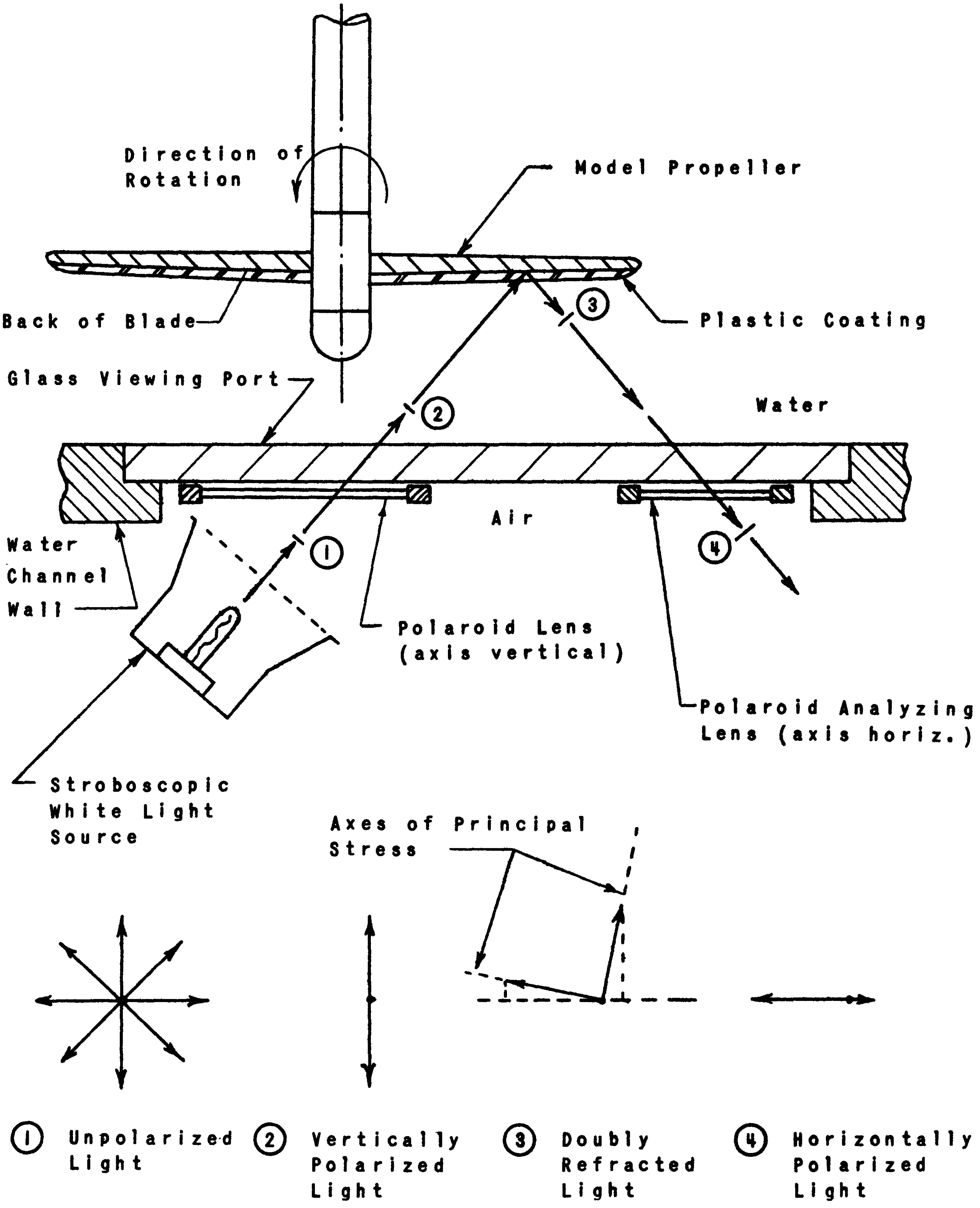
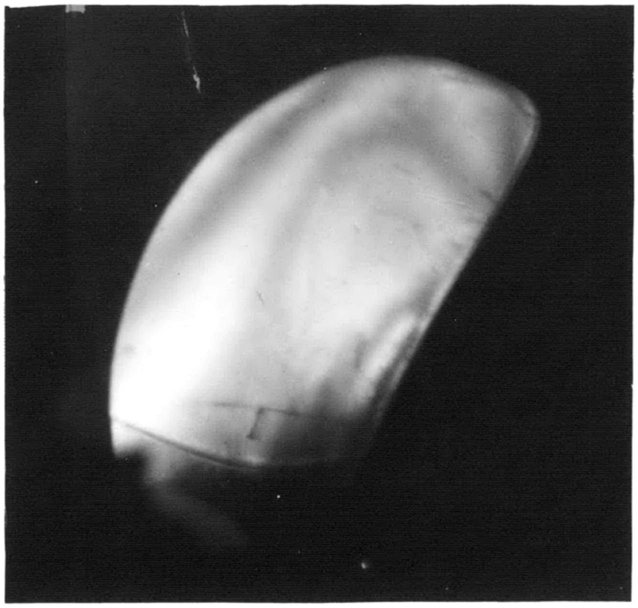


Figure 5 - Test Arrangement to Detect Photoelastic Stress Patterns



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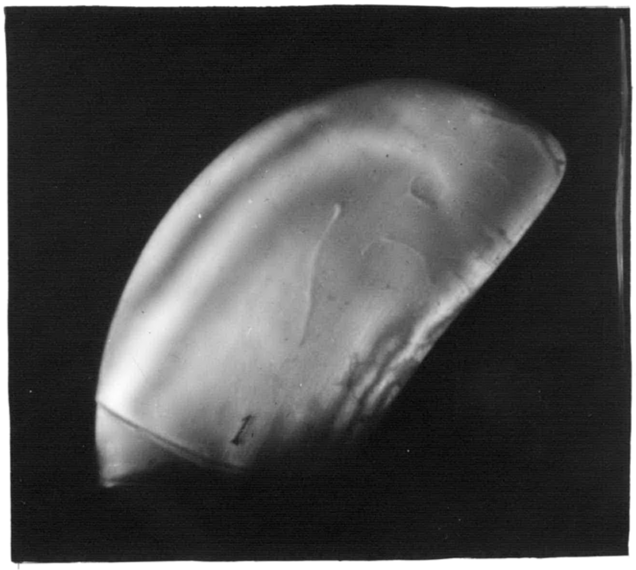

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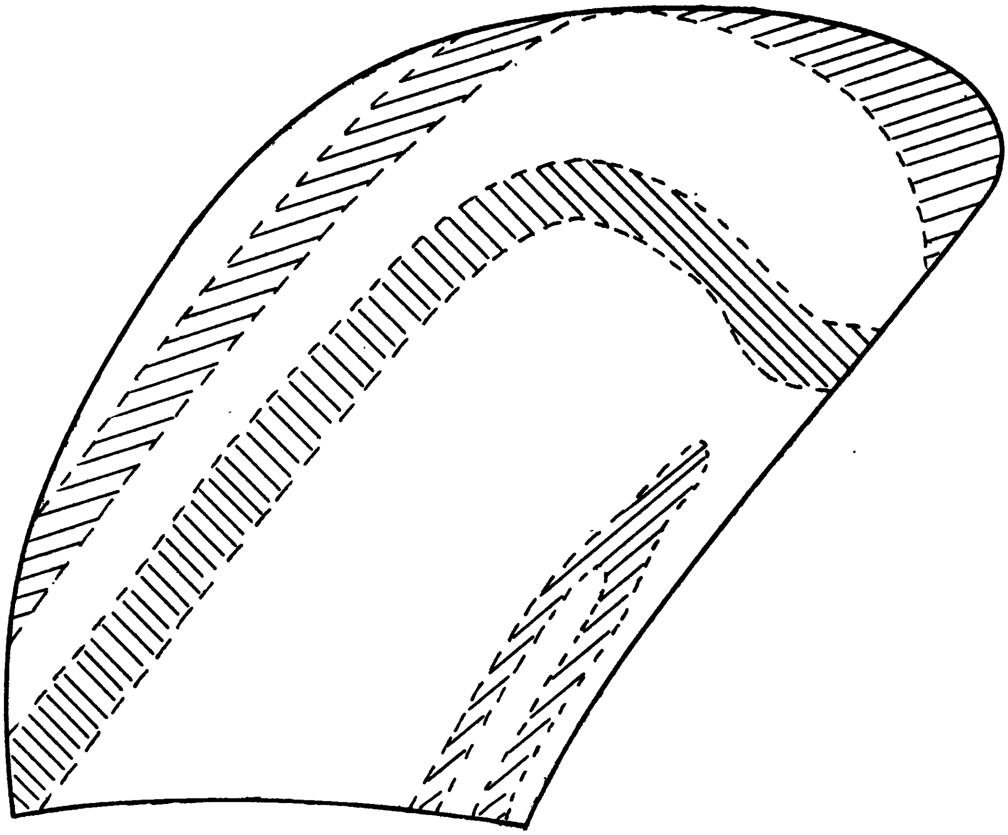
Figure 6 - Typical Stress Trajectory Patterns Caused by Hydrodynamic Loading



Each Band Represents a Different
Region of Constant Difference in
Principal Stresses.

Figure 7 - Significance of Photoelastic Stress Patterns

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Figure 8 - Stress Trajectories Before Failure

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Figure 9 - Actual Mode of Failure

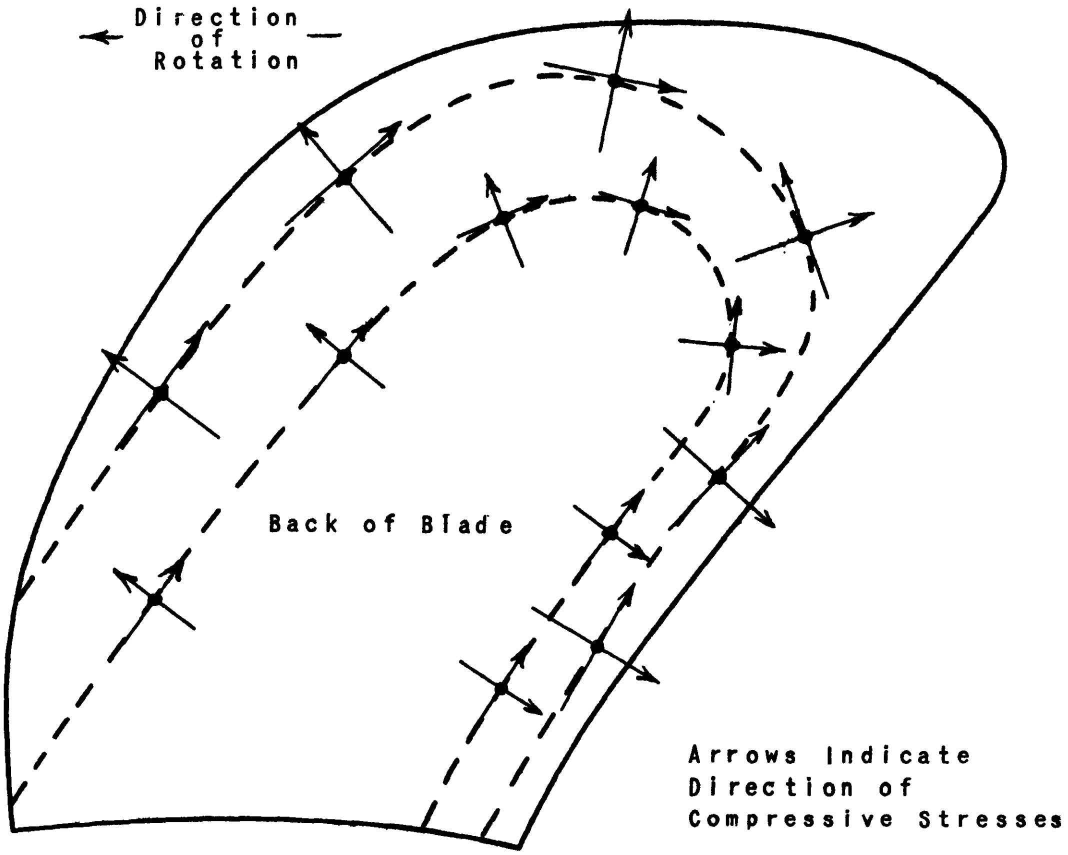

Figure 10 - Orientation of Simple Direct Stresses Based on Photoelastic Studies

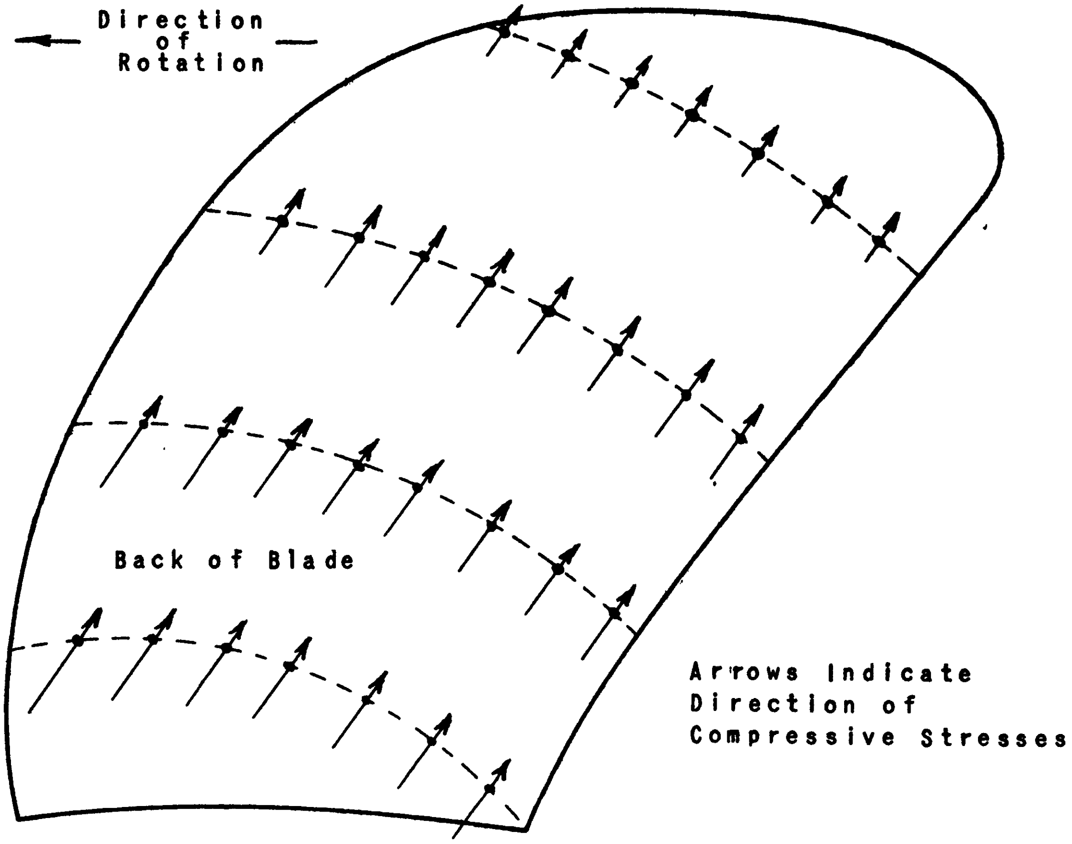

Figure 11 - Orientation of Simple Direct Stress Based on Taylor's Method

APPENDIX I

The following additional literature references are appended for possible use by some readers. This list is not to be considered as including all published literature on propeller strength calculations.

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APPENDIX II

The following paragraphs are intended to provide assistance to those who may wish to similarly apply bi-refringent plastic to model propeller blades.

As stated earlier, the material used was a product of the Tatnall Measuring Systems Co. called Photostress Plastic. In the beginning of the experimental program, attempts were made to use heated mixtures of liquid Photostress material and hardener. Following the manufacturer's suggestions as to mixing proportions and heating temperature, the liquid material was allowed to become plastic on a sheet of Teflon coated with a silicon releasing grease. This method proved unsuccessful because the Photostress material tended to solidify before it could be lifted from the Teflon sheet and molded to the shape of the propeller blade. Additionally, the material surface that had been in contact with the Teflon was sufficiently roughened to make it nearly opaque.

Attempts at use of cold mixtures of liquid Photostress material were next tried. This material was poured onto three different types of covered glass plate before a successful way to lift the soft plastic was found. First a glass plate was covered with domestic type Saran Wrap and then the liquid Photostress plastic was poured onto the Saran Wrap. It was found that it was impossible to remove the Saran Wrap from the soft plastic without great difficulty with the Wrap tearing and bonding at isolated points to the plastic. The only good thing about this method was that success was achieved in removing the plastic from the glass plate.

Next, glass plates coated with a special releasing varnish suggested by the manufacturer were used, but once again it was found extremely difficult to separate the plastic from the glass. When the plastic finally became free of the varnished plate, it was found that the plastic was no longer sufficiently soft to permit molding it to the propeller blades.

Finally, the glass plates were first thinly coated with mineral oil over which another domestic type plastic wrap called Reynolon was laid.

Mold forms made of thin aluminum bars were laid beneath the Reynolon so as to contain the liquid Photostress material on the plate. Then the material was poured to a thickness of 0.08 inch and allowed to become plastic during a 2½ hour period.

Next, the softly plastic Photostress material was lifted from the glass plate and was easily separated from the Reynolon. In the meanwhile, the model propeller blades had been coated with mineral oil as had been the hands of the person who was to mold the plastic to the shape of the blades. The plastic coating was then cut with scissors to the rough outline of the blades and was next formed onto the blades in shape. Considerable care has to be exercised to prevent leaving fingerprints in the soft plastic as well as preventing locked-in stresses from occuring. Such stresses will be caused by forced bending of the semi-plastic Photostress material after it has ceased to be sufficiently plastic to permit it to bend to a new shape. When this forced bending is achieved by use of tapes stuck to the material's surface, resultant locked-in stresses are almost inevitable.

The Photostress material was allowed to harden for twenty-four hours while resting on the propeller blades. Following this hardening period the coatings are then cut to a more exact outline of the blades and are then glued to the blades by use of special Photostress adhesive material. Once again, a hardening period of twenty-four hours is allowed to elapse, and then the attached coating is scraped and filed down to the exact shape of the blade edges. These coating edges are rounded and faired to make them hydrodynamically smooth. In all of these scraping and filing operations extreme care has to be taken to avoid injuring the face of the coating through which light must be reflected. Finally, it is noted that the Photostress material is easily worked once it is hard and there is little danger of causing locked-in stresses due to mechanical working.

With regard to photoelastic performance of the metal blade - plastic coating combination it was found that a metal having a low modulus of elasticity had to be utilized in order to cause visible stress distribution lines in the coating. For this reason, a special alloy of tin and bismuth, called "white metal", was employed in all propellers tested, except Propeller No. 3707.

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