PRELIMINARY DESIGN OF A VARIABLE PITCH,

TROPOSKEIN BLADE FOR THE DARRIEUS WIND TURBINE


by


David Roland Mustelier


SUBMITTED TO THE DEPARTMENT OF
MECHANICAL ENGINEERING IN PARTIAL
FULFILLMENT OF THE
REQUIREMENTS FOR THE
DEGREE OF

BACHELOR OF SCIENCE


at the


MASSACHUSETTS INSTITUTE OF TECHNOLOGY

January 1982


ⓒ   David Roland Mustelier

Signature of Author _____
                        Department of Mechanical Engineering
                                        January 25, 1982


Certified by _____
                                        N. D. Ham
                                        Thesis Supervisor


Accepted by _____
              Chairman, Undergraduate Thesis Committee

PRELIMINARY DESIGN OF A VARIABLE PITCH,

TROPOSKEIN BLADE FOR THE DARRIEUS WIND TURBINE

by

David Roland Mustelier

A list of design inputs are presented along with
criteria for the selection of desired design parameters.
A design is proposed using a chordwise stiffened, flex-
ible foam for the blades.  Two spars running the length
of the blades, with an approximate troposkein shape, are
used to provide the load-carrying member and the pitch
control member for the design.  A one-meter model is
constructed for testing in the 5' by 7' Acoustic Wind
Tunnel.

Initial testing of the two-blade design indicated
that the model would not operate outside of the stall
regime (tip-speed < 3).  The model was redesigned by
combining the airfoil sections of the two-blade design
into a single-blade configuration to improve the aero-
dynamic characteristics of the blade.  Subsequent testing
of the one-blade design in a no-pitch attitude indicated
its ability to operate in an acceptable tip-speed regime
of 4 to 5.

The semi-flexible blade has shown an ability to
operate as an acceptable alternative to previous designs.
The blade has also demonstrated an ability to be pitch-
controllable.  Further investigation and design considera-
tions are proposed.

Thesis Supervisor:  Norman D. Ham

Title:  Professor of Aeronautical & Astronautical Engineering

TABLE OF CONTENTS

## ACKNOWLEDGEMENT

I appreciate all the help directly and indirectly that has brought me to this point in time 24 years later; thank you, all of you.

FORWARD

The design process relies on knowledge, intuition, conceptualization, and investigation, quantifiable and nonquantifiable properties, each equally important and without which the process is incomplete. This thesis presents the first step in an idea's final outcome, an outcome that has yet to be determined with still further iterations of investigation and knowledge.

SYMBOLS

$A_s$    - turbine swept area

$C$    - blade chord

$C'$    - characteristic system constant

$C_L$    - lift coefficient

$C_n$    - blade torsion/chord-wise bending coupling coefficient

$C_p$    - power coefficient:  pressure coefficient

$D$    - drag:  turbine coefficient

$E$    - Youngs modulus

$EI_2$    - chord-wise bending stiffness

$G$    - torsional modulus

$GK$    - torsional stiffness

$H$    - turbine height

$K'$    - characteristic system stiffness

$L$    - lift

$m$    - mass per unit blade length

$M'$    - characteristic system mass

$n$    - modal shape number

$N$    - number of blades

$R$    - turbine radius

$S$    - blade length

$W'_n$    - characteristic system natural frequency

$\omega_n$    - flatwise bending natural frequency

$\bar{\omega}_n$    - blade torsion/chord-wise bending natural frequency

iv

$\bar{\omega}_{n_o}$    - free vibration of elastic ring natural frequency

$\Omega$    - turbine rotational velocity

$\Omega_F$    - rotational velocity at flutter

$\sigma$    - solidity

$\sigma_{UTS}$ - ultimate tensile strengh

# I.  INTRODUCTION

The recent concern in energy has created a burgeoning
interest in all manners of alternative energy resources.  Among
these, wind power played an important role in this country well
into the twentieth centry only to be supplanted by cheap and
abundant supplies of oil

While windmill configurations abound (primarily dominated
by horizontal-axis machines) considerable interest has develop-
ed in a class of vertical-axis wind turbines (VAWT) known by
the name of their inventor, G. J. M. Darrieus (1).  Although
originally patented in 1931, the Darrieus Wind Turbine (DWT)
remained virtually unknown until its rediscovery by P. South
and R. S. Rangi of the National Research Council of Canada (2).

Wind energy could be a valuable addition to world energy
production.  While much research has gone into the development
of large megawatt systems due to their purported "economic
benefits of scale," there is every indication that there are
still many applications where centralized systems of this sort
are not economic.*

---

*It may yet be shown that a cluster of smaller windmills
will provide a more reliable and economic energy source.  The
economics of mass production are real.  In addition, the loss
of one windmill in a cluster is less severe to users than the
loss of a single generating windmill in an already variable
power source.

Smaller systems could be more economic due to mass production and ease of maintenance. Also, by making people more accountable for their energy use, it might promote greater conservation.

The purpose of this thesis is to present an individual investigation into the problems, limitations, and some new proposals concerning the design of the Darrieus Wind Turbine (DWT). The author envisions a DWT of 5 to 15 meters in diameter whose size would provide adequate power for use in a single- or multi-family dwelling. Unfortunately, a wind turbine alone as the sole source of energy is not currently feasible without a substantial investment and/or radically changing ones energy use pattern (except for a few selected areas). The purpose of developing a wind turbine is to introduce a design that will produce energy at close to equal costs of conventional sources (based on initial and lifetime investments). Already four public utilities* have taken major steps toward using windpower to supplement their generating capacity, supporting the fact that windpower is, and can be,

---

*Oahu Electric Power Company. Currently generating 200kw from a demonstration project with contracts to develop an 80mw wind farm by 1985.

Bonneville Power Administration. First of threee 2.5mw turbines recently began operation in conjunction with the DOE and NASA.

Pacific Gas & Electric Co. Contracted with Windfarms, Inc. to purchase up to 350mw from proposed wind farm north east of San Francisco.

Southern California Edison. Testing machines east of Los Angeles with signed agreements to purchase 85mw from independent companies in the area.

a cost effective power source.  Improving the cost effective-
ness of the wind turbine willallow siting in many more areas
than those selected locations that have already been chosen.

## II. DESIGN PROCESS

### 2.1. The Design Progression

Being convinced of the previous argument, the considerations for proposing a windmill blade design need to be reviewed. Proposing a design requires the recognition of necessary inputs in order to produce an optimized end product. A comprehensive list of inputs into the design of a wind turbine is presented in Table 1.

### Table 1. RECOGNIZED DESIGN INPUTS

- function
- operational requirements
- production quantity
- stress requirements
- economics
- maintenance aspects
- manufacturing producibility
- geometry
- mass
- materials
- environmental factors

Each factor needs to be addressed and the benefits in one area weighed against the restrictions imposed by each choice in another area. The finalized design will result from the hierarchy that an individual or group of designers imposes on itself with respect to the importance of each input.

Function. The WT blade functions as an aerodynamic surface transforming the kinetic motion of wind into a lift force which is transmitted as a torque through the central axis of the turbine to a generator for power output. The degree to which it will perform this function in a reliable and efficient manner is dependent on trade-offs with other design inputs.

Operational Requirements. Even under the best conditions, wind power is typically a variable power source requiring alternate generating capacity or an effective storage capability. The ability to produce energy reliably is the foremost consideration. This requires configuring the blade design to be of sufficient size to provide a desired output under "average" conditions; equally important is providing for "worst case" situations.

Production Quantity. The selection of a small-scale wind turbine is intended to allow for production of large quantities with maximum usage of the most favorable mass production techniques. Smaller sizes allow for ease of handling, a necessity to produce more wind turbines for a desired output and the distribution of initial tooling costs over a greater output.

Stress Requirements. Gravitational, aerodynamic and dynamic (both vibrationally and rotationally induced) stresses need to be addressed. The proper selection of geometry, mass and material qualities are the single most important values in determining a viable design with an ability to minimize these external loadings and extending the operational lifetime and capabilities.

Economics. Ultimately, this will be the single decisive issue to be addressed. In the early stages, considerations beyond ordinary "engineering sense" are of lesser importance but never out of mind. As the design progresses, the process of trading features to obtain the optimum economic product is an important phase.*

Maintenance. Simplicity, accessability, repairability, component life, and size reflect important descriptions for ease of maintenance. The amount of maintenance is desirably minimal yet sufficient to insure the maximum desired dependability without failure.

Manufacturing Producibility. The design does best to capitalize on existing technologies or combinations thereof. Simplicity, ease of material fabrication, and reproducibility of the developmental product lead themselves to the benefits of mass production, economics, and reliability of the end product.

---

*The optimum economic product does not disregard the operational requirements. The wind turbine must compete with alternatives on a strict cost per kwh of power generated for a particular location.

Geometry. For height to diameter ratios equal to one
(H/D = 1), it can be shown that the swept area is maximized
for a given blade length. Ratios of H/D > 1.0 have been pro-
posed for large-scale systems to reduce their sensitivity to
gravitational and dynamic forces (3). This trend is at the
expense of reduced generating capability (proportional to
area) and increased cost (proportional to blade length).

Solidity ($\sigma$ = $NcS/A_s$) has been shown to have a minimal
effect on the power coefficient (actual Cp exhibits a small
increase with decreased $\sigma$). This is true both for the
troposkein-shaped DWT (3) as well as the cyclogyro with its
variable pitch capability (4).

It has been demonstrated that ideally there is no aero-
dynamic advantage to using nonsymmetric airfoil shapes result-
ing in the use of NACA 00XX series profile for most investiga-
tions of the DWT. For turbines with the blade chord line
perpendicular to the direction of rotation, it is desirable
to maximize the lift-to-drag (L/D) ratio. The L/D ratio does
not vary rapidly for variations in profile thickness allowing
the use of thicker profiles to provide for stress requirements.

The number of blades used in a wind turbine configuration
is dependent on the degree of variability in the output that
is desirable for synchronous power operation. At operational
tip-speeds, three-blade configurations provide a smoother
output than two-blade configurations. Resolving the choice
of blade numbers requires examining the cost of the extra
blade versus the costs incurred to handle a nonsynchronous
output.

Mass. Material properties and stress requirements have previously dictated the wind turbine mass properties. Yet, the lowest rotating mass is favorable with respect to aero-elastic, dynamic, and statically induced stresses. This indicates that materials for the turbine blade should possess a high strength-to-weight ratio to minimize the anticipated loads. Additionally, one would intuitively expect a lighter wind turbine to be able to successfully operate at lower windspeeds.

Materials. The selection of materials must consider the arguments and considerations previously discussed. Requirements for modulus, strength, density, cost and manufacturability must be weighed and selected to meet the desired optimum wind turbine design.

Environmental Factors. The variability of climatic conditions over the globe requires that a design be tailored to meet anticipated conditions. Temperature ranges exceeding 200°F indicate that material selection for cold climates may not be equally suitable for hot climates. The effects of solar degradation, moisture, corrosion, and wind erosion are not equal from site to site and a turbine design with unnecessary capabilities increases its cost. A good design should have a degree of adaptability to which particular needs for a given location can be added.

## 2.2. Design Concept

The range of design concepts that have been built
to investigate the DWT are presented in Figure 1 along
with three proposed designs for a low cost blade in
Figure 2 (5). It would be fair to assume that a majority
of researchers of the DWT are principally aeronautically
oriented which is not surprising considering the fact that
the WT is an aerodynamic machine. It is also not surprising
that design principles have adhered strongly to those used
in aircraft wing design. As a result, it is probable
that the approach from a narrower discipline background may
manifest potential shortcomings in its approach. Typically,
in the aerospace industry this may be a lack of familiarity
with low cost, high production manufacturing methods. Also,
all the requirements for producing an aircraft wing may not
ncessarily need to be met in order to satisfy the functional
and operational requirements of the WT blade.

The initial concept of this thesis for the WT blade was
influenced primarily with mass production as a driving
force while retaining a high degree of its functional
characteristics and meeting the load carrying requirements
it would encounter (Figure 3).

Initially, shape and capability generated a concept
in line with previous concepts of load carrying structure
(Figure 1). While vibration-induced bending stresses

compounded centrifugally- and aerodynamically-induced tensile
stressed, it appeared that a high directionally strengthened
material was best suited to deal with a loading pattern that
was principally tensile in nature with an alternating and
significantly smaller compressive component (Figure 4). This
idea was characterlized by the concept of Figure 5, using a
lightweight foam airfoil section over which a high-strength
sleeve of a material, such as kevlar, boron, or graphite fibers,
might be used. Weight was to be a reoccurring and major con-
sideration. Low weight could be correlated with low cost.

Later it was discovered that the DWT blade could, under
certain conditions, be prone to a blade-flutter problem (3)(6).
Since this was a vibration problem, low blade mass could re-
duce the possibility of the problem occurring by pushing the
flutter rotational speed beyond the range of system operation.
This is reasonable to assume in view of basic vibration know-
ledge:

$$\Omega_F \propto W_n' \propto C' \times K'/M' \tag{1}$$

The desire for low weight indicated the use of structural
foams which had been selected by several previous investiga-
tors. It also was evident (since the blade comprised a com-
lex three-dimensional shape) that a _flexible_ foam was desirable,
allowing the airfoil to be produced flat and easily shaped to
the troposkein shape.

Reducing the mass of the blade, unfortunately for most materials, causes similar reductions in other qualities (depending on the material) such as $\sigma_{UTS}$, E and G. As the mass of the overall blade is reduced, geometry or material properties must be varied to increase the stiffness of the blade in order to keep the flutter speed suitably high. The need to retain blade stiffness generates a need for a stiffening and load-carrying element to run the length of the blade. This is represented by the concept of Figure 6.

The conceptual design of Figure 6 was modeled using a rectangular piece of urethane foam and two semicircular hoops. The outcome of this modeling was that a blade constructed in this manner possessed a unique property. It became possible to impart blade pitch to the troposkein blade shape illustrated in Figure 7.

This was a very favorable potential, indeed, as it allowed the possibility of capitalizing of the characteristics of a special class of the VAWT known as a cyclogiro aeroturbine (4) (7), particularly, its superior power coefficient and a capability to be self-starting. Other favorable characteristics of the pitchable troposkein blade was that the blade shape eliminated the need for extensive supporting of flat cyclogiro blades and retained the lower operating tip-speed of the cyclogiro.

## III.  EXPERIMENTAL INVESTIGATION

### 3.1.  Experimental Model

A model utilizing the design concepts of the previous chapter was constructed for testing in the MIT 5' x 7' Acoustic Wind Tunnel.  The overall dimensions for the two-blade design are presented in Figure 7 hereafter designated as a one-meter design in order to characterize it in relation to previous two-, five-, and seventeen-meter designs.  The blade shape utilized the straight-curved segments approximation for the troposkein shape previously described.  Figures 8 and 9 illustrate the blade construction and the configuration of the pitching mechanism, respectively.

The blade consisted of segments of a closed-cell poly-propylene foam* three inches in length alternating with ribs of nylon.  The airfoil sections were formed using a 'hotwire' cutting devise and assembled with a commercially available contact cement.  Blade characteristics are provided in Table 2.  The blades were assembled over a 0.25-inch diameter aluminum structural rod chosen to withstand centrifucally-induced stresses while operating at a tip-speed ratio of 6 in a 40mph

---

*ROG 260 3.0 lb/ft$^3$ provided by Rogers Foam Corporation of Somerville, Massachusetts.

Table 2.  ONE-METER BLADE DESIGN PARAMETER

NACA 0015 cross-section

2.5"  chord

26.0"  length

0.15  solidity

27.0g  weight (foam/nylon only)

wind with added margins for aerodynamic and aeroelastic loads.
The pitch control rod consisted of 0.100 diameter brass rod
running parallel to the structural rod nearer the trailing
edge.

The pitching mechanism in Figure 9 consisted of two
circular bearings, one eccentric to the other at either end
of the blade.  By adjusing the eccentricity of the bearings
through the two screws, it was possible to impart a sinusoidal
pitch to the blades as they revolved around the central axis.
A maximum 1/2 inch of eccentricity allowed the blades to have
a pitch amplitude of 15°.  The finished model is shown in-
stalled in the MIT 5' x 7' wind tunnel in Figure 10.  It can
be seen that the blades do not extend the entire span of the
troposkein shape (approximate).  This was a result of the
difficulty in producing the foam airfoil sections of adequate
smoothness and a minimum of defects.  Nevertheless, since the
extracted power is a function of the vertical component of
the blade shape, these minimal blades would extract 60 percent
of the power compared to the model with blades spanning the
entire length.

Since the efficiency of the wind turbine is highly dependent on the aerodynamic quality of the airfoil, a suitable coating was selected to apply over the assembled turbine blades. An elastic latex solution was applied to provide a smoother surface than the foam presented. It also served to smooth out any defects and discontinuities in the alternating foam/nylon pieces.

## 3.2. Experimentation

The experimental set-up consisted of the one-meter model mounted atop a three-foot, freely rotating shaft. A caliper brake devise along with associated strain gauges (2) was used to monitor power output from the turbine. A piezo-electric accelerometer was mounted on top of the wind turbine to register any gross vibrations that might be encountered during operation. In addition, a strobe-tachometer and a three-cup anemometer were used to monitor turbine rotational velocity and windspeed, respectively. Operational testing of the design model occurred during December 1980 and January 1981. The experimental set-up is illustrated in detail by Figure 11.

It was anticipated that the semi-flexible blade would encounter loads that would deform the blade in a manner that could detract from operational capability (principally chord-wise bending, discussed in Section 4.1.b). The caliper brake of Figure 12 was devised for this purpose to monitor the power output of the model for later comparison with the output of a conventional DWT.

-14-

The test procedure consisted of determining the operational data for pitch angles from 0° to 15° (3.6°-increments based on two turns of the 8-32 screws used to regulate bearing eccentricity). For each respective pitch setting, the minimum operating windspeed was determined and thereafter increased by variable amounts to a maximum of 40mph.

## 3.3. Results

Through monitoring of the power output of the test model and qualitative observations on the model's ability to avoid serious vibration problems, it was anticipated that the operational viability of a design of this nature could be determined.

Preliminary testing of the turbine demonstrated that the semi-flexible blade could be pitched by way of the pitching mechanism as the blade revolved around its axis. Since the pitching required an actual deformation of blade material (see Figure 13) the force necessary to impart the degree of pitch was extracted from the wind (by way of the vane pictured in Figure 10b). The necessary force for blade pitch precluded operation below 12mph (at maximum blade pitch [15°], rotating the turbine by hand). This was the result of the particular orientation and size of the pitch-vane, which tended to be pulled around the rotational axis at lower windspeeds.

Initial wind tunnel results for the turbine were very poor. The turbine exhibited an inability to rotate at windspeeds below 33mph and the tip-speed ratio did not exceed 0.2

at any windspeed. It was observed that the blade contained a number of twists along its length due to deviations in the shapes of the load and control spars. Most of this was eliminated by progressive bending of the control bar until the blade followed a smooth arc along its length. With this 'fine tuning' of the shape, a noticeable increase in the tip-speed ratio was observed. Nevertheless, it did not exceed values greater than 0.6.

At the recommendation of the thesis advisor, attempts were made to reduce the drag that the exposed spars created. It was believed that this might be the principal reason for the turbine's inability to operate at a satisfactory tip-speed ratio. Fairings of paper and polyethylene sheet were tried and both provided significant increases to the observed operating tip-speed ratio as well as dropping the minimum operating windspeed to 17mph. for the turbine with poly-ethylene fairings in a no-pitch attitude, the tip-speed ratio was calculated to be a maximum of 2.0 for any windspeed.

The favorable effect created by the fairings resulted in the reconfiguration of the two-blade turbine into a counter-weighted, single-blade configuration. The single-blade turbine is pictured in Figure 14. The single-blade turbine was con-structed by disassembling the existing two blades and reassemb-ling the foam/nylon sections on to a single set of the load and control spars. Two six-inch lengths of threaded rod were installed at the upper and lower attach points for the missing

blade and appropriate weights were added to mass-balance the system.  The solidity was reduced to a value of 0.11 for the single-blade turbine.

Due to scheduling restrictions for the wind tunnel and my own time restrictions, testing of the single-blade turbine was severely limited in its scope.  The testing consisted solely of measuring the rotational velocity at various wind-speeds with the aid of the strobe-tachometer.  These measure-ments were taken for the turbine in a no-load, no-pitch atti-tude and plotted in Figure 15.  An interesting feature of the data in Figure 15 is that the rotational velocity changes relatively slowly with increased windspeed.  This indicates the potential for the deforming characteristics of the blades to be a natural speed governor for the DWT.

# IV. CONCLUSIONS

## 4.1. Discussion and Analysis

The demonstrated ability of the semi-flexible blade
to operate as an alternative blade design and possessing
a capability to impart a pitch to a blade of such a design
is a unique departure from concepts previously investigated.
While the need for further investigation is indicated, two
areas have been selected for additional consideration.

First, previous investigation by past researchers (3), (6),
had identified the dynamic response of the blades during
operation. Additionally, it was determined that under
certain conditions the turbine blades were also prone
to flutter, situations which adversely affected the opera-
tional life and capability of the turbine.

Second, the pressure distribution varies over the air-
foil's lower and upper surfaces during rotation causing
deformation of the airfoil which has an undetermined
effect on the turbine's operation.

### 4.1.a. Blade Vibrations

While the troposkein blade shape results primarily
in tensile loading during operation, aerodynamic loading
coupled with blade rotation results in significant bending

stresses due to blade vibrations. As a result, the blade
must be constructed to withstand the combined centrifucal
and aerodynamic loading while providing sufficient stiffness
to minimize bending stresses resulting from vibrations. In
fact, the design needs to be such that any system-harmonic
frequencies are well separated from the operationally-induced
frequencies in order that the DWT not shake itself to failure.

The natural frequency associated with flat-wise bending
was shown by Ham (6) to be closely represented by the
equation:

$$\omega_n = [n^2 - 1]^{1/2}\Omega \qquad\qquad n = 2, 3, \ldots \qquad\qquad (2)$$

Since the approximation of Equation 2 is independent of
blade characteristics other than operational speed, vibra-
tions of this type can be easily identified and designed
against. In Figure 16, the natural frequency spectrum
for flat-wise bending is plotted along with the 1/rev,
2/rev, and 3/rev excitations associated with one-, two-,
and three-blade turbine operations, respectively. While
actual experimental determination of the natural frequencies
would be important for large-scale design operations, several
observations can be made from this information. First, the
3/rev excitation follows the second mode (n=3) very closely
requiring an accurate determination of the frequency spectrum
in order to avoid harmonic excitations if a three-blade
turbine design is to be used. Second, at low rpm values

the n/rev excitations and modal frequencies begin to coincide. Large turbines will be operating at a lower rpm and, therefore, may be more susceptable to flat-wise bending.

Natural frequencies for blade torsion/chord-wise bending have been characterized for the rotating turbine blades by the equation:

$$\bar{\omega}_n = [\bar{\omega}_{n_o}^2 + (n^2 - 1)\Omega^2]^{1/2} \qquad n = 2, 3, \ldots \qquad (3)$$

where:

$$\bar{\omega}_{n_o}^2 = \frac{n^6 - 2n^4 + n^2}{\frac{GK}{EI_2} n^2 + 1} \quad \frac{GK}{mR^4} \qquad (4)$$

represents the free vibration of elastic rings. Equation 4 can be expressed differently as:

$$\bar{\omega}_{n_o}^2 = \frac{(n^3 - n)^2 (GK)(EI_2)}{(GKn^2 + EI_2)(mR^4)} \qquad (5)$$

The torsion/chord-wise bending frequencies are important in determining the operational speeds at which flutter will occur for the turbine. The flutter speed is determined from the equation (6):

$$\Omega_F = \frac{\bar{\omega}_{n_o}^2}{-2C_n - (n^2 - 1)} \qquad n = 2, 3, \ldots \qquad (6)$$

where:

$$C_n = -\frac{n^2(1 + \frac{GK}{EI_2})}{(1 + \frac{GK}{EI_2} n^2)} \tag{7}$$

represents the coupling coefficient for torsion/chord-wise bending, a parameter which blade instabilities have been sensitive to.

It has been indicated by Ham that the suppression of blade flutter can be accomplished by increasing the torsional stiffness (GK) of the blade. The choice for increasing GK is indicated since, if we look at Equation 5 and 6, the natural frequency increases more rapidly for increased values of torsional stiffness. This will reflect as a higher rotational speed for blade flutter ($\Omega_F$).

While favorable, increasing GK is not the only method available for suppressing flutter. Increasing the chord-wise bending stiffness* ($EI_2$) will also tend to increase $\Omega_F$ though at a slower rate. Reducing the overall mass of the ability to retain values for GK and $EI_2$, decreasing the overall mass has a more pronounced effect than increasing $EI_2$. The ability to increase $EI_2$ while decreasing the mass with the use of special materials (advanced composites) may provide a method for achieving this effect though possibly at the expense of increased costs.

_____

*It is noted that increasing $EI_2$ will also tend to increase GK at a proportional rate and vice versa.

Looking again at Equation 5, one method for suppressing $\Omega_F$ should not be overlooked. This is decreasing the turbine radius (R). More than any other factor, decreasing R will raise $\Omega_F$ at a rate equal to approximately the fourth power of changes in R. While not indicated by the literature, this is another reason for designs to favor height-to-diameter ratios greater than one. While this trend increases the over-all cost of generated power (decreased swept area snd increased blade length) it could be an acceptable trade with an appropriate low cost design. It should be pointed out that these changes cannot be carried out independently of the others and that an optimized selection of each value needs to be made for individual design proposal.

### 4.1.b. Aerodynamic Deformation

Previous blade designs for the DWT have been typical of aerospace airfoil designs; principally, rigid, load-carrying configurations. The proposal of a semi-flexible blade concept has, to my knowledge, not been presented. If such a concept can adequately perform the function of the turbine blade in stationary and operating conditions, then it can be added to the many existing configurations as an alternative approach.

Looking at Figure 8 again, along with the absolute pressure distribution profile for the NACA 0015 in Figure 17, an observation is made: for the range of lift coefficients experienced, the semi-flexible blade will experience a

deforming load along the unsupported leading and trailing edge of the blade during significant portions of its rotation. In order to compensate for this adverse condition, several alternatives are available. Redesign the blade to provide support along the leading and trailing edge as necessary, or investigate the phenomena in order to propose modifications to the airfoil shape to minimize any effects that may detract from turbine operation (or both).

While redesign for and investigation of the aerodynamic deformation is beyond the scope of this thesis, several observations are provided on this point:

1. Increasing the profile thickness reduces the magnitude of the adverse pressure distribution and increases the load-carrying cross section but at the expense of reduced lift-to-drag ratio (Figure 18).

2. Adding to or moving the load-carrying spar(s) most easily compensates for the loading on the airfoil but requires the reconfiguration or elimination of the pitching capability.

3. A beneficial outcome of this problem is that since centrifugal loads also add to the pressure loads, it is possible that the blade deformation may, in fact, provide a speed-governing ability. This may account for the relatively constant rotational speed at varying wind-speeds observed in the single-blade redesign.

## 4.2. Further Design Considerations

The as-built semi-flexible blade requires redesigning to overcome observed and anticipated problems including aerodynamic deformation and blade vibration.

Based on Figure 15, additional support of the airfoil is indicated along the leading and trailing edges. This could be accomplished by moving the load-carrying and pitch-control spars, by the addition of extra ribs along the blade length or the addition of extra spars (Figure 19). The first and second solutions provide the simplest and most direct approach; though the first leaves a large portion of the blade chord between the two spars unsupported, the second detracts from the desired simplicity that totally eliminating ribs would provide. The last alternative, while simple in concept, would require a more complex pitching mechanism.

For a rotational velocity up to approximately 500rpm*, no adverse vibrations were observed in the one-meter, single-blade model in a no-pitch attitude. Based on maximum $C_p$ for the 'cycloturbine' at a tip-speed ratio of 3 and the previously described rotational velocity, this indicates that vibration would not be present for wind speeds under 22mph in the operating pitch-controlable blade. For the two-blade configuration, this drops to 11mph due to 2/rev excitation. This

---

*In one instance, the blade was observed to exceed a rotational velocity of 500rpm in a 17mph windspeed. Due to the blade's inability to retain this $\Omega$ (attributed to blade warping previously described) the recorded notation was taken as the rotational speed slowed down past the 500rpm reading on the strobe-tachometer.

indicates that blade vibration may yet have to be compensated for in the operating range. The determination of the lowest $\Omega$ at which detrimental vibrations occur in the current model will provide a basis for establishing the amount of additional chordwise and torsional stiffness necessary to drive adverse blade frequencies beyond the operating range. The necessary increase in stiffness will also dictate the configuration and number of internal spars that may be necessary for a functional design.

Returning to the preliminary design considerations, shape, capability and process are presented again for further design consideration.

Shape. The selection of the NACA symmetric airfoil was dictated because of its superior L/D ratio and its insentivity to positive or negative attack angles. With the advent of pitch-controlable configurations and the use of optimum pitch variation, a review of existing airfoils may uncover a superior airfoil for use in the DWT.

Capability. Retaining the ability to resist the combined operational loads of the DWT remains the principal issue of blade capability. A factor affecting this capability has been material properties. While current designs have favored extruded aluminum blades for their strength-to-weight ratio and ease of manufacturing, the advent of advanced composite materials introduces a material alternative (See Table 3).

The use of composite spars in conjunction with foam airfoil sections would produce a very low mass blade which would

Table 3.  COMPARISON OF BLADE MATERIAL PROPERTIES

| | E(psi) | G(psi) | $\sigma_{UTS}$(ksi) | $\rho$(lb/in$^3$) |
|---|---|---|---|---|
| Wood | $2.0 \times 10^6$ | ------ | 1.2 | .025 |
| Aluminum | $10.1 \times 10^6$ | $3.8 \times 10^6$ | ~50.0 | .100 |
| Graphite/ Epoxy | $23.6 \times 10^6$ | $0.6 \times 10^6$ | ~200.0 | .057 |

be desirable from an operational and fabrication standpoint. Would such a design prove to be possible?  The indication is that it would not provide equal stiffness in a one-for-one trade with an extruded aluminum shape due to its low torsional modulus.  Theoretically, the pure composite extrusion would also have a very high coupling coefficient which is not desirable since it drives $\Omega_F$ down.  The actual coupling coefficient needs to be experimentally determined; it may be that the current design configuration is not accurately determined by Equation 7 due to its semi-flexible nature.

Process.  Fabrication costs increase with the complexity, number of parts and the steps required to generate the final product.  The use of extruded foam airfoil sections provides the optimum solution for fabrication of the airfoil shape. Similarly, spars of aluminum or composite materials can easily be fabricated and formed to the desired troposkein shape with common manufacturing technology.

## 4.3. Recommendations for Further

### Investigation

Expanding the information on the operating characteristics
of the current model configuration with pitch control should
be the initial thrust for further investigation. This should
include the determination of operating speeds, power coeffi-
cients and blade natural frequencies as primary aims.
Additionally, blade aerodynamic (and centrifugal) deformation
problems along the leading and trailing edges should be
compensated for and the operating characteristics should be
determined for this design iteration.

The concept of the semi-flexible blade introduces several
new variables to the design of the DWT. Similarly, it has
increased the complexity of the analysis required to under-
stand the operation of the turbine with variations in the
system. Further understanding of the semi-flexible blade
will require that questions be answered and characteristics
of the design be understood. Among these should be included:

1.  Determine the potential of the semi-flexible blade
    design without pitching capability as a possible
    low-cost alternative blade design.

2.  Characterize the properties of the foam NACA blade.
    The pressure distribution over the airfoil will alter
    the section shape thereby altering the lift and drag
    vs. angle of attack values.

3.  Characterize the foam properties for an optimized
    material selection. Blade deformation requires energy

to be diverted from power generation. What degree
of strength, stiffness or density is desirable?

4. How will blade aeroelastic response vary for the
   semi-flexible blade? The foam material's damping
   characteristics and loading patterns resulting from
   pitch control will alter the magnitude and location
   of blade natural frequencies.

5. Determine the limitations of possible semi-flexible
   designs as to size, shape and operating conditions.

6. Perform a cost analysis of the materials and process-
   es necessary to produce the various design alterna-
   tives.

7. Evaluate the conditions necessary for governing
   blade rotational velocity by blade deformation.

8. Evaluate the semi-flexible, variable pitch, tropo-
   skein blade DWT as an alternative to the 'Cycloturbine'.

This author will be continuing his investigation in the
future with these directions in mind. With further experi-
mentation and the aid of computer methods, the 'Semi-Flexible
Darrieus' wind turbine may yet find itself a proven alternative.

# REFERENCES

1. Darrieus, G. J. M., "Turbine Having its Rotating Shaft Transverse to the Flow of the Current", U.S. Patent No. 1,835,018, December 8, 1931.

2. South, P. and Rangi, R. S., "Preliminary Tests of a High Speed Vertical-Axis Windmill Model", National Research Council of Canada, LTR-LA-71, March 1971.

3. Blackwall, B. F., et al., "Engineering Development Status of the Darrieus Wind Turbine", Journal of Energy, Vol. 1, No. 1, 1977.

4. Drees, H. M., "An Analytical and Experimental Investigation of a Darrieus Wind Turbine Employing Cyclic Blade Pitch Variation", M.S. Thesis, Department of Aeronautics and Astronautics, MIT, 1976.

5. Feltz, L. V., "Low-Cost Blade Design Considerations", Proceedings of the Vertical-Axis Wind Turbine Technology Workshop, National Technical Information Service, SAND 76-5586, July 1976.

6. Ham, N. D., "Aeroelastic Analysis of the Troposkein-Type Wind Turbine", National Technical Information Service SAND 77-0026, April 1977.

7. Kreidler, J. F. and Kreith, F., Solar Energy Handbook, McGraw-Hill Book Company, 1981.

FIGURES
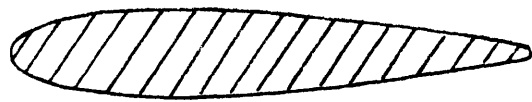
solid aluminum/solid plastic

extruded aluminum

laminated wood

formed steel sheet

steel tubing/wood/
fiberglass skin
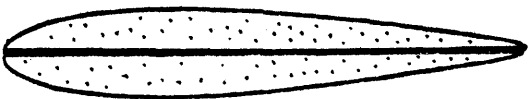
aluminum/foam/
fiberglass skin
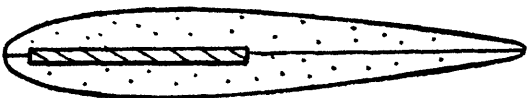
steel/foam/
fiberglass skin
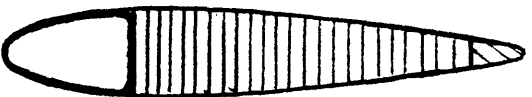
aluminum extrusion/
paper honeycomb/
fiberglass skin
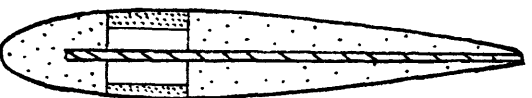
aluminum/foam/
heat shrink skin

Figure 1.   BLADE CONSTRUCTION OF VARIOUS TURBINES
BUILT TO DATE
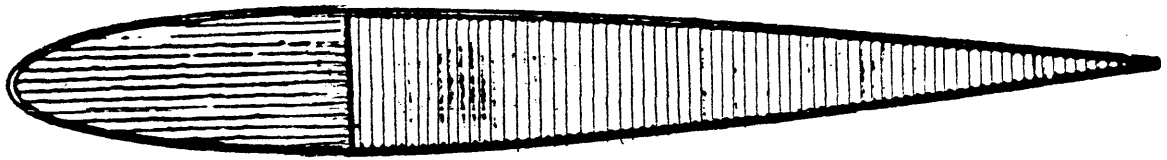
o laminated wood
o honeycomb
o fiberglass skin
o fiberglass ribs
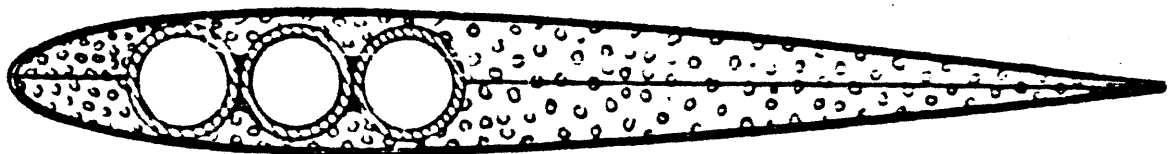
o commercial tubing
o foam
o fiberglass skin
o fiberglass ribs
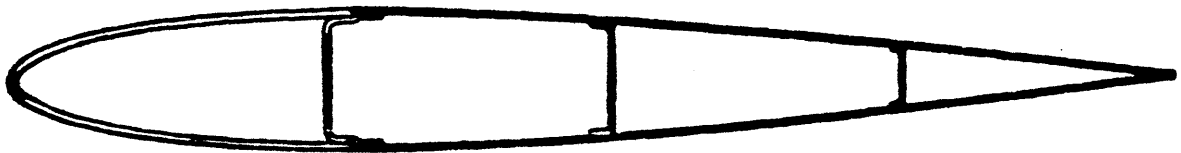
o roll formed steel
o weld construction

Figure 2.  THREE IDENTIFIED LOW COST DESIGNS
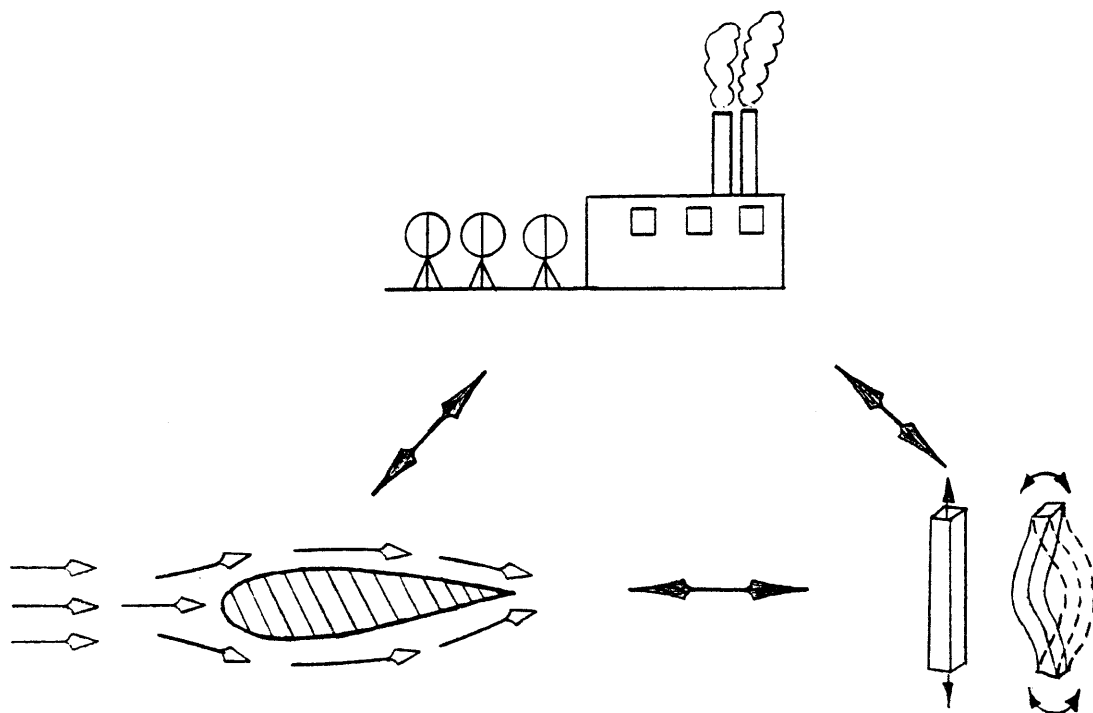
Process + Shape + Capability → Blade Configuration

Figure 3. PRIMARY BLADE DESIGN CONSIDERATIONS

Alternating Tensile

o centrifugal loads
o aerodynamic loads

+
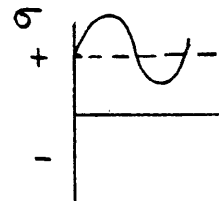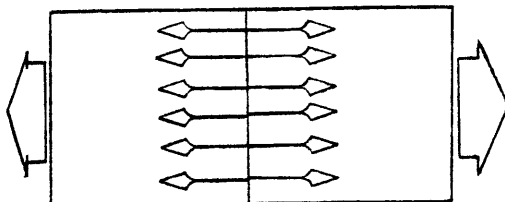
Bending

o vibration loads
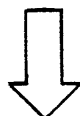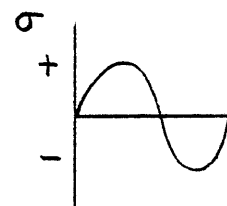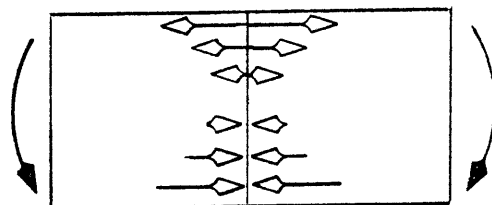
Combined loads
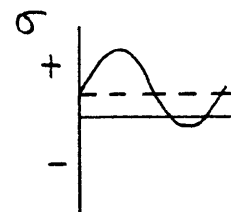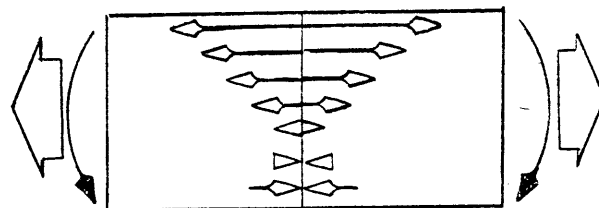
Figure 4.  ANTICIPATED BLADE LOADING
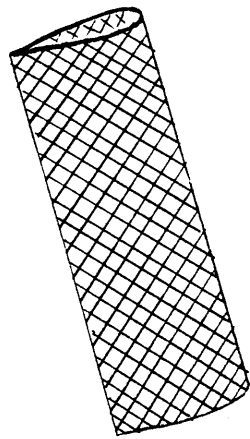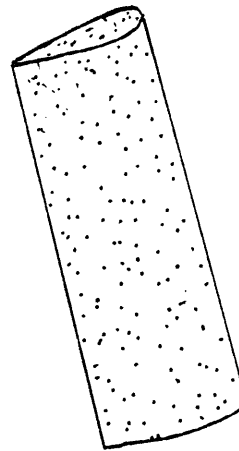
high-strength
fiber sleeve

o kevlar
o graphite
o boron

+

foam airfoil shape

o light
o flexible

Bend to desired shape
and spray with resin binder
to form rigid turbine blade.

Figure 5.   PRELIMINARY DESIGN CONCEPT –
RIGID BLADE
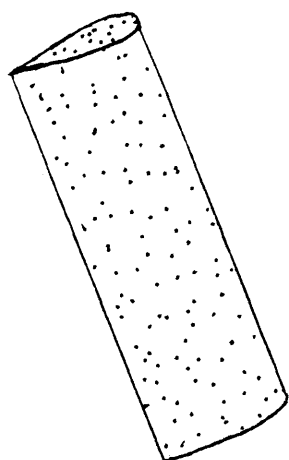
flexible foam
airfoil section

+
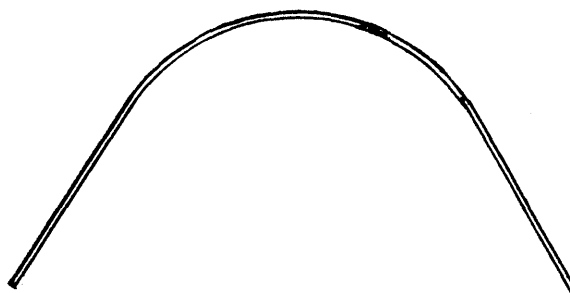
load-carrying
spar
tube or rod
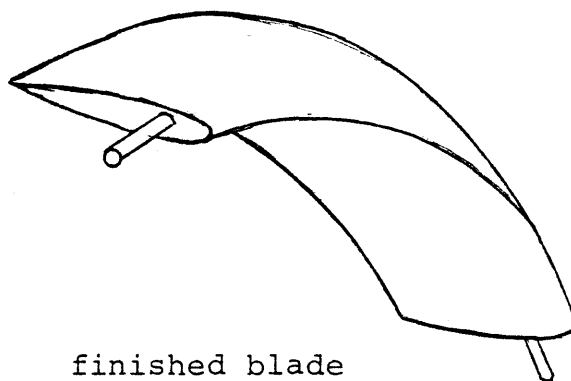
finished blade
design

Figure 6.    PRELIMINARY DESIGN CONCEPT
SEMIFLEXIBLE BLADE
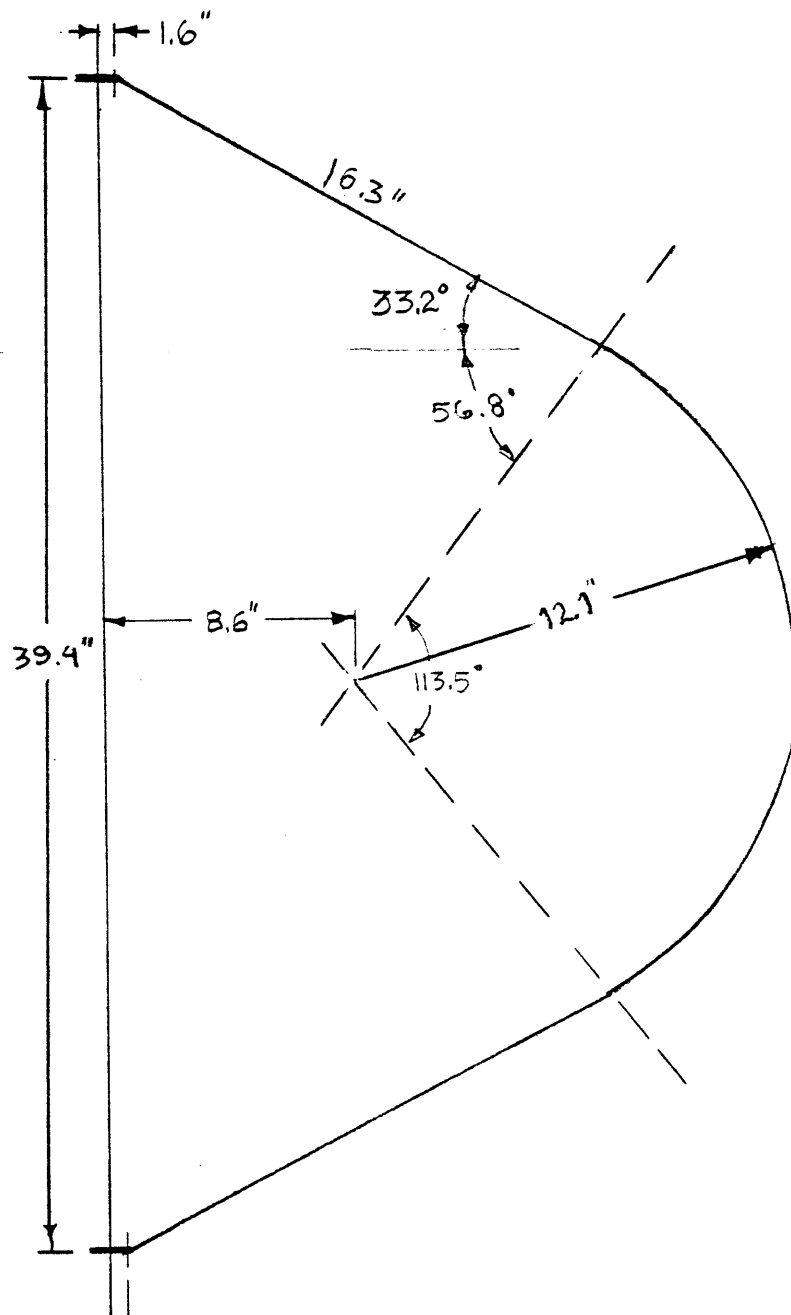
Figure 7.   TURBINE BLADE MODEL DIMENSIONS

Closed-Cell Polypropylene Foam

Nylon Rib

.875"

aerodynamic center

Structural Spar

Pitch
Control Spar

Elastic Skin
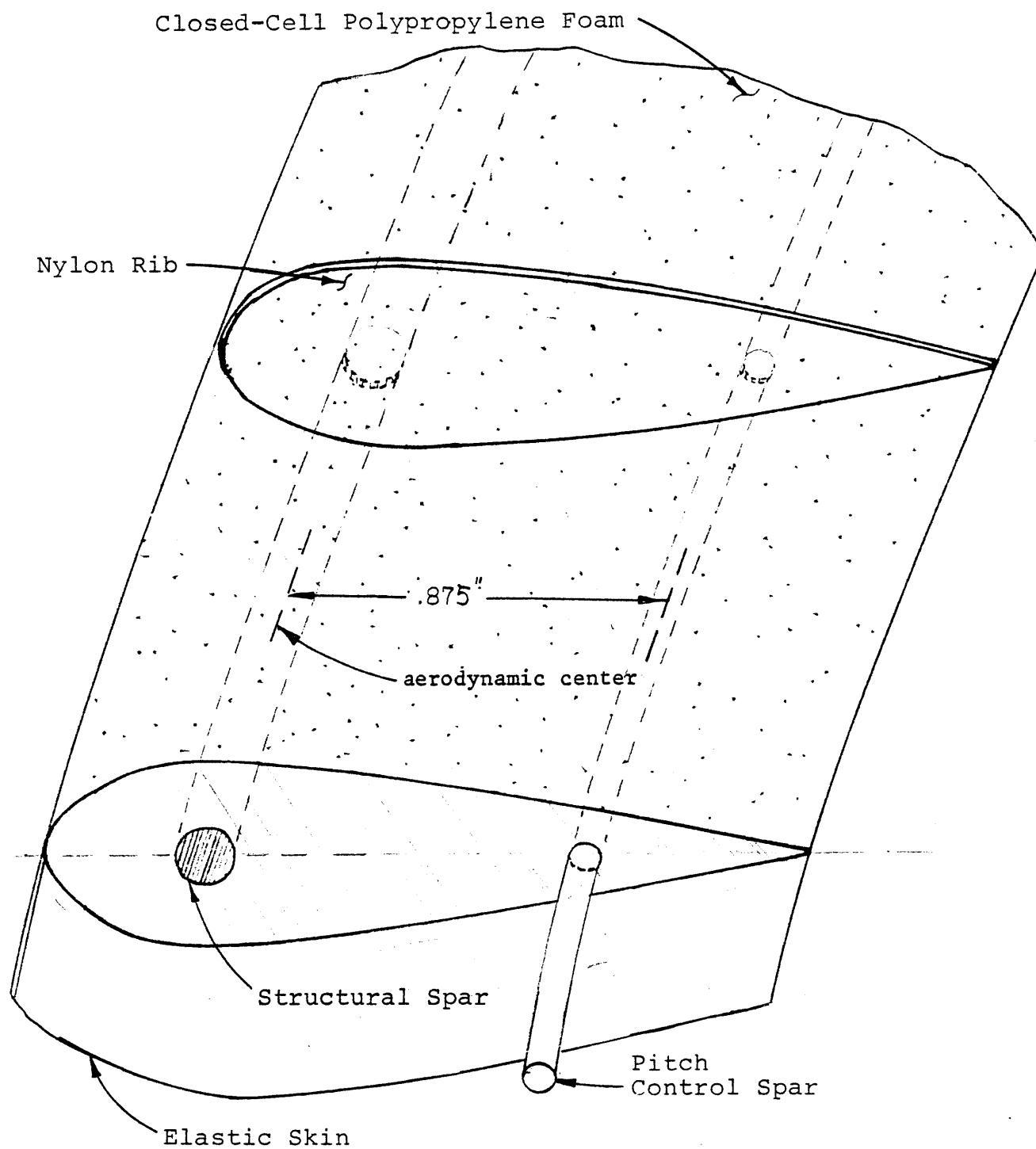
Figure 8. MODEL BLADE CONSTRUCTION
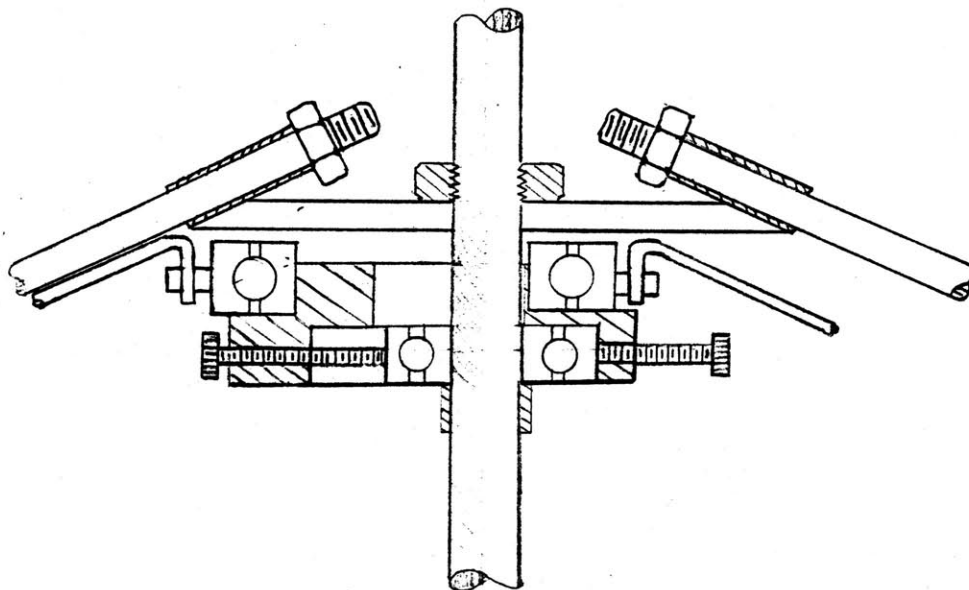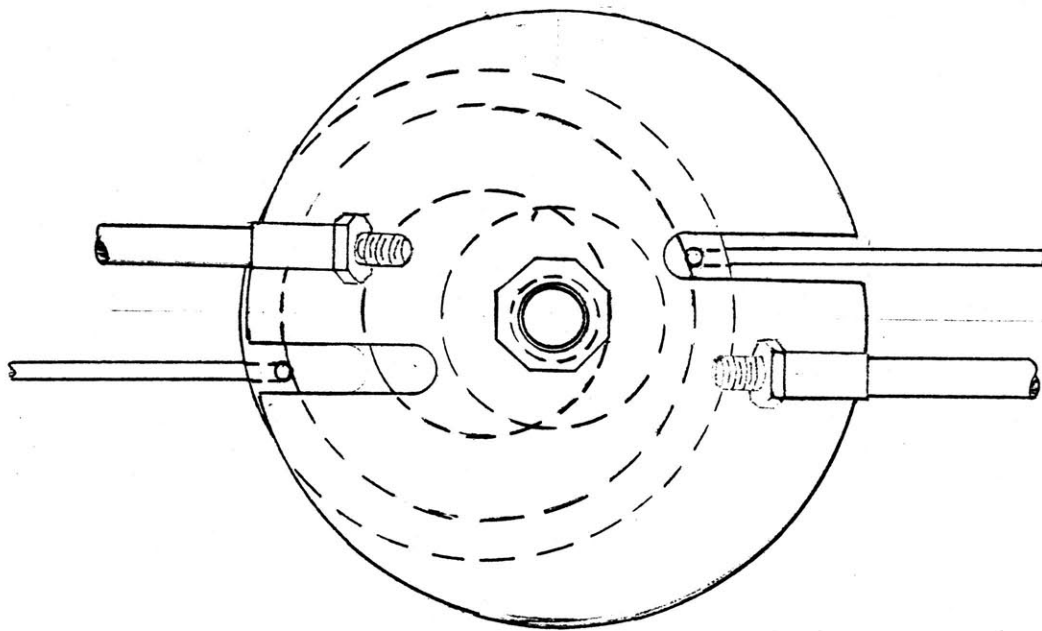
Figure 9.  MODEL PITCHING MECHANISM
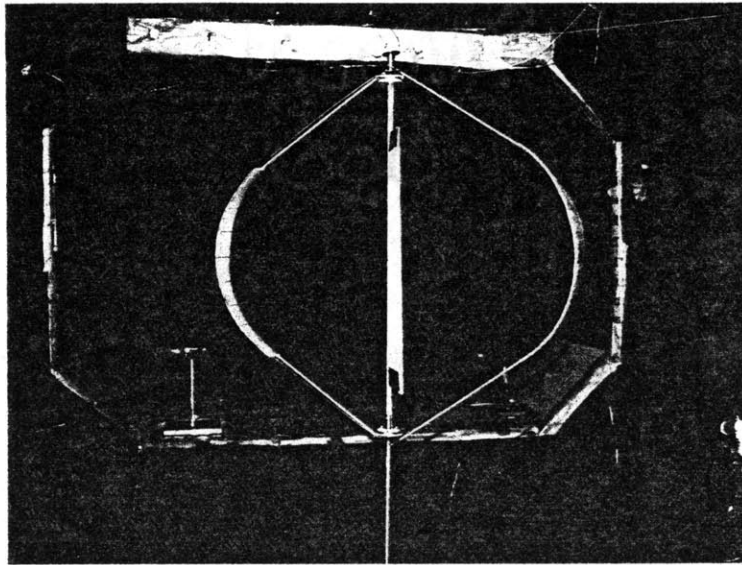
Figure 10-a.  TEST MODEL INSTALLED IN 5' by 7' WIND TUNNEL
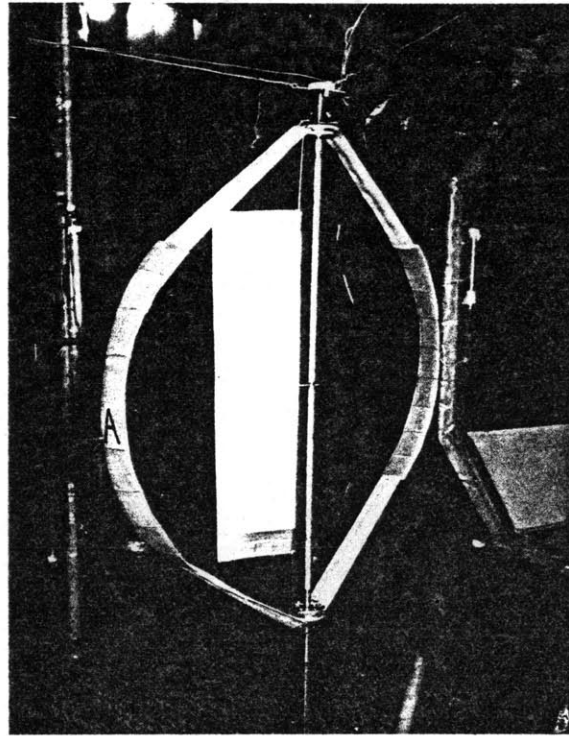
Figure 10-b.  TEST MODEL WITH FAIRINGS ATTACHED

Upper Support Bearing

Supporting Guy
Wires (3)

Accelerometer

Blade B

Blade A

Blade
Pitching Vane

Exposed Spars

Blade Pitching
Mechanism (2)

Rotating Brake
Disk

Disk Brake

Shaft Support
Bearings

Caliper Contact Force

Caliper Bending Force

Accelerometer

Strobe-Tachometer
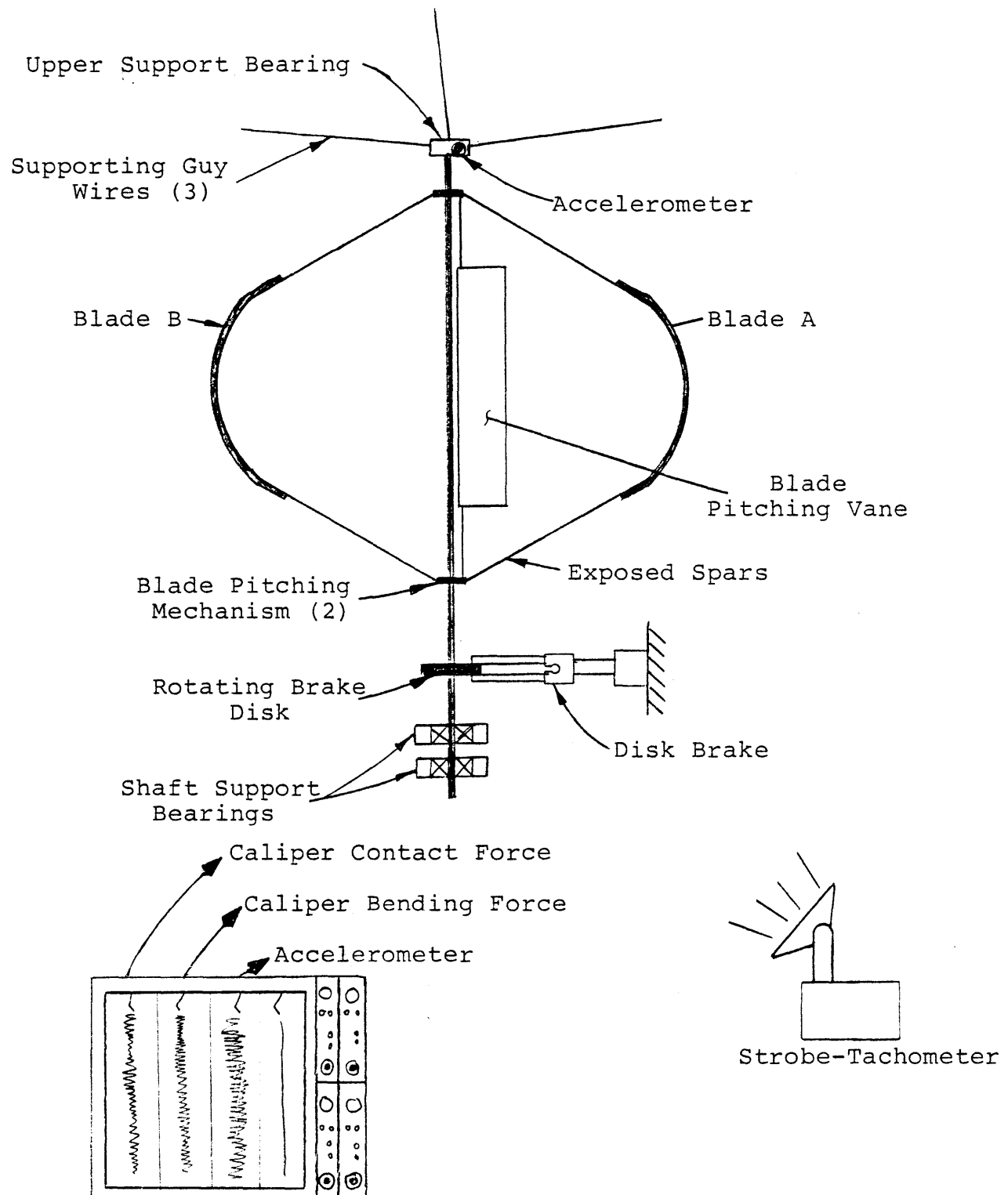
Figure 11.   EXPERIMENTAL SET-UP

To Chart Recorder

To Chart Recorder
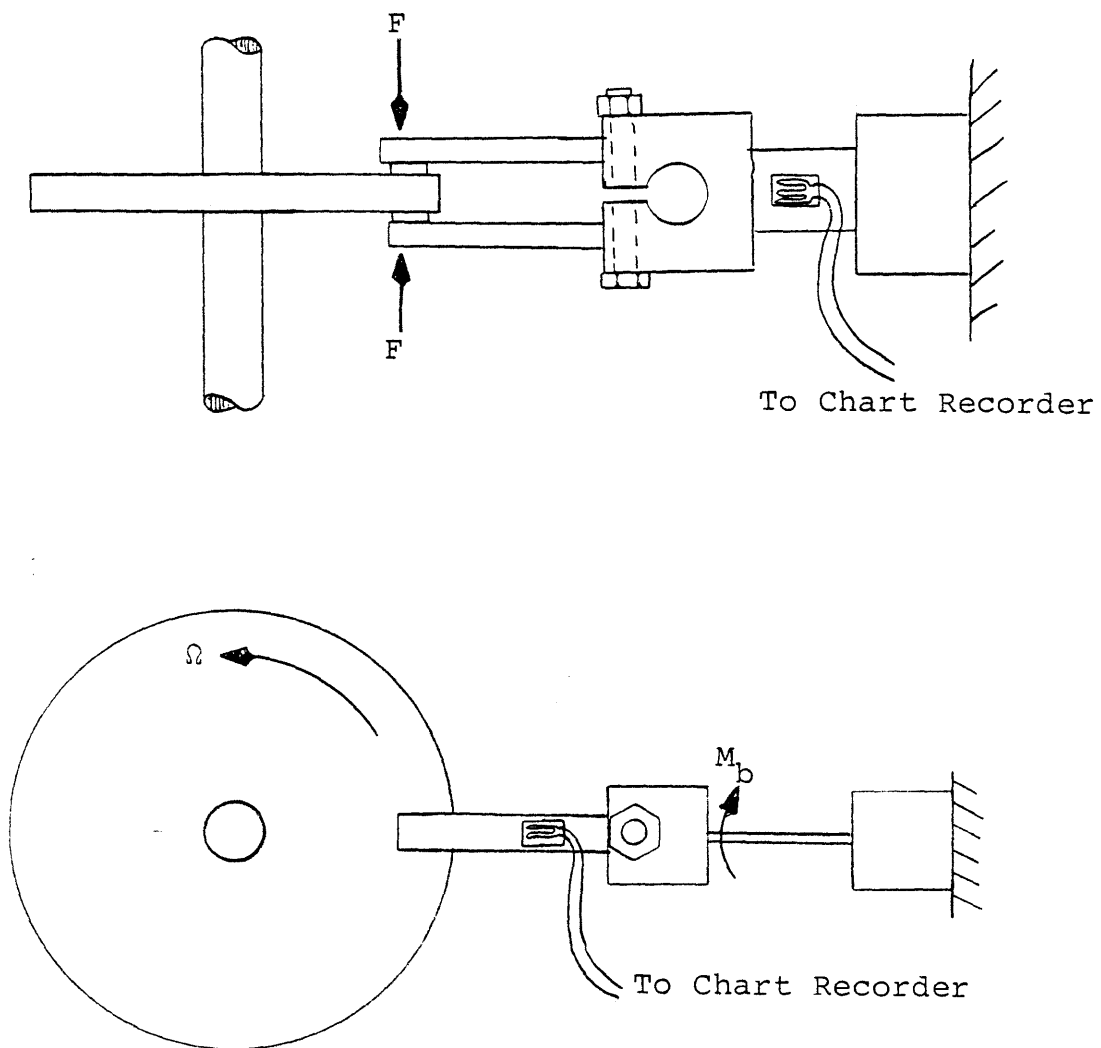
Figure 12.   CALIPER BRAKE POWER MONITERING DEVICE

compressive stress along
leading edge

tensile stress along
trailing edge

pitching force
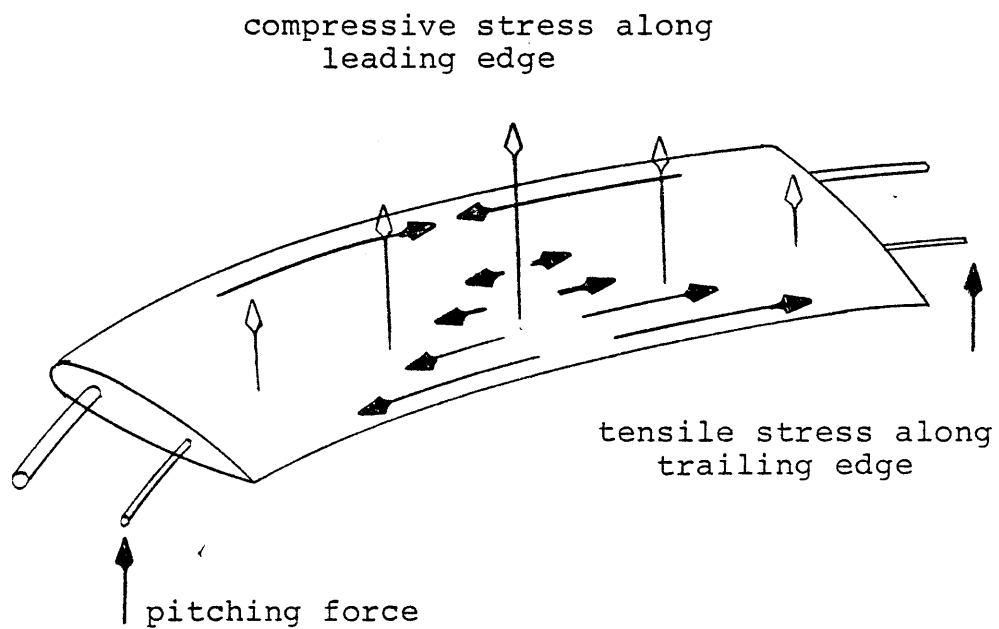
pitch angle varies along blade
maximum at $R_{max}$

Figure 13.  SEMI-FLEXIBLE BLADE DEFORMATION
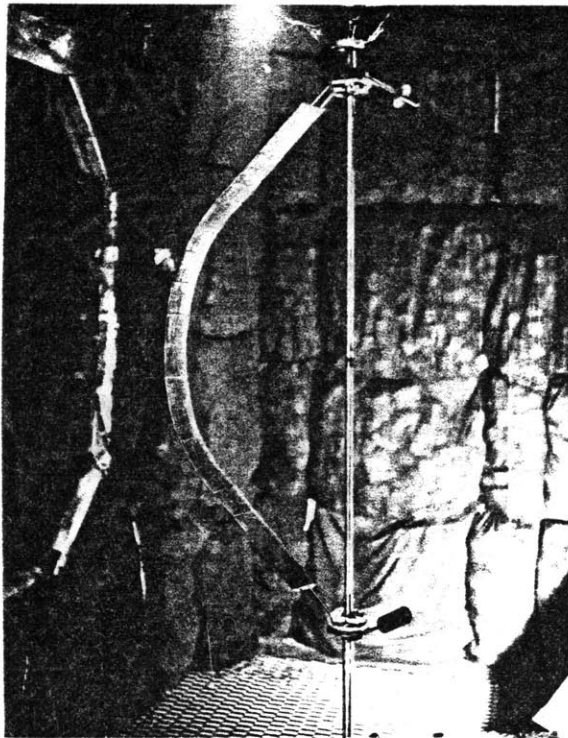
Figure 14.   SINGLE BLADE MODEL IN WIND TUNNEL
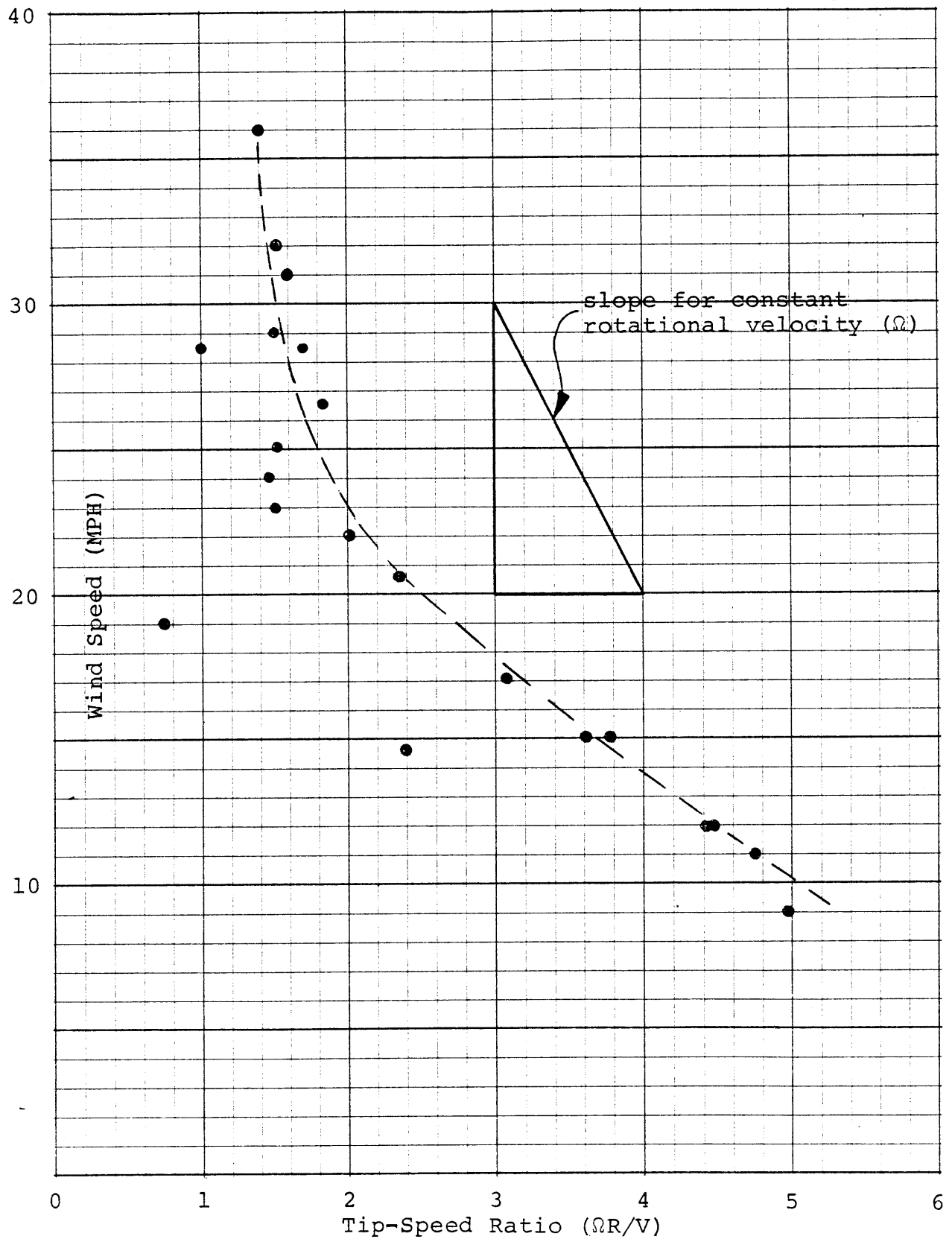
Figure 15.   TIP SPEED RATIO VS. WIND SPEED
SINGLE-BLADE RECONFIGURATION
NO PITCH-NO LOAD
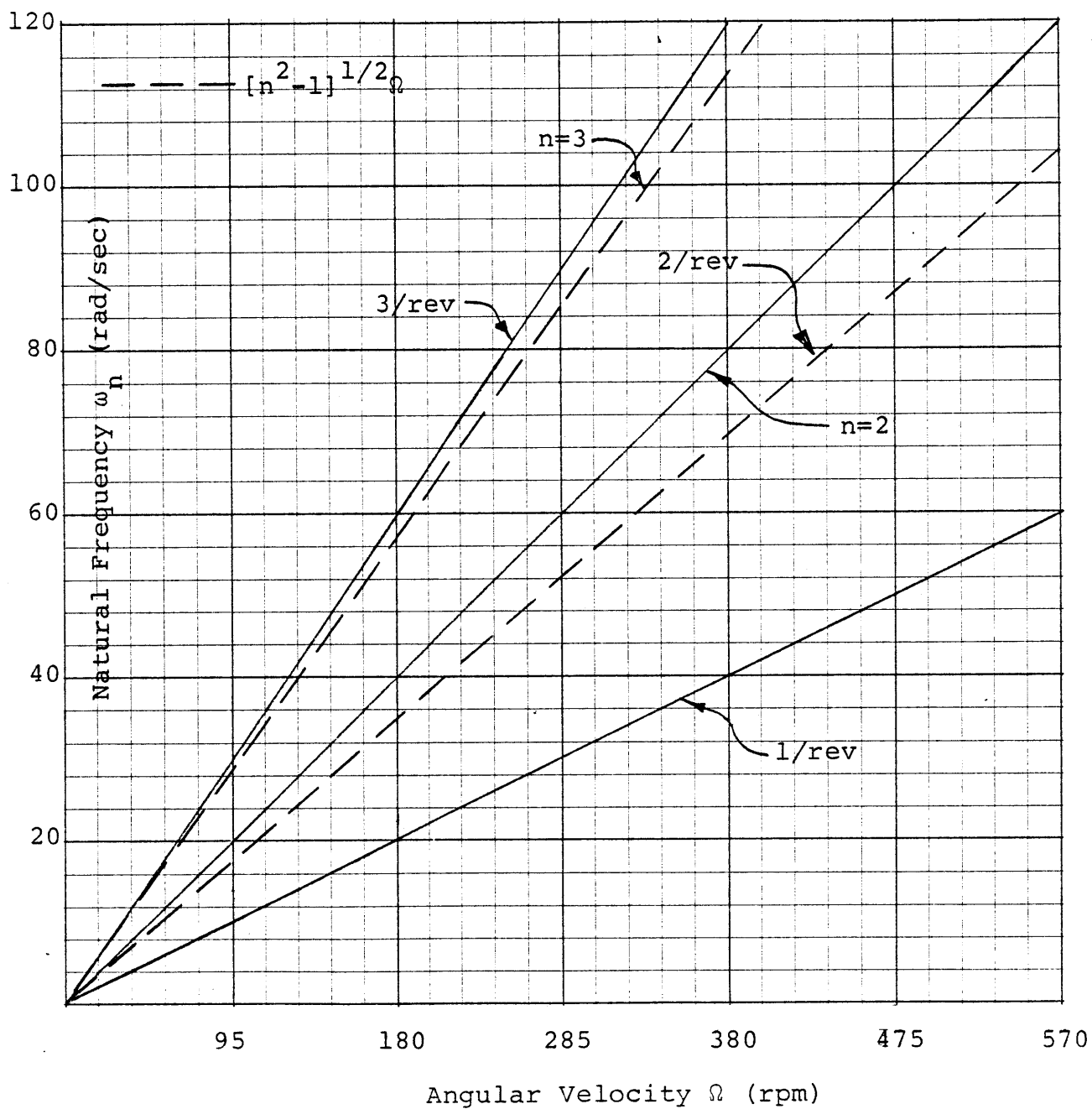
Figure 16.   NATURAL SPECTRUM, FLATWISE
BENDING, FIRST TWO MODES
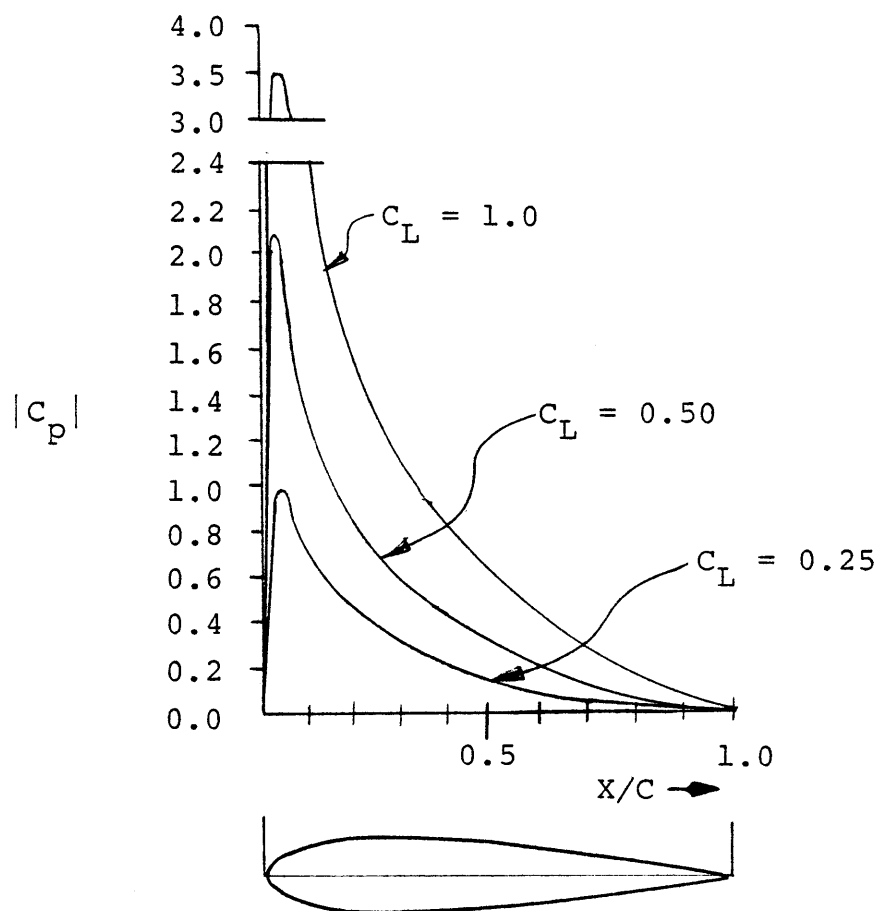
Figure 17.   ABSOLUTE PRESSURE COEFFICIENT
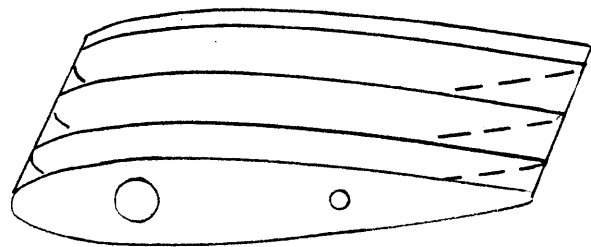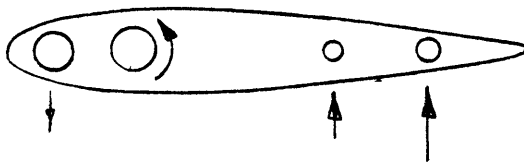             LOWER SURFACE NACA 0015 AIRFOIL
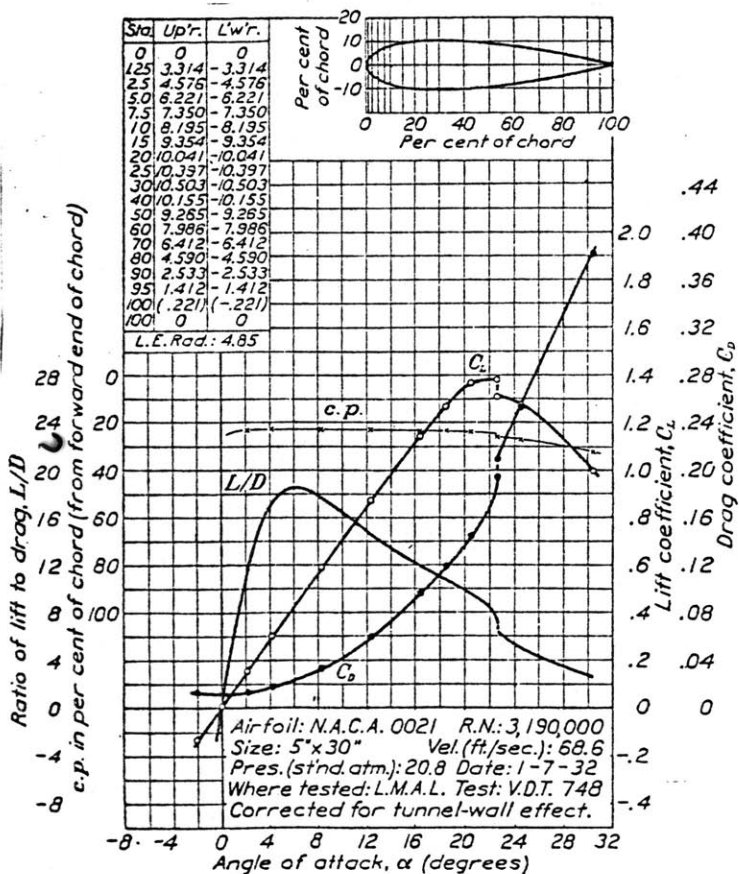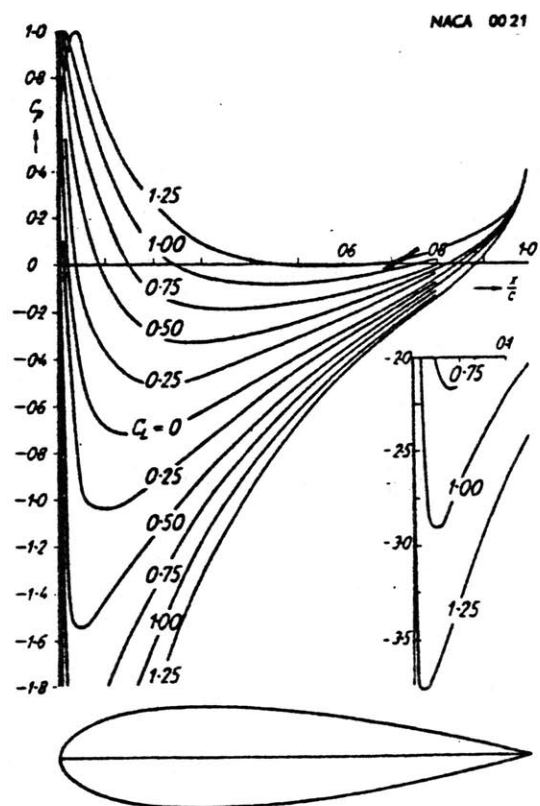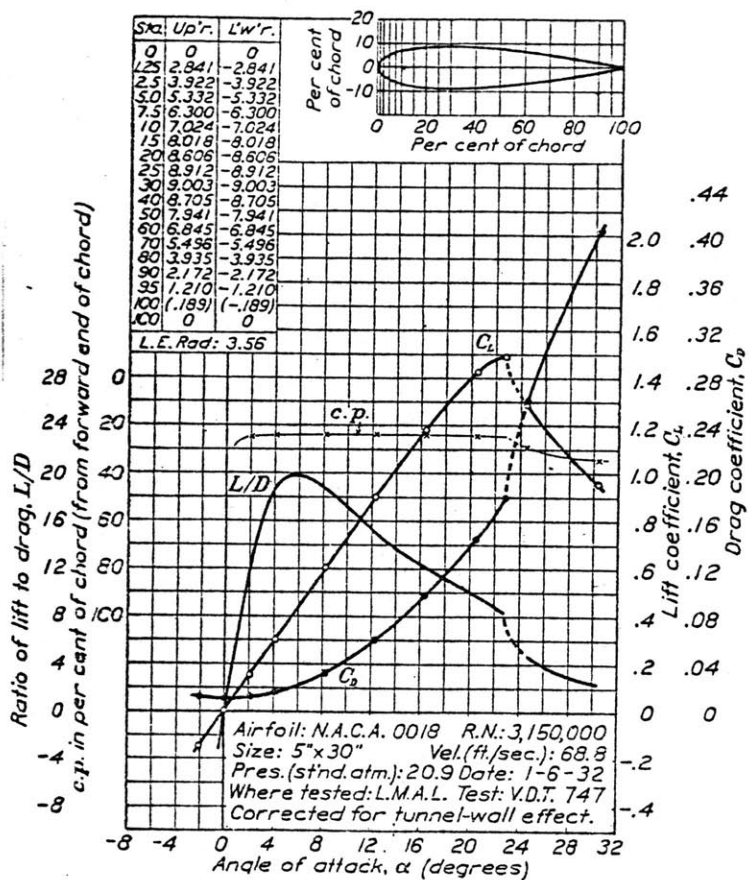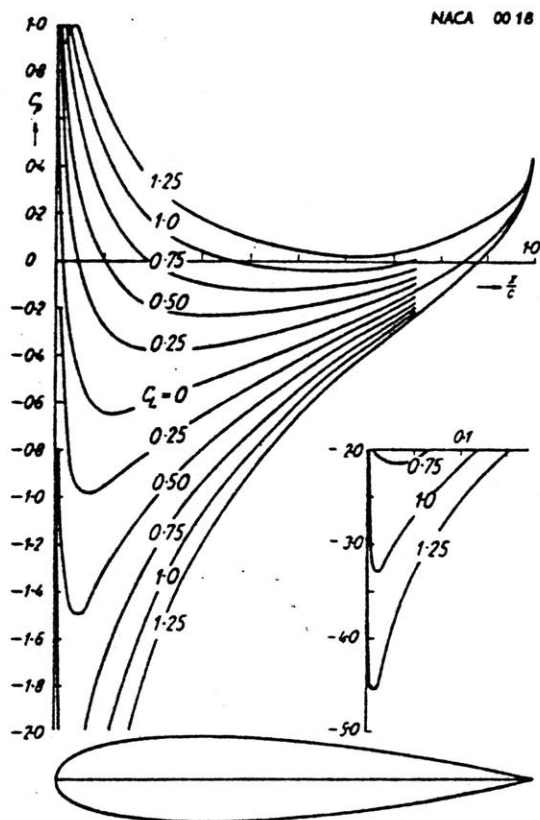
Figure 18. AERODYNAMIC DATA FOR NACA 0018
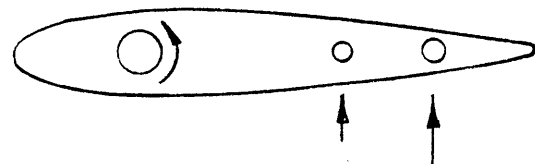AND 0021 AIRFOILS
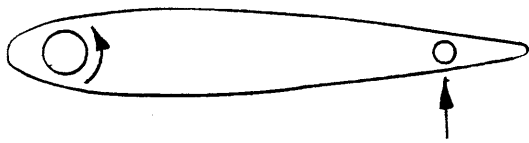
increase spar separation

add ribs

extra leading and trailing edge spars

extra trailing edge spar

Figure 19.    DESIGN ALTERNATIVES TO OVERCOME
AERODYNAMIC DEFORMATION