IMPROVED AERODYNAMIC CALCULATIONS

FOR HIGH ALTITUDE SCIENTIFIC RESEARCH BALLOONS

by

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ABSTRACT

A high altitude scientific balloon is a flexible structure where the shape and stress are dependent on the pressure differential across the envelope. When a balloon is floating at a constant altitude, the pressure distribution over the envelope is given by the hydrostatic equation. However, when a balloon is climbing to its float altitude, the pressure distribution is also affected by the airflow over the balloon. Usual simple aerodynamic estimation methods are not applicable because the balloon is not a slender body. In previous studies, the balloon was represented by a distribution of sources located on the axis of symmetry. In this paper, improvements to this potential flow solution are introduced, and limitations of the method are examined. With results from the improved potential flow solution, a boundary-layer calculation has been programmed to provide separation point and skin friction estimates.

NOMENCLATURE

b = specific buoyancy of lifting gas, $\rho a - \rho g$

Cp = coefficient of pressure, $(P-P_\infty)/q$

g = gravitational constant

m = source strength

ΔP = differential static pressure across the film, Pg. - Pa:

q = dynamic pressure, $1/2 \rho V_\infty^2$

r = radial coordinate

R = radius of curvature

s = doublet strength

V = velocity

W_f = film weight

z = height, measured from zero pressure point

θ = angle between film and vertical axis of symmetry

σ = stress

ρ = density

ψ = stream function

Subscripts

a = designates air

c = circumferential direction

g = designates helium gas

i = designates points on the balloon

j = designates sources on axis of symmetry

m = meridional direction

n = number of sources

o = design conditions

r = radial component

z = vertical component

∞ = upstream conditions

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Introduction

Balloon research is a relatively new field of engineering science. Dating back to the 18th century when practical applications for balloon flight first evolved, very little was done on improving the design and construction of the atmospheric balloon until the 1930's. This is when an extensive study on atmospheric balloon design by the University of Minnesota resulted in two major contributions to the state of the art. These were: 1) lightweight plastic envelopes and 2) a simple balloon shape and stress analysis.

Since 1972 Texas A&M University has been involved in an extensive atmospheric balloon research program. This study is a continuation of a study started last year on the influence of rate of climb on balloon stress.[1] The Main purpose of this paper is to improve the aerodynamic calculations for high altitude scientific research balloons and examine the new methods for limitations. With the results given by the new potential flow solution, a boundary layer calculation has been programmed to provide separation point and skin friction estimates.

Description of Balloon Body

A high altitude scientific balloon shape studied in this paper is the natural shaped balloon. A natural shaped balloon is an envelope that is fully tailored to the shape it would naturally assume at its design altitude in float.[2] Figures 1, 2. The size of these balloons are terrific. A typical scientific research balloon is 300-500 feet tall and 400 feet in diameter in its float configuration. The film thickness is on the order of 0.7 mils which is about 60% as thick as the plastic in a sandwich bag.

Scientific balloons used today are vented by air ducts at the base of the balloon so that the inside gas pressure is equal to the outside atmospheric pressure at the base. This is done to insure the location of the zero pressure point for which the balloon was designed. Their theoretical shape is calculated by using the membrane equation assuming zero circumferential stress, and that the pressure differential across the envelope is given by the hydrostatic equation. However as shown by a previous study,[1] the contribution of rate of climb to the differential pressure is significant and should be included.

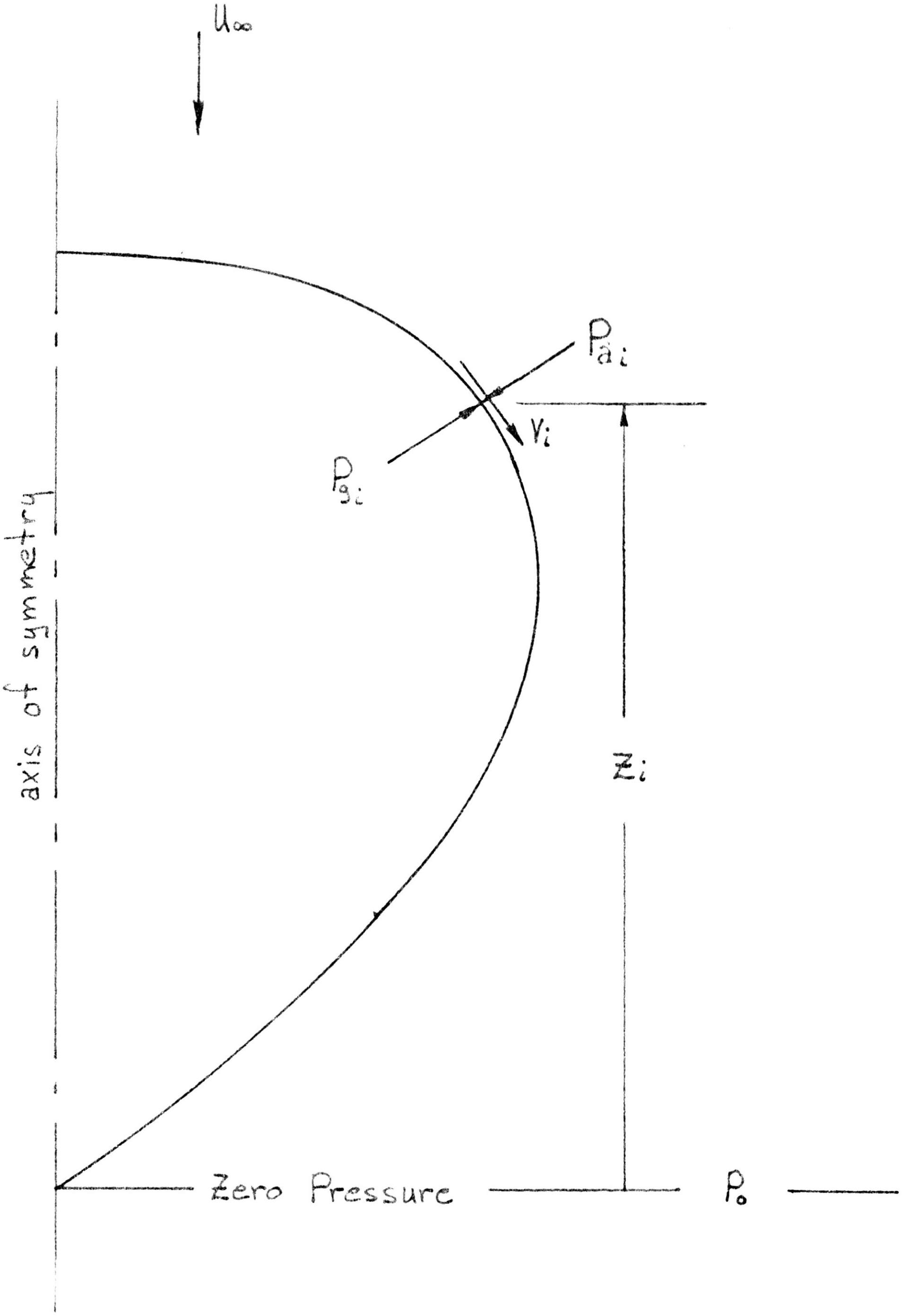


Figure 1

"Geometry of a typical Scientific Balloon."

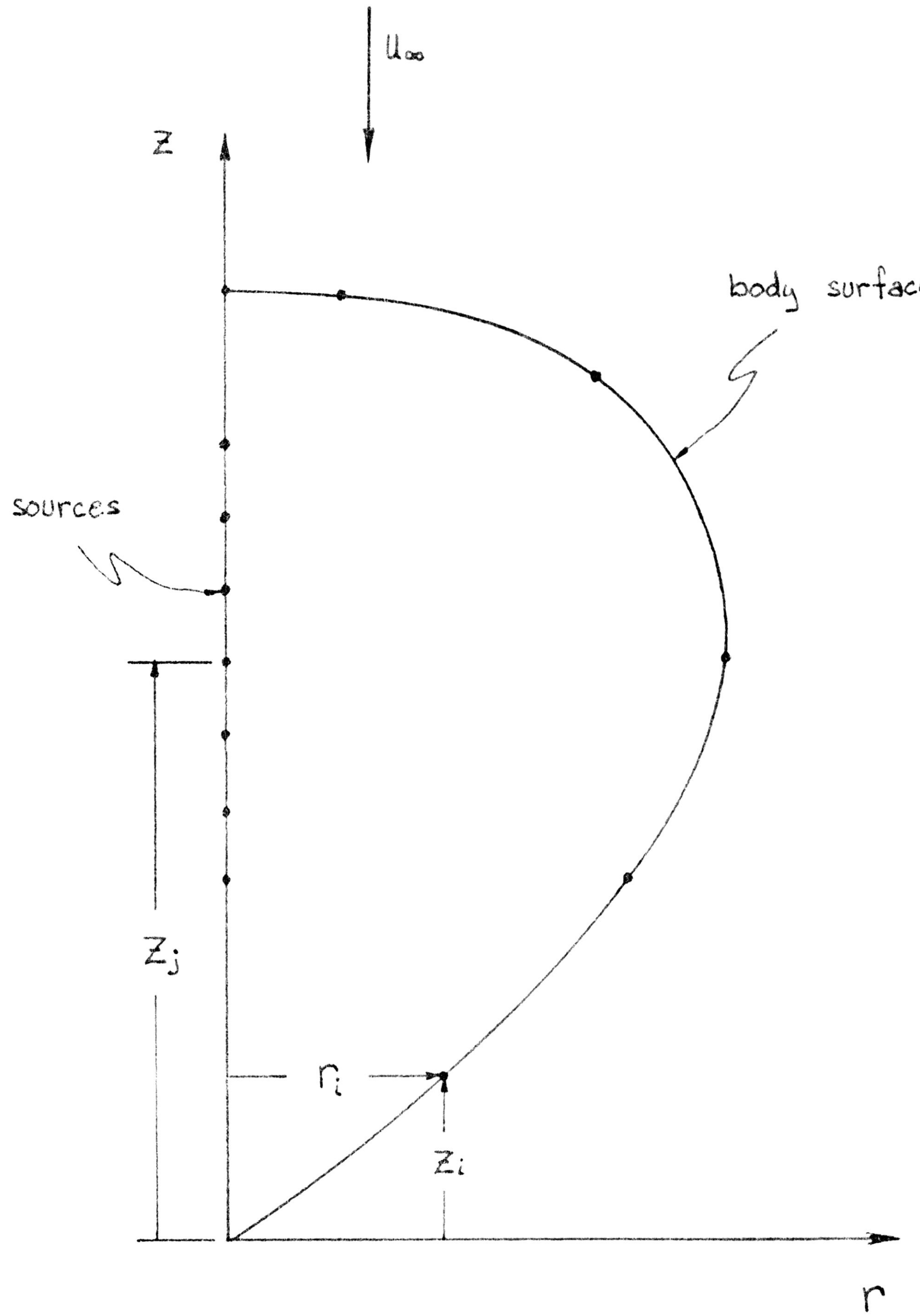


Figure 2

"Source distribution for Scientific Balloon model."

Balloon Design

When designing a scientific research balloon, it is essential to make the envelope as light as possible so that the balloon can reach the extremely high float altitudes demanded by today's scientists and continue to carry large payloads. Another design criteria is that the balloon must be structurally sound so that failure will not occur. To optimize the balloon design, a thorough stress analysis in the balloon film must be made.

The foundation to the stress analysis is the membrane equation:

$$\frac{\sigma_c}{R_c} + \frac{\sigma_m}{R_m} = \Delta P + W_f \sin\theta \quad .$$

The differential pressure across the balloon film is directly affected by the rate of climb of the balloon.

This differential static pressure may be found by the following derivation with reference to Figure 1.

Using Bernoulli's equation, the pressure on the outside is found:

$$P_{ai} + 1/2\ \rho_a V_i^2 = P_o + 1/2\ \rho_a V_\infty^2 - \rho_a g z_i$$

when solved for static pressure only, the equation becomes:

$$P_{ai} = P_o - \rho_a g z_i + q_\infty C_P \ .$$

The static pressure on the inside of the balloon is unaffected by the airflow on the outside and therefore described by the hydrostatic equation. This pressure is:

$$P_{gi} = P_o - \rho_g g z_i \ .$$

Therefore, the differential pressure across the balloon film is:

$$\Delta P_i = b_o z_i - q_\infty C_P \ . \qquad (1)$$

Previous Potential Flow Solution

In previous studies[1] the potential flow about a balloon shape was similar to one used by von Karman[3] to simulate the air flow about an axisymmetric body. The main difference is that von Karman modeled slender bodies. Balloon shapes are definately not slender bodies and as a result the potential flow for this case is more difficult to solve. This method replaced the body with a series of sources on the axis of symmetry and an upstream velocity. Figure 2. The strength of each source is calculated by satisfying boundary conditions that are characteristic of the potential flow about the body. The stream function for such a model is described by:[4]

$$\psi_i = 1/2\ r_i^2\ V_\infty + \sum_{j=1}^{n} m_j[((z_i - z_j)^2 + r_i^2)^{\frac{1}{2}}] \qquad (2)$$

In order to describe the flow around a balloon with this mathematical model, the stream function must be zero on the surface of the balloon. In addition, the air flow must stagnate at the top of the balloon, and to ensure a closing condition, the summation of the source strengths must equal zero.

Using this potential flow solution and the stress analysis it was shown last year that the circumferential stress in the balloon film is increased significantly with an increase in balloon rate of climb. Figure 3. In this particular case, seven sources were used to describe the airflow, Figure 4, and the potential flow solution produced favorable results. However, when nine sources were used, the solution became unrepresentative of the natural balloon shape, Figure 5, and the potential flow solution produced results which were clearly not accurate. As a result of this potential flow solution becoming worse with the addition of sources, an intensive study to improve the aerodynamic calculations for balloon shapes was begun.

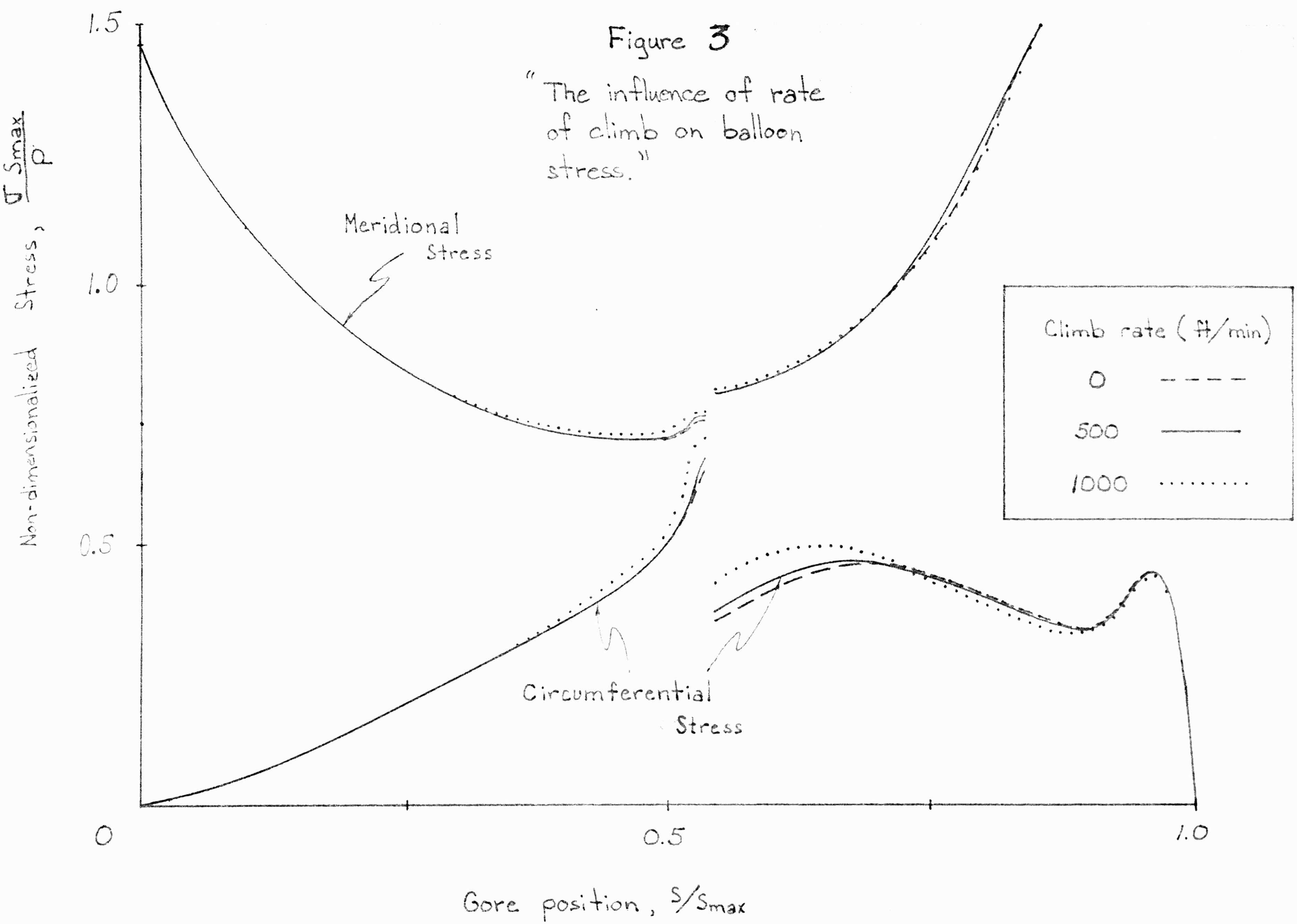


Figure 3

"The influence of rate of climb on balloon stress."

FIGURE 4

"A good solution using a 7 source model."

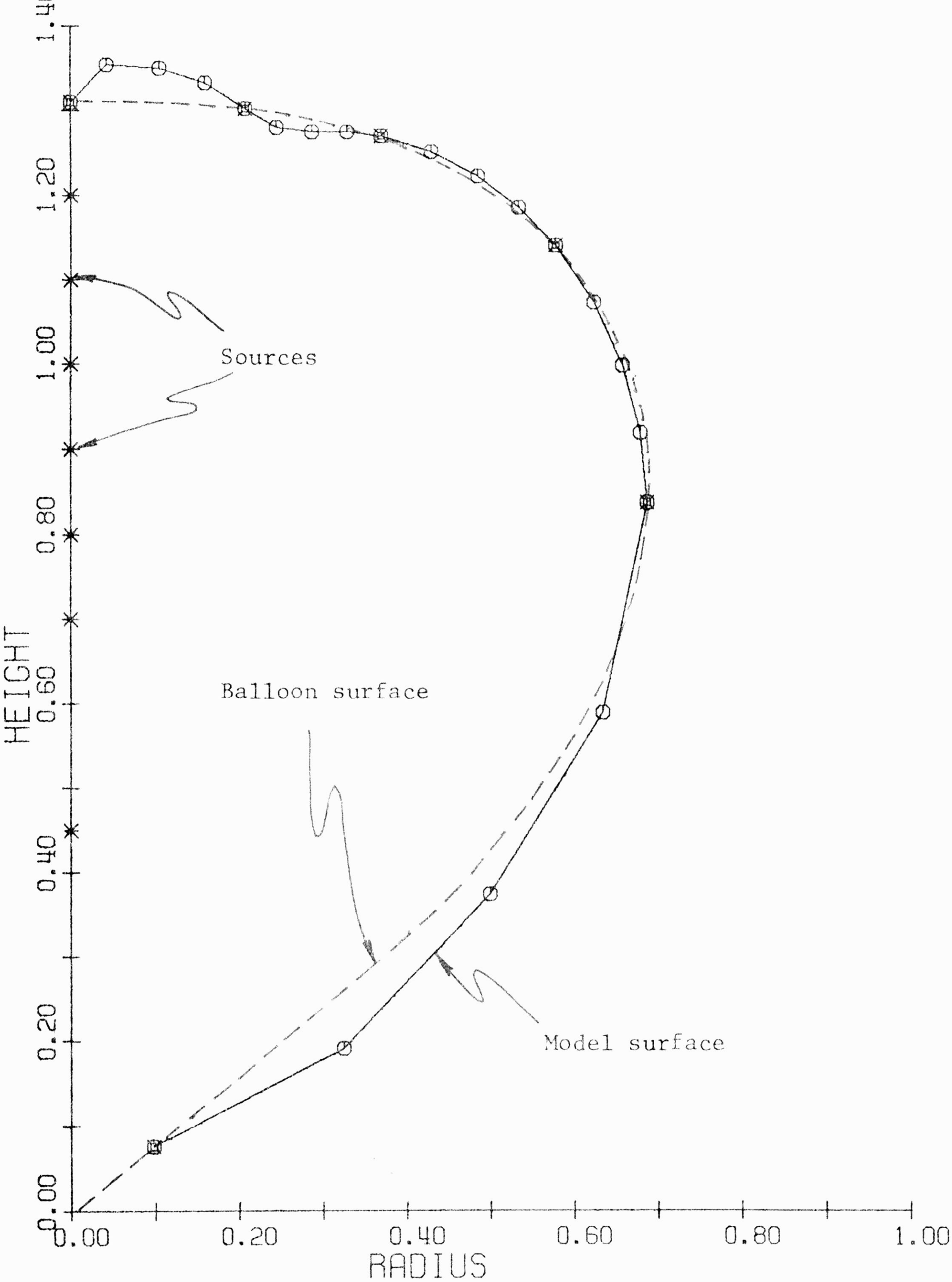
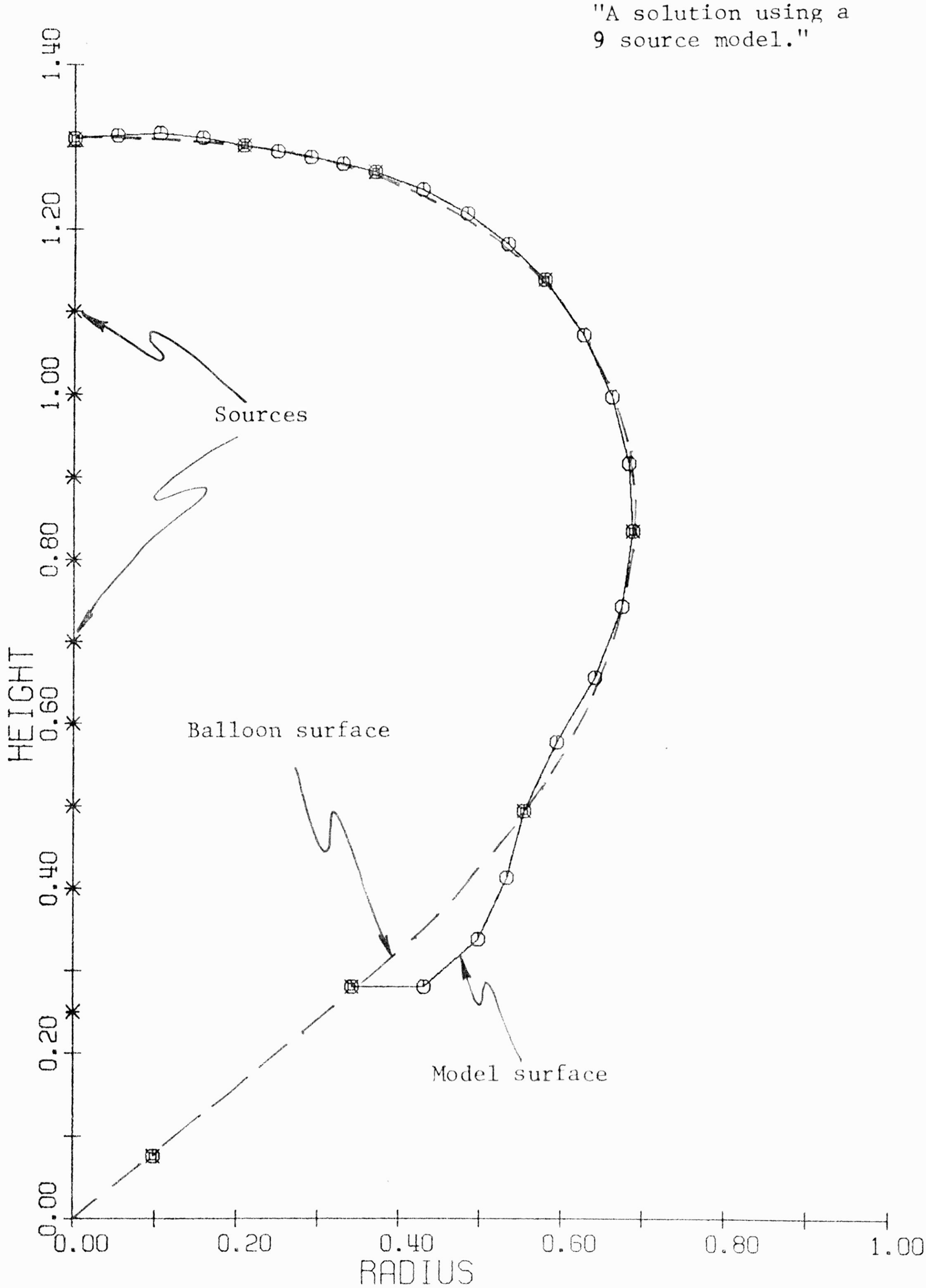


FIGURE 5

"A solution using a
9 source model."



Improvement of the Aerodynamic Calculations

The problem with the previous potential solution is that it was very unstable even for the natural balloon shape, which is the easiest balloon configuration to model mathematically.

First of all it was observed that if the order of the points on the balloon surface were input differently, the resulting source strengths for each case were different. Originally it was thought that the Gaussian Elimination method used was at fault, however this was not the case. After studying the problem in depth, it was found that due to the structure of the matrix, double precision was needed to produce consistent results. This, however, did not solve the instability problem.

The next step was to develop a method to visually inspect and compare the shape of the model to that of the desired balloon shape. This was accomplished by finding points on the model between the points on the balloon where the stream function is zero and plotting the results on a Versatec plotter. The method used took three points on the perpendicular bisector of the line between the points on the surface where the stream function was forced to equal zero. Figure 6. Then by using a Lagrangian interpolation method the location on the perpendicular bisector where the stream function equals zero is determined.

With this visual aid, the accuracy for each case could be determined very quickly. This aid also made it feasible to develop another potential flow solution to compare with the previous one.

The new potential flow solution is similar to the previous solution except rather than sources, doublets were used. The main difference between the doublet model and the source model is that

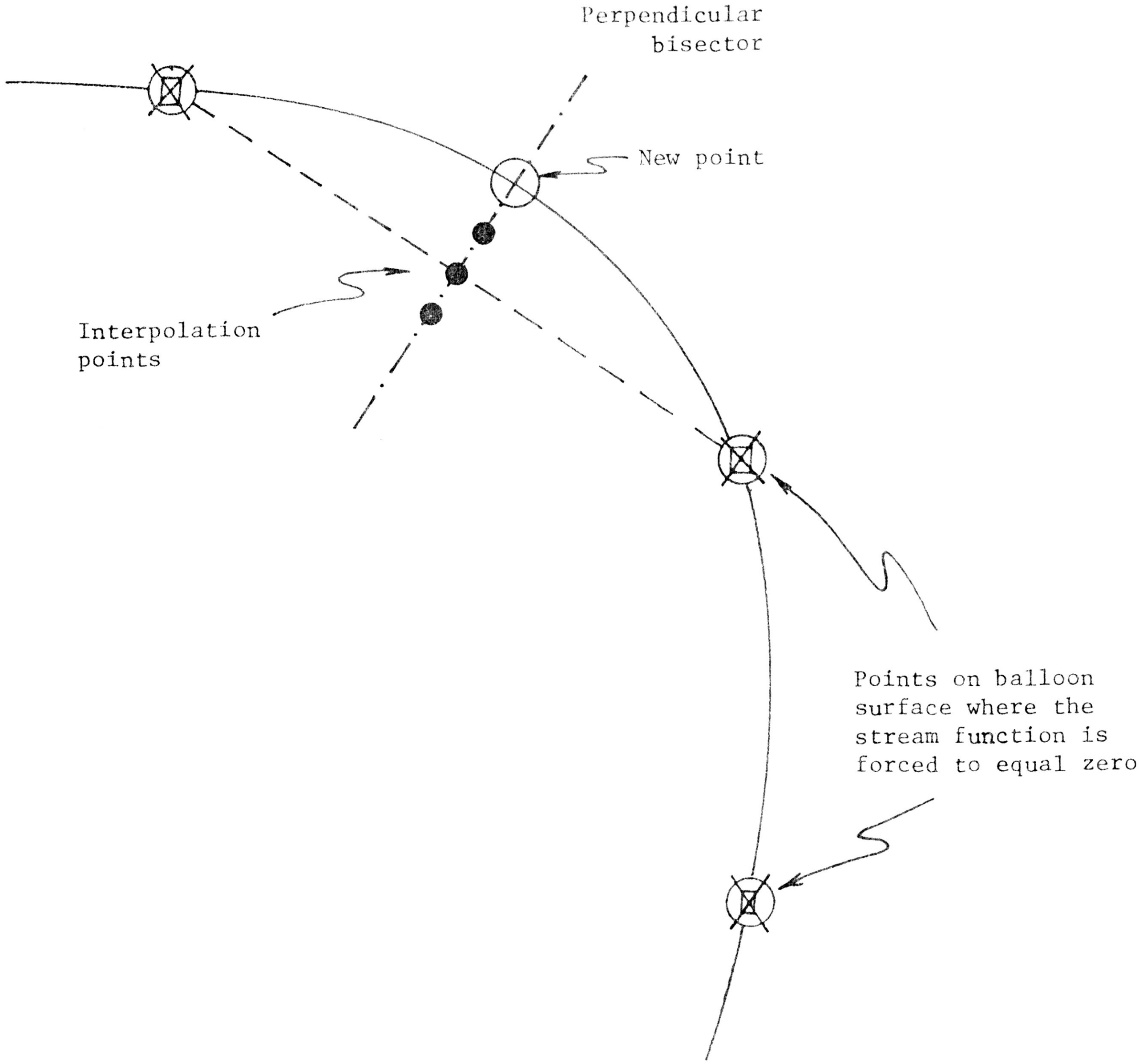


FIGURE 6

"Finding points on
the model's surface."

a closing condition is identically satisfied, thus enabling one extra point on the balloon surface where the stream function is forced to zero. Also in the case of the balloon shape a doublet has a greater influence on points close to it than a source would. This results in a matrix structure less likely to be ill conditioned.

The stream function for the doublet model is described by:[4]

$$\psi_i = \tfrac{1}{2} r_i^2 V_\infty + \sum_{j=1}^{n} S_j \left[r_i^2 / ((z_j - z_i)^2 + r_i^2)^{1.5} \right]$$

The local velocity components are:[4]

$$V_{zi} = \frac{-1}{r_i} \frac{\partial \psi_i}{\partial r}$$

$$V_{ri} = \frac{1}{r_i} \frac{\partial \psi_i}{\partial z}$$

$$V_i = (V_{zi}^2 + V_{ri}^2)^{\frac{1}{2}}$$

The coefficient of pressure is:[5]

$$C_p = 1 - (V_i / V_\infty)^2$$

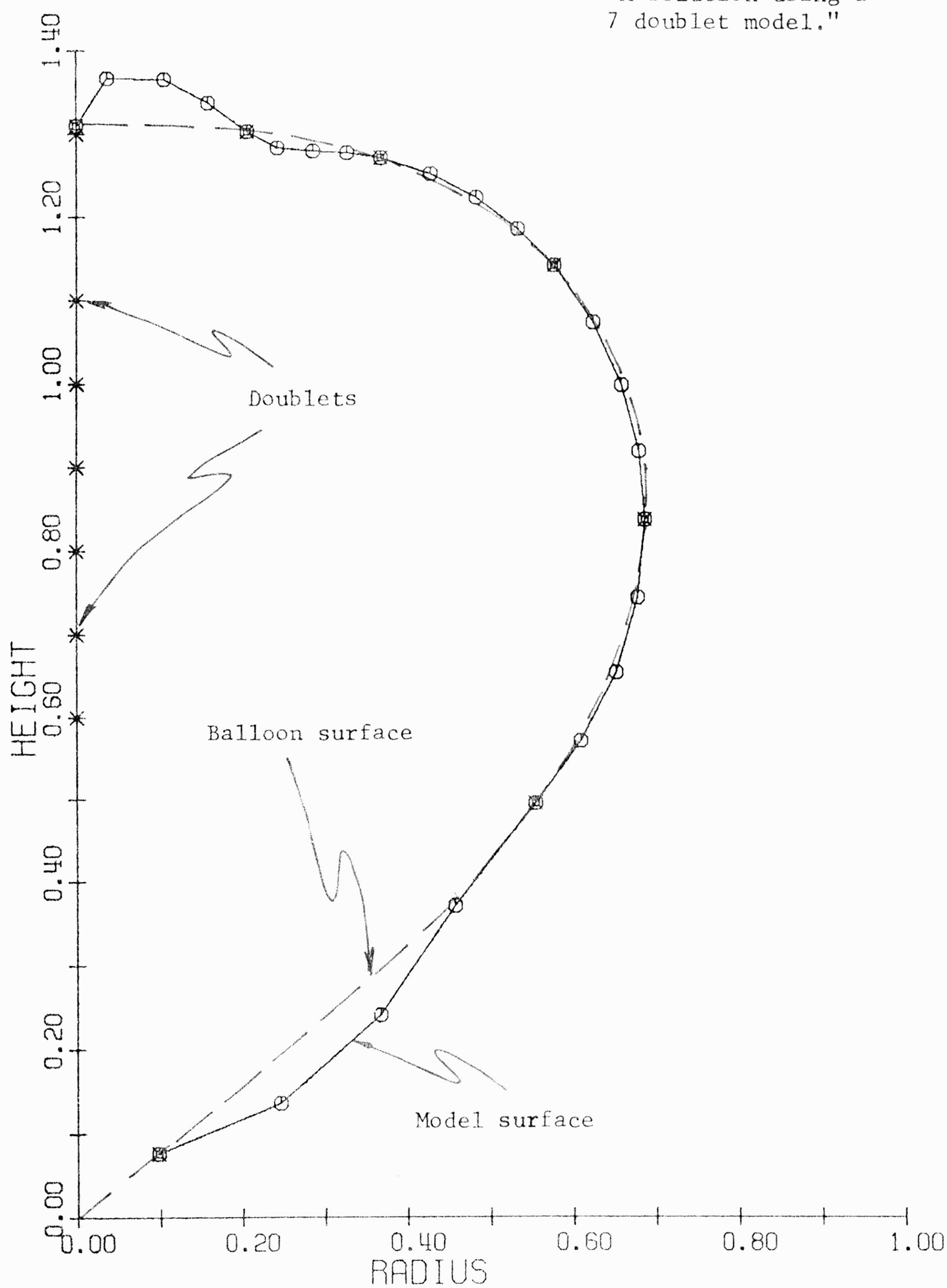
In order to describe the flow, the stream function must be zero on the surface and the vertical velocity must be zero at the top of the balloon.

Comparing the previous source solution with the doublet solution, it was found that although seven doublets, Figure 7, was a good solution, nine doublets resulted in a better solution, Figure 8. This implies that the doublet solution is better behaved than the source solution, which was expected.

Although the doublet solution is superior, it continues to have limitations. These limitations are directly related to the structure of the matrix of simultaneous equations characteristic to the balloon

FIGURE 7

"A solution using a
7 doublet model."



shape. In order to obtain the best matrix structure and therefore best solution, it was found that placement of the doublets on the axis of symmetry made a terrific difference. Figure 8, 9. Also the points on the balloon surface where the stream function is force to equal zero should be spaced closer to each other near the axis of symmetry than at the maximum radius of the balloon.

Using this doublet solution, thirteen doublets were tried and the resulting model was no better than the model using nine doublets but produced good results none the less. This test clearly displays that the structure of the matrix for the doublet solution is better than that of the source solution.

With the improvement on the aerodynamic calculations the stress in the balloon film can now be determined for other shapes which are more difficult to model, with more confidence in the results.

FIGURE 8

"The best solution which used a 9 doublet model."

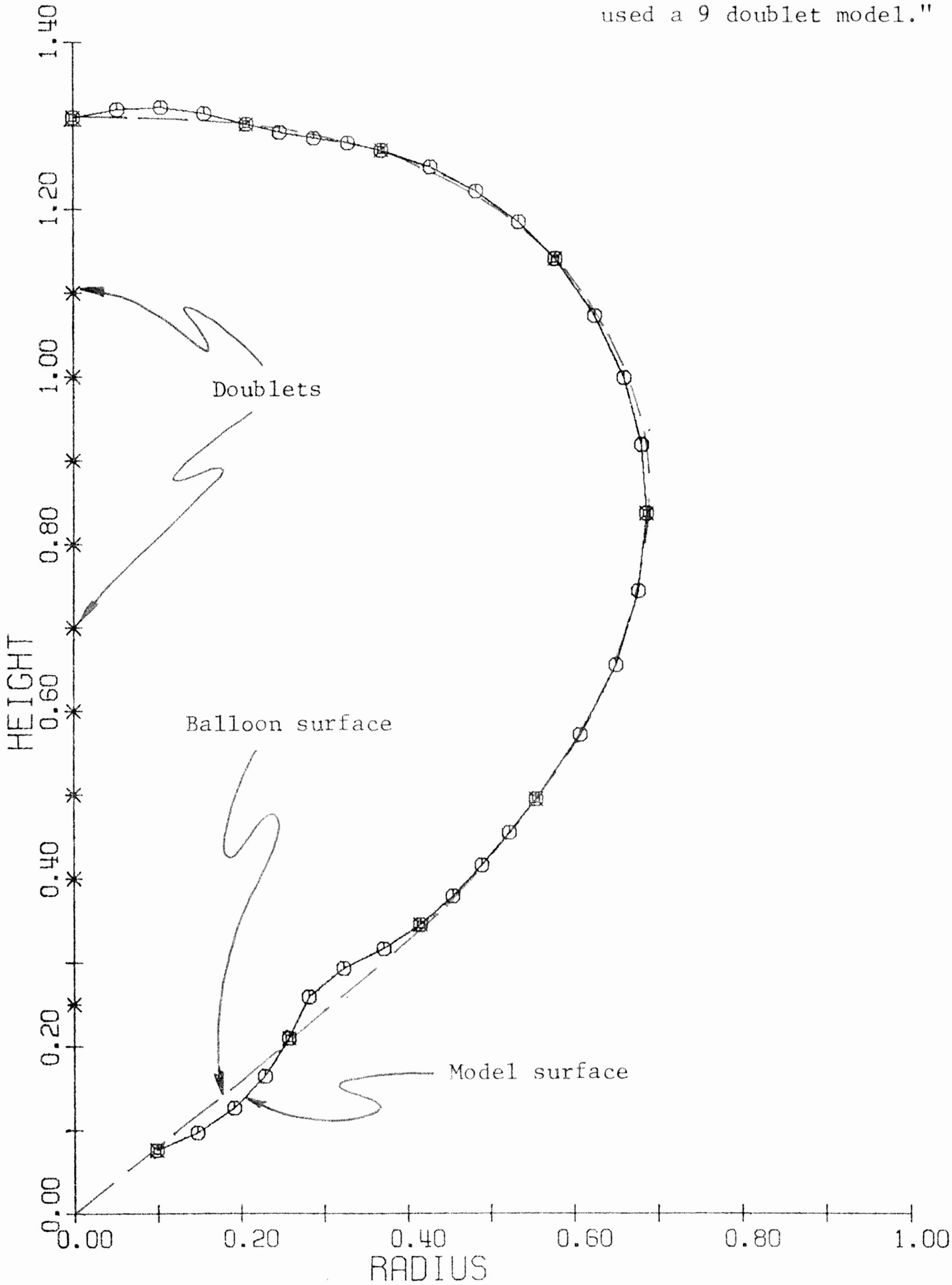
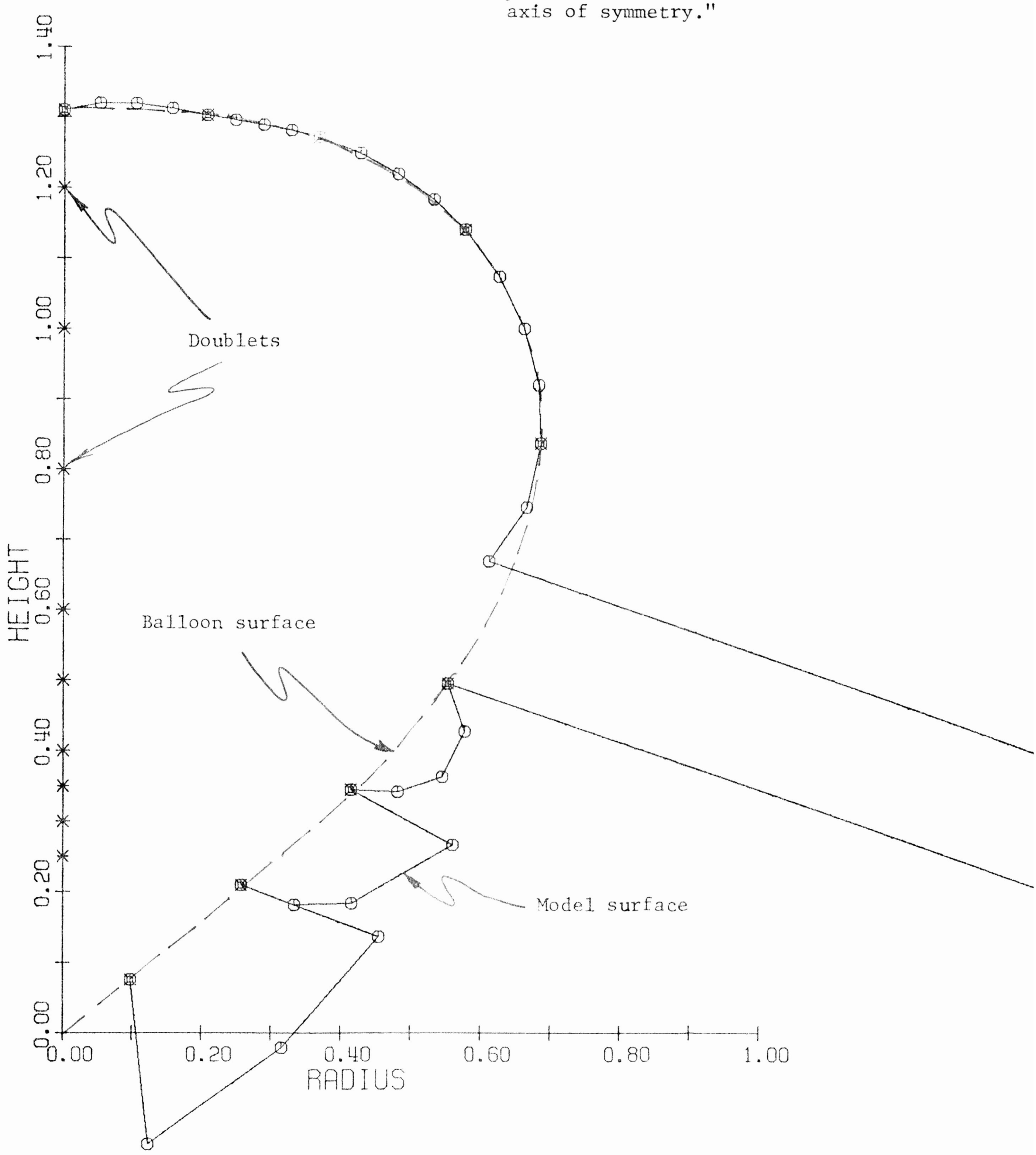


FIGURE 9

"This is a 9 doublet model which shows the importance of doublet placement on the axis of symmetry."



Boundary-Layer Calculations

In existing balloon stress analyses, the effect of skin friction is completely ignored in calculating the meridional stress. The drag estimates, where needed, are based on crude assumptions which ignore the balloon shape. The potential flow solution itself assumes the air flow does not seperate. For all these reasons it is desirable to calculate the boundary layer over the surface of the balloon.

As part of the present study a boundary-layer calculation[6] using a Crank-Nickolson difference method[7] has been programmed and partially checked. With the results from the new potential flow solution the boundary-layer calculation will be used to find the seperation point on the balloon surface, and drag estimates. The base drag can be estimated once the seperation point is known and the skin friction drag can be found when the velocity profile is known along the balloon surface. At this present time the boundary-layer calculation has not been integrated with the potential flow solution already described, but futher work is planned in this area.

Conclusions

The improved aerodynamic calculations described in this paper show that a good potential flow solution may be found for balloon shapes. Since balloons are not slender bodies the matrix of simultaneous equations must be structured so that it has a strong diagonal in order to keep the matrix from being ill conditioned. Based on this, it has been determined and shown that the potential flow solution is best when:

1) Double-Precision is used instead of single-precision when solving the matrix,

2) Doublets are used instead of sources because the influence of a doublet is greater than that of a source on a point near the doublet/source element. Also, doublets allow one extra point on the surface where the stream function is forced to equal zero,

3) The doublets are evenly spaced toward the center two-thirds of the balloon on the axis of symmetry, and

4) The points on the balloon surface where the stream function is forced to equal zero are slightly closer spaced near the axis of symmetry than at the maximum radius of the balloon.

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BIOGRAPHICAL DATA

John Charles Vassberg was born on January 28th, 1959 in Raymondville, Texas. He has lived in Lyford, Texas since then, with the exception for the time in College Station. John grew up on a farm and feedlot where the princple crops grown are cotton and grain sorghum and about 500 cattle were feed continuously. Because of this life style, he has come to enjoy physical activities such as hunting, fishing, sports (football, baseball, tennis, raquetball, etc.), hang gliding, water skiing, and the list continues. John started his education at a private Lutheran Church school at the age of five, was admitted to second grade the next year, completed high school at Lyford High, and went to college at Texas A&M University in the fall of 1976. At Texas A&M, John has been majoring in Aerospace Engineering and has been accepted to graduate school, where he will continue in Aerospace Engineering, specializing in Aerodynamics.