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FLIGHT PERFORMANCE OF A TRANSONIC TURBINE-DRIVEN

PROPELLER DESIGNED FOR MINIMUM NOISE

By Thomas C. O'Bryan and Jerome B. Hammack

Langley Research Center
Langley Field, Va.

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FLIGHT PERFORMANCE OF A TRANSONIC TURBINE-DRIVEN PROPELLER DESIGNED FOR MINIMUM NOISE

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SUMMARY

Results are presented of a flight investigation to determine the aerodynamic characteristics of a transonic-type propeller. This propeller was designed for an advance ratio of 4.0 at a forward Mach number of 0.82 in an effort to limit the noise production.

The measured efficiency of the propeller was 68 percent at the design Mach number of 0.82. This value compares with an efficiency as much as 15 percent higher with the same Mach number for a propeller designed for an optimum advance ratio of about 3.0. This penalty in efficiency must be considered in light of the resulting noise reduction. The noise under static and take-off conditions was measured to be 117.5 decibels, which represents a noise reduction of about 5 decibels (at 1,400 horsepower) compared with the advance-ratio-3 design.

INTRODUCTION

Efficient propeller operation in the transonic speed range requires optimum angle of advance and minimum-thickness-ratio distribution. In this range, profile efficiency is a primary consideration since profile losses are high and induced losses are low. Consequently, the most efficient propeller for operation at transonic forward speed is one in which the pitch distribution is designed to correspond to an angle of advance close to 45°. It was shown in reference 1, however, that some departure from optimum advance angle (or optimum pitch distribution) resulted in no loss in efficiency for propellers incorporating low-thickness-ratio airfoils. As a result, a modified supersonic propeller could be designed with lower tip speed and a consequent reduction in noise.

In an effort to lower the noise production still further, and in an attempt to establish an end point in design advance ratio for transonic forward speeds, a propeller with higher than optimum advance ratio was tested. It was designed for an advance ratio of 4.0, which represented a rather large deviation from optimum, and a forward speed corresponding to a Mach number of 0.82. The propeller retained the concept of low-thickness-ratio sections of references 1 and 2, the "supersonic" and "modified-supersonic" propellers.

The noise characteristics of the propeller have been described in reference 3 which shows lower noise production for this propeller than for either the supersonic or the modified-supersonic propellers.

SYMBOLS

A	area of propeller disk, sq ft
b	blade chord, ft
C_L	propeller design lift coefficient
C_P	propeller power coefficient, $P/\rho n^3 D^5$
C_T	propeller thrust coefficient, $T/\rho n^2 D^4$
D	propeller diameter, ft
h	blade thickness, ft
p_t	total pressure, lb/sq ft
J	propeller advance ratio, V/nD
M	free-stream Mach number
n	propeller rotational speed, rps
P	power, ft-lb/sec
p	static pressure, lb/sq ft
r	radius of an element on blade from center line of rotation, ft
r_s	radial dimension from center line of rotation measured along survey rake, ft
T	thrust, lb

V velocity, ft/sec

$x = 2r/D$

$x_s = 2r_s/D$

Δp_t total-pressure rise in slipstream, lb/sq ft

β blade angle, deg

η propeller efficiency

ρ density of air, slugs/cu ft

Subscripts:

∞ free-stream conditions

t propeller tip condition

APPARATUS

Test Vehicle

The propeller test vehicle shown in figure 1 is the McDonnell XF-88B propeller research airplane and is described in reference 2. In the tests reported herein a gearbox that provided 1,700 revolutions per minute was used. The basic propulsion system consists of two J-34 turbojet engines and thus the airplane performance is independent of the propeller operation. As a result, the propeller could be operated at any power setting without changing the test conditions of speed or altitude.

Test Propeller and Spinner

The propeller was a three-blade configuration of 6.85-foot diameter, and was designed for a forward Mach number of 0.82 at an altitude of 35,000 feet, and an advance ratio of 4.0. The blades are constructed of solid steel, machined from SAE 4340 steel forgings. The blades were of rectangular plan form with NACA 16-series airfoil sections and the design lift coefficient was 0.50 outboard of the 0.35 radius station. The thickness ratio varied from 7.7 percent at the 0.35 radius to 2.0 percent at the 0.80 radius and then had a constant value of 2.0 percent to the tip. The blade-form curves are shown in figure 2.

The propeller was tested in conjunction with an elliptical spinner that was 55 inches in length and 30.2 inches in diameter at the propeller plane. A photograph of the spinner, propeller, and test vehicle is presented as figure 1. The blade seals shown in the photograph were alined with the spinner surface at the design advance ratio to provide an aerodynamically smooth surface.

INSTRUMENTATION AND DATA REDUCTION

The XF-88B airplane is instrumented to gather aerodynamic and structural information concerning the propeller undergoing investigation. Quantities measured produce the following information: power, thrust, propeller efficiency; root blade angles, steady and vibratory bending and torsion stresses, and rotational speed. Also recorded are airspeed, altitude, free-air temperature, throttle and governor control position, normal and longitudinal acceleration. A schematic drawing showing the instrumentation is presented in figure 3.

Power Measurements

Power was determined from measurements of torque and propeller rotational speed. The torque input to the propeller gearbox is measured by a modified Allison electronic torquemeter. A complete description of the modified torquemeter unit is contained in reference 2. Power is considered to be accurate to ±20 horsepower or a ΔC_p of ±0.035 at 30,000 feet.

Thrust Measurements

Propeller thrust is measured by a slipstream survey rake in the manner described in reference 4. Incremental or section values are determined directly from the rise in total pressure in the slipstream and total thrust is obtained from integration from the fuselage surface to the rake station showing zero incremental thrust. The survey rake and probes used on the XF-88B propeller research airplane are shown in detail in reference 2. These probes measure total-pressure rise and static pressure. The reference total-pressure tube is at the extreme end of the survey rake out of the influence of the propeller slipstream. Recording manometers register the difference in total-pressure rise between each probe and the reference probe. This total-pressure rise is a function of propeller thrust.

Under conditions of the survey covered by this paper, the short-form equation of reference 4 can be used to evaluate the thrust:

$$dT = \left(\frac{p_\infty}{p_{t_\infty}}\right)^{5/7} \Delta p_t \; dA \tag{1}$$

or

$$\frac{dT}{d\left(x_s^2\right)} = \pi\left(\frac{D}{2}\right)\left(\frac{p_\infty}{p_{t_\infty}}\right)^{5/7} \Delta p_t \tag{2}$$

and in thrust-coefficient form

$$\frac{dC_T}{d\left(x_s^2\right)} = \frac{dT/d\left(x_s^2\right)}{\rho n^2 D^4} = \frac{\pi\left(\frac{p_\infty}{p_{t_\infty}}\right)^{5/7} \Delta p_t}{4\rho n^2 D^2} \tag{3}$$

The thrust distribution determined from the slipstream survey is considered to be accurate to ±2.0 percent.

The total thrust coefficient was determined from integration of the total-pressure rise in the slipstream referenced to free-stream conditions for both the left and right rakes and then averaging these two values. Thus, the equation for the thrust coefficient is the integral of equation (3) or

$$C_T = \frac{\pi\left(\frac{p_\infty}{p_{t_\infty}}\right)^{5/7}}{4\rho n^2 D^2} \int \Delta p_t \; d\left(x_s^2\right) \tag{4}$$

Inasmuch as the total-pressure probes are insensitive to small changes in angle, the thrust calculated in this fashion does not account for rotation of the slipstream. The incremental thrust was corrected for slipstream rotation by using the method of reference 5.

Efficiency

Propeller efficiency was calculated from measured values of C_T, C_P, and J_∞ by means of

$$\eta = \frac{C_T}{C_P} J_\infty \tag{5}$$

The efficiency measurements reported herein are considered to be accurate to ±3 percent.

RESULTS AND DISCUSSION

Propeller Efficiency

Figure 4 presents the variation of propeller efficiency with forward Mach number. The corresponding thrust coefficient, power coefficient, and advance ratio are also included. At the design Mach number of 0.82 the efficiency is 68 percent. The advance ratio at this design Mach number of 0.82 corresponds fairly well to the design advance ratio of 4.0 in one series of runs at an altitude of 30,000 feet; in another series of runs at an altitude of 20,000 feet the resulting advance ratio was somewhat higher, being on the order of 4.5. The data obtained with the higher than design advance ratio show somewhat lower propeller efficiency.

Calculation of the optimum efficiency of this propeller at the design forward Mach number of 0.82 in an undisturbed free stream indicates a value of 70 percent. These calculations were made by using propeller strip theory and utilizing two-dimensional airfoil data. Lift coefficients for maximum lift-drag ratio were used in the calculations. The value of J_{∞}, C_P, and C_T are shown along with the efficiency as black diamonds in figure 4. The experimental efficiency of 68 percent was somewhat lower than the calculated value. Calculations show that a propeller operating at an optimum advance ratio of about 3 could be designed that would produce 85-percent efficiency. The 15-percent penalty in efficiency between the two calculations must be considered in light of the attendant reduction in noise resulting from the lower tip speed of the advance-ratio-4 propeller. The noise, under static and take-off conditions, of the advance-ratio-4 propeller was measured to be 117.5 decibels at 1,400 horsepower. This is about a 5-decibel decrease compared with the estimated noise level of the advance-ratio-3 propeller under the same conditions. A complete discussion of the noise characteristics of the advance-ratio-4 propeller is found in reference 3.

The design advance ratio of 4.0 at a forward Mach number of 0.82, resulted in a propeller speed of 1,700 revolutions per minute and a diameter of approximately 7 feet. This combination produced a propeller design which was somewhat undersize for the available engine power; the design power coefficient C_P was 1.88. Therefore, it was possible to increase the power over the design to measure the resulting effect on propeller efficiency. This was done at a constant Mach number of 0.84. Figure 5 presents the measured propeller efficiency plotted against power coefficient. Although the peak efficiency did not occur at the design value of power coefficient increasing the coefficient beyond design tends to lower the resulting efficiency even more.

Thrust Distributions

Thrust distributions for the range of Mach numbers from $M = 0.658$ to 0.956 are shown in figure 6. The distributions are presented as variations in differential thrust coefficient with radial station for both left and right survey rakes.

The thrust distributions are smooth and uniform with no breakdown in the outboard regions such as occur with subsonic propellers encountering compressibility losses. It can be seen from these figures that the differential thrust extends past the propeller tip station $\left(x_s^2 = 1.0\right)$. This extension is due to the expansion of the air mass by the conical fuselage. It appears to expand slightly more on the right side than on the left; the difference is only of the order of 1 inch at the measuring station.

The characteristic difference in thrust-distribution levels between right and left survey rakes results from propeller-thrust-axis inclination. The decrease in the magnitude of this thrust difference with increasing Mach number reflects the usual decrease in angle of inclination of the thrust axis with Mach number. This result is in agreement with the variation in the slope of the lift curve and zero-lift angle of the airplane as noted in references 1 and 2.

CONCLUDING REMARKS

Results are presented of a flight investigation to determine the aerodynamic characteristics of a transonic-type propeller design for an advance ratio of 4.0 at a forward Mach number 0.82. This value of advance ratio (4.0) was considered to be a reasonably large variation from the optimum advance ratio ($J \approx 3$) at the design forward speed and was chosen in an effort to lower the tip speed to produce as quiet a propeller as possible.

The efficiency of the propeller was 68 percent at a forward Mach number of 0.82. For comparison, calculations indicate that if a propeller with an advance ratio of about 3 were designed for this forward Mach number, the efficiency would be increased by as much as 15 percent. This penalty in efficiency must be considered in light of the resulting noise reduction. The noise under static and take-off conditions was measured to be 117.5 decibels, which represents a noise reduction of about 5 decibels (at 1,400 horsepower) compared with the advance-ratio-3 design.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., January 27, 1959.

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1. Hammack, Jerome B., and O'Bryan, Thomas C.: Effect of Advance Ratio on Flight Performance of a Modified Supersonic Propeller. NACA TN 4389, 1958.

2. Hammack, Jerome B., Kurbjun, Max C., and O'Bryan, Thomas C.: Flight Investigation of a Supersonic Propeller on a Propeller Research Vehicle at Mach Number to 1.01. NACA RM L57E20, 1957.

3. Kurbjun, Max C.: Noise Survey Under Static Conditions of a Turbine-Driven Transonic Propeller With an Advance Ratio of 4.0. NASA MEMO 4-18-59L, 1959.

4. Vogeley, A. W.: Flight Measurements of Compressibility Effects on a Three-Blade Thin Clark Y Propeller Operating at Constant Advance-Diameter Ratio and Blade Angle. NACA WR L-505, 1943. (Formerly NACA ACR 3G12.)

5. Pankhurst, R. C.: Airscrew Thrust Grading by Pitot Traverse: Allowance for Rotation of Slipstream at High Rates of Advance. R. & M. No. 2049, British A.R.C., 1945.

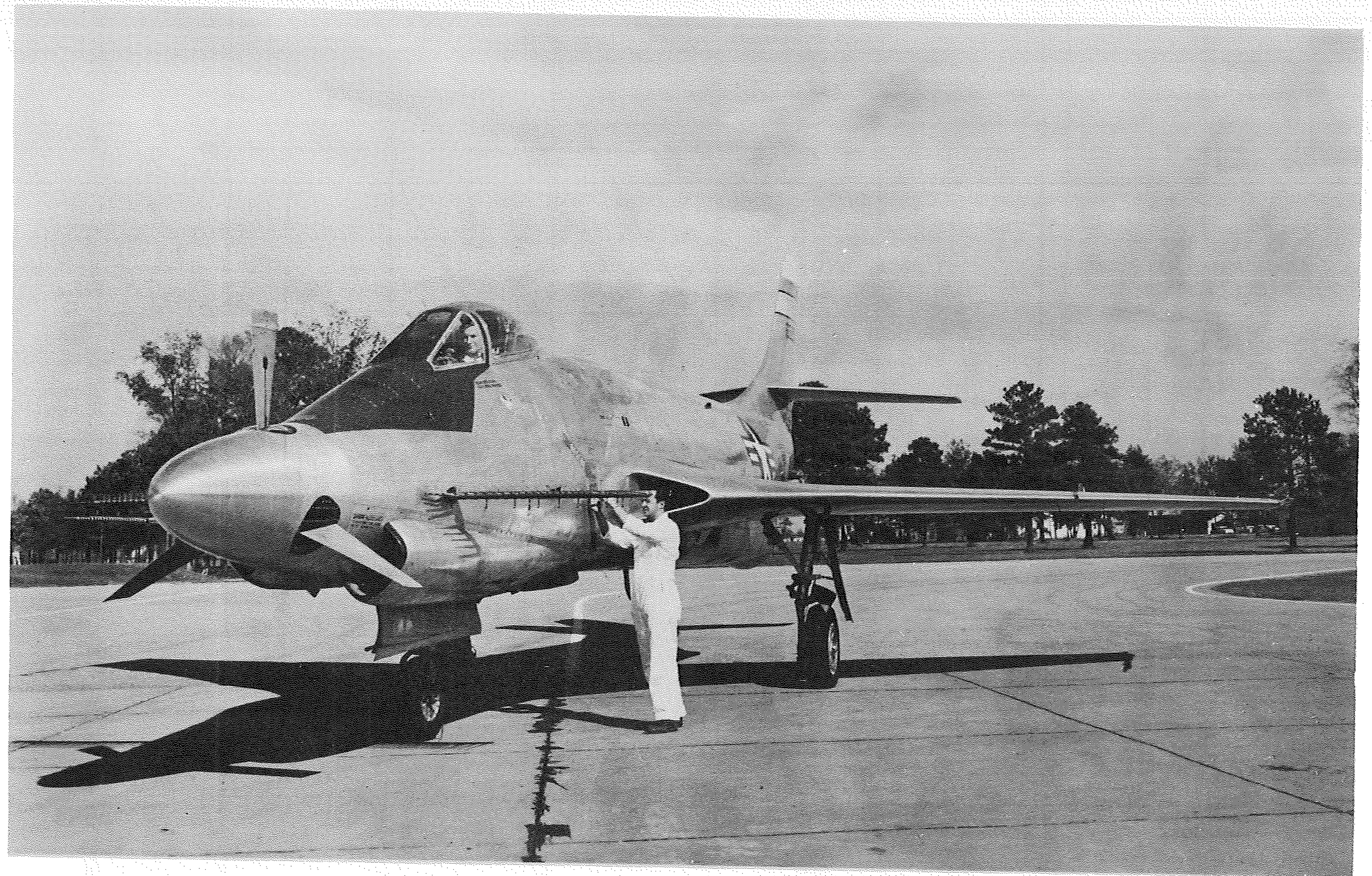

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Figure 1.- Photograph of McDonnell XF-88B airplane showing test propeller and spinner.

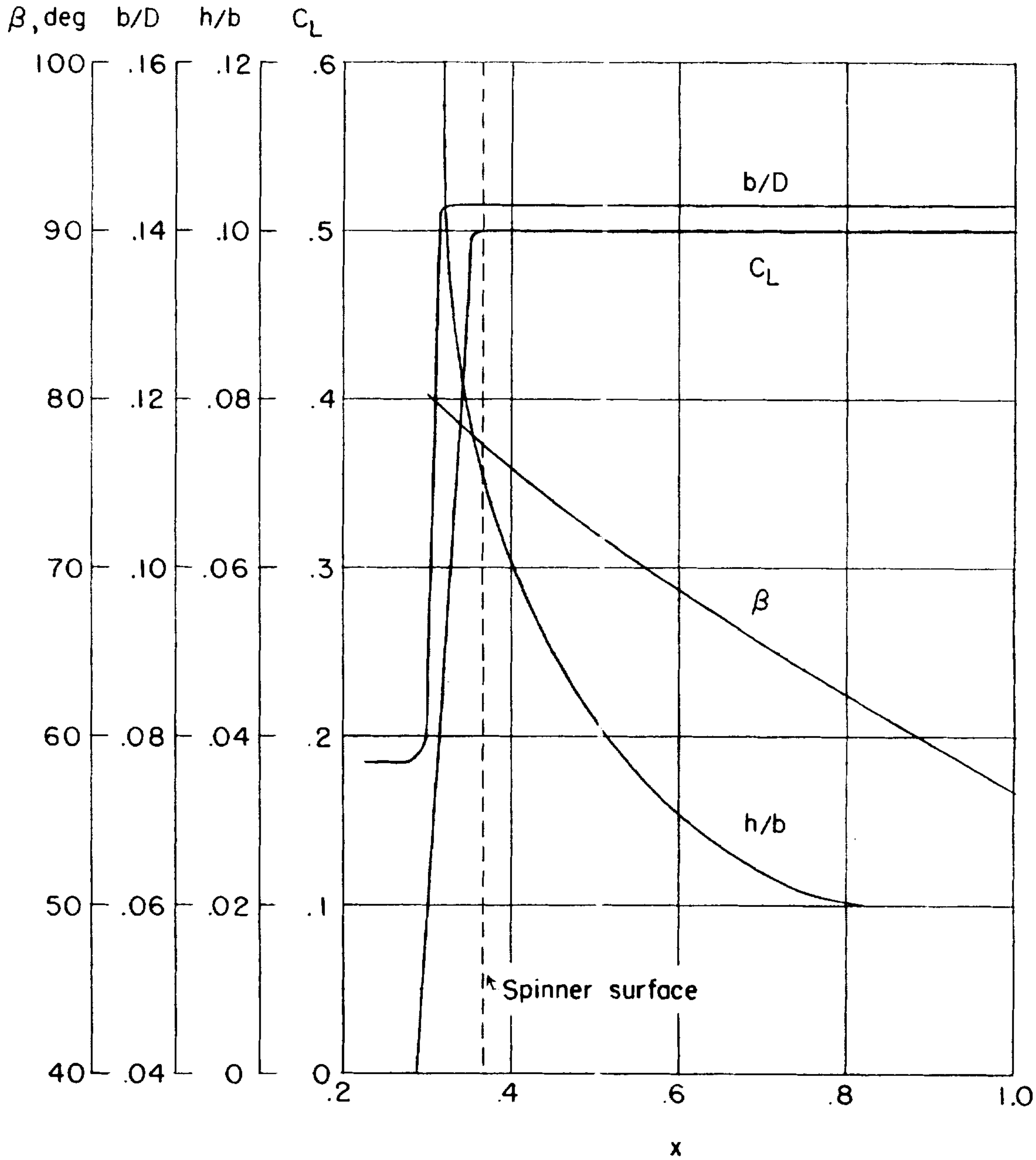

Figure 2.- Blade-form curves of transonic propeller used in present investigation. (J = 4.0)

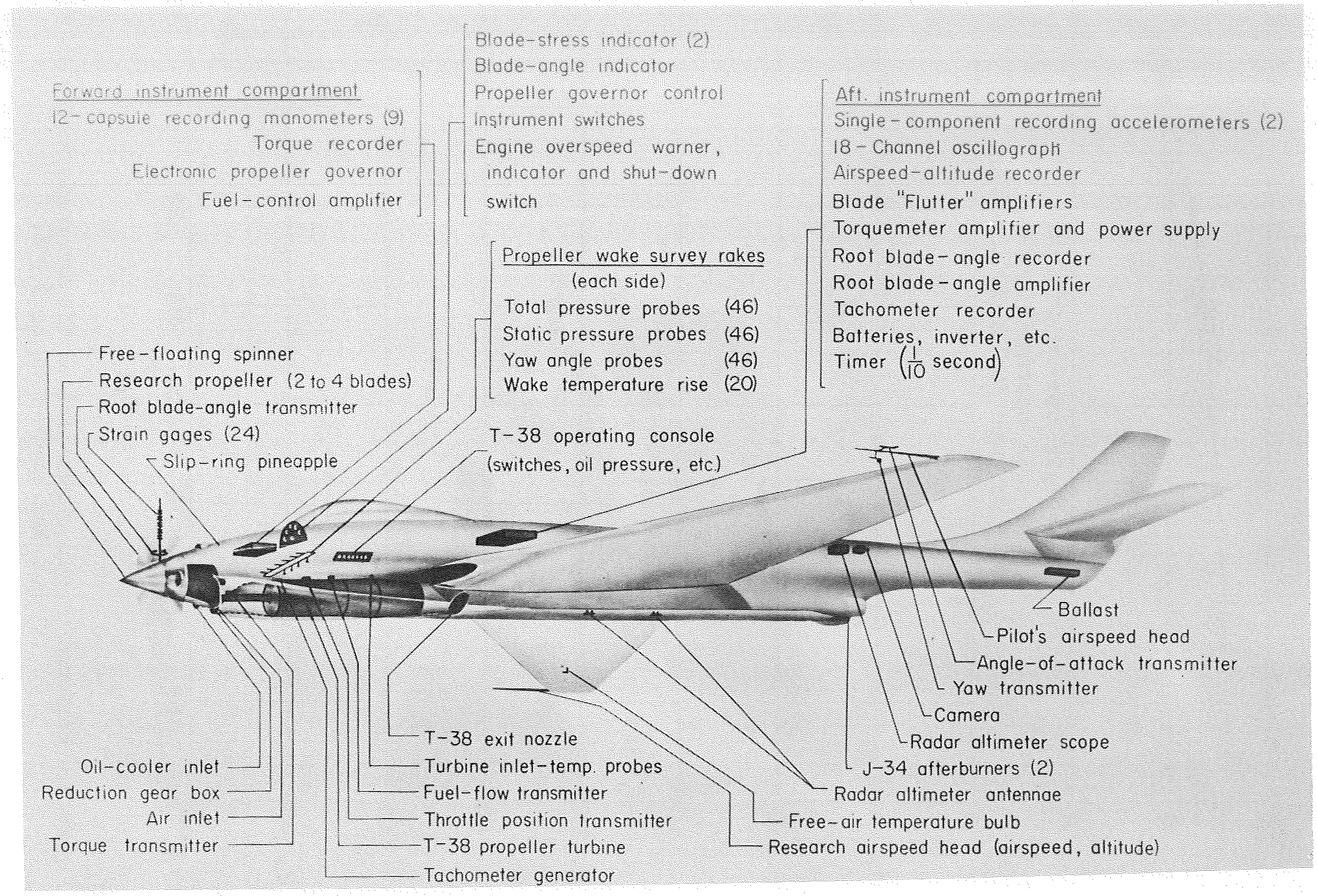

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Figure 3.- Instrumentation layout on the McDonnell XF-88B airplane.

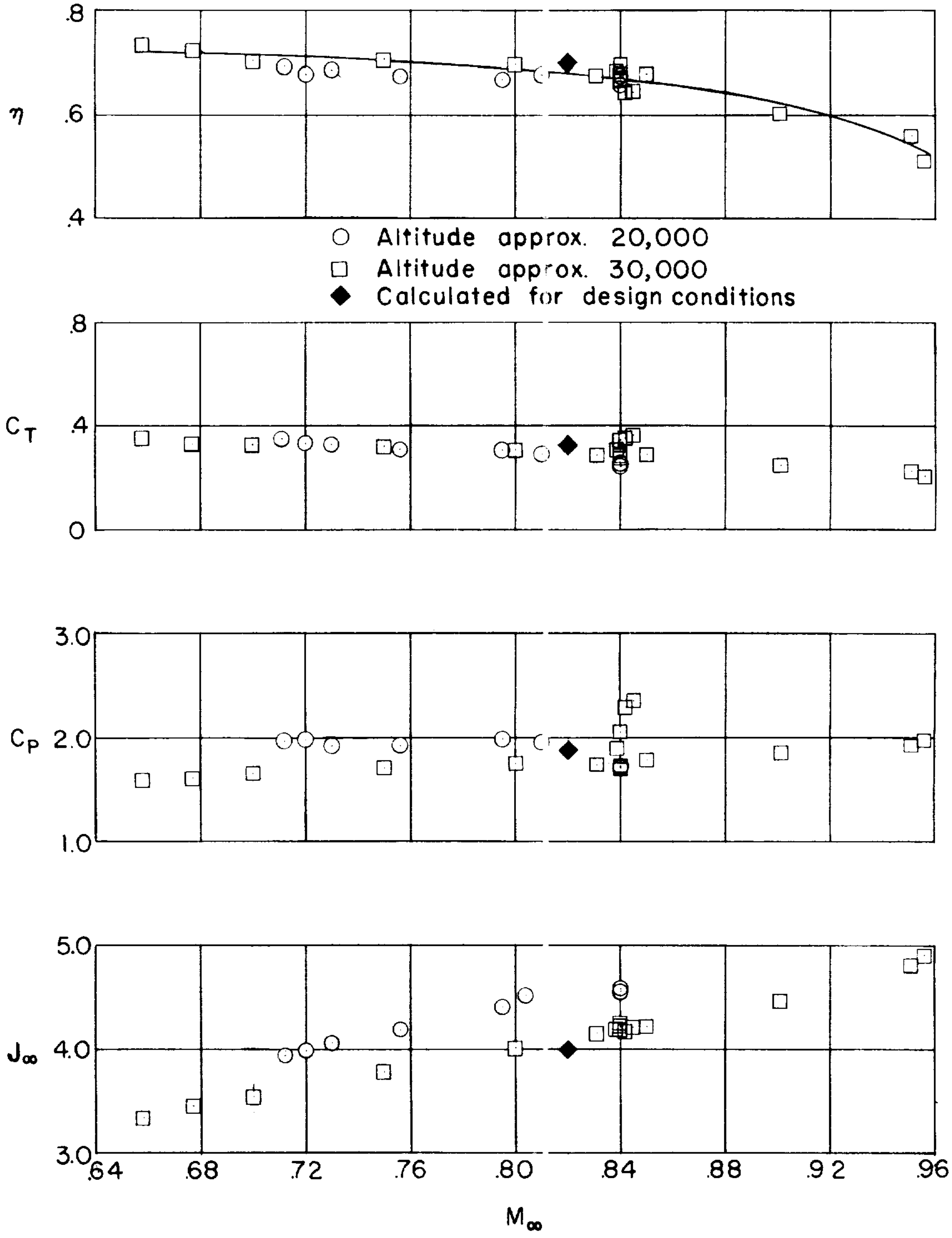


Figure 4.- Performance characteristics of the transonic propeller for flight Mach numbers up to 0.956.

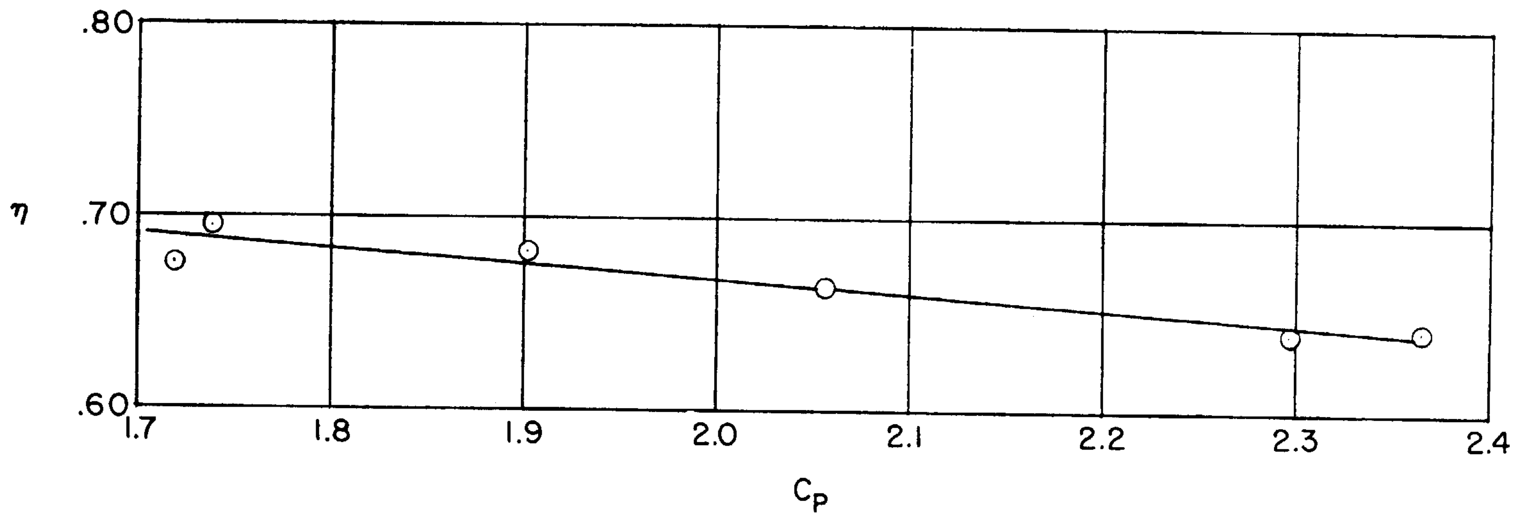
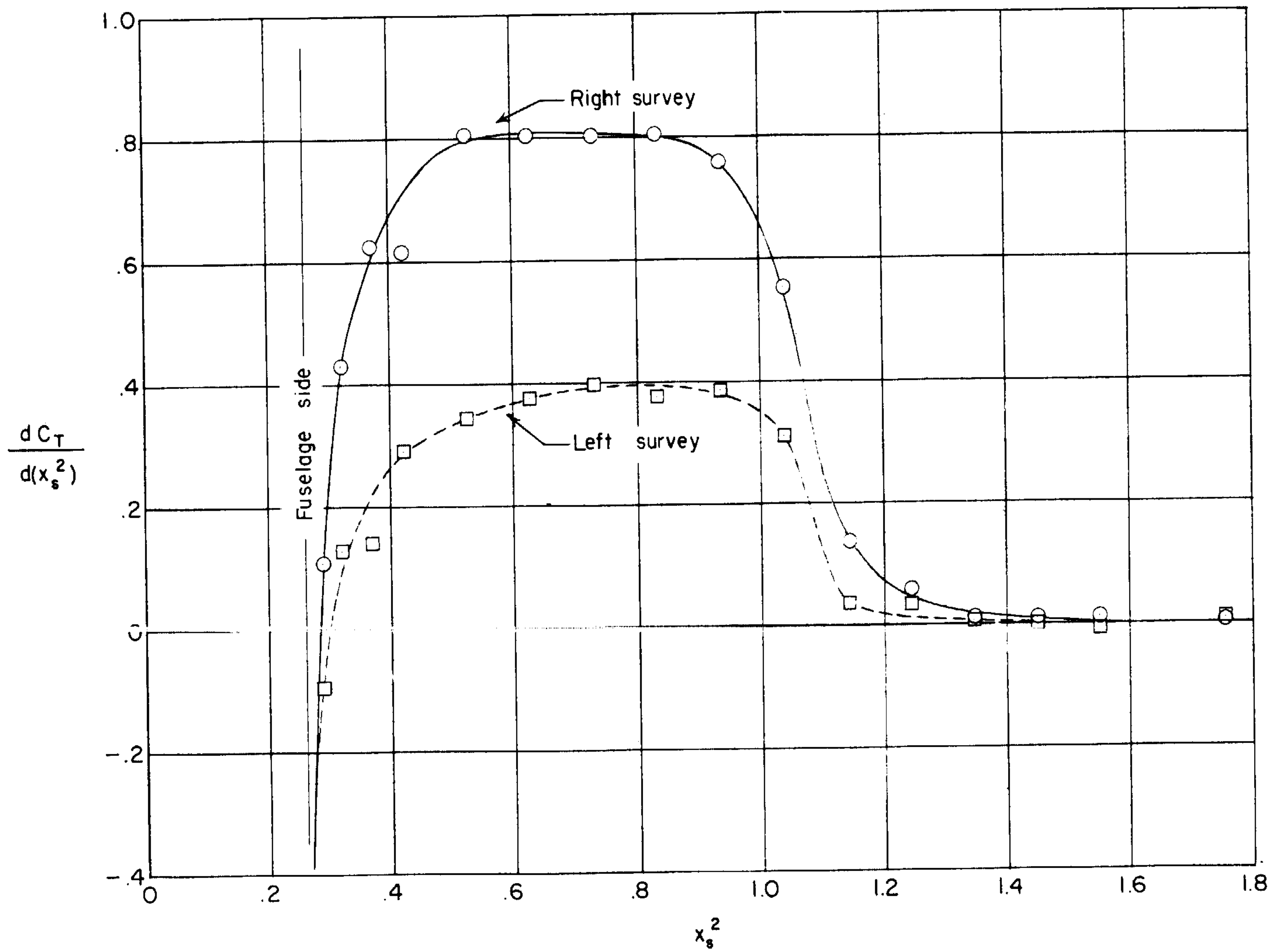
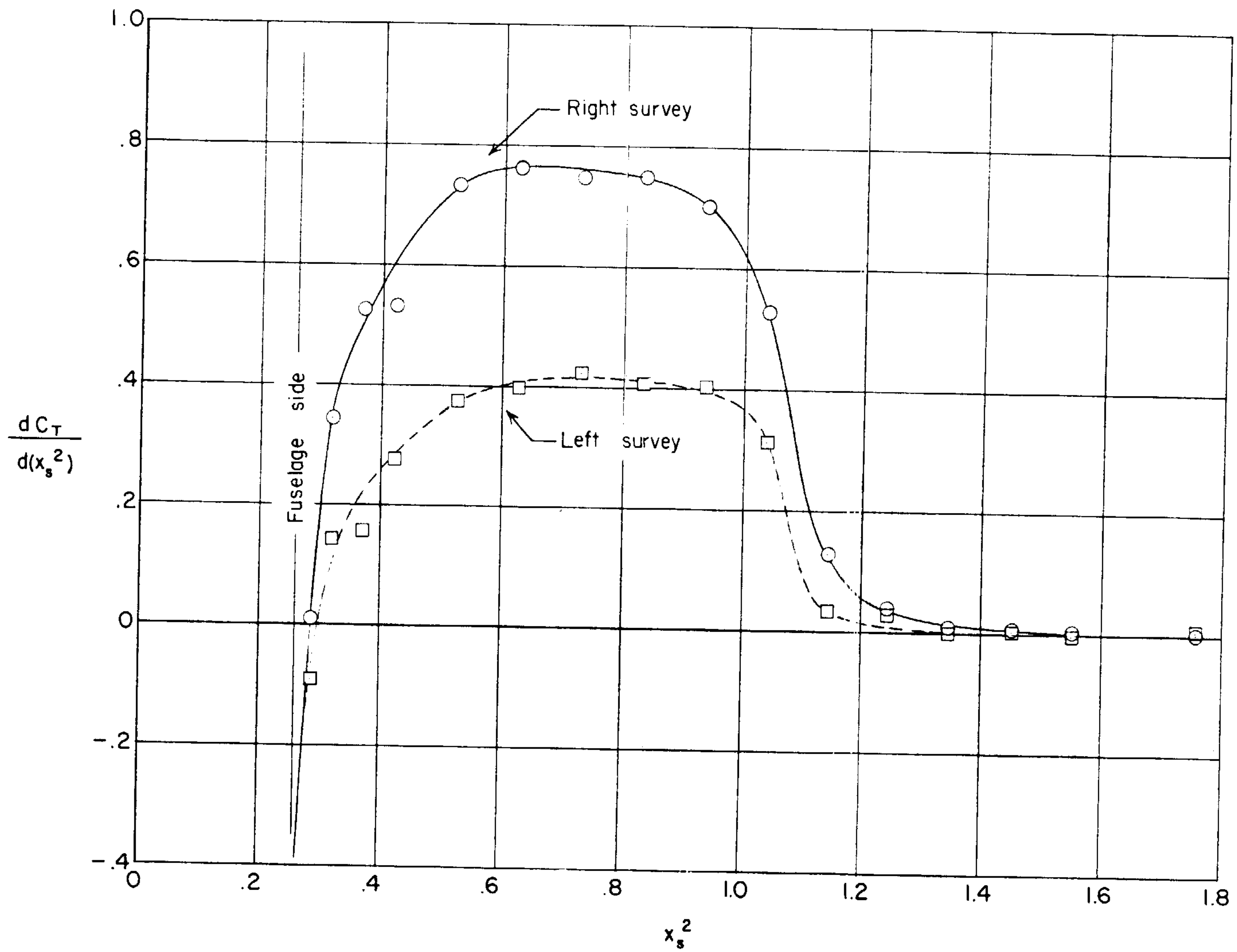


Figure 5.- Variation of propeller efficiency with power coefficient at a Mach number of approximately 0.84.



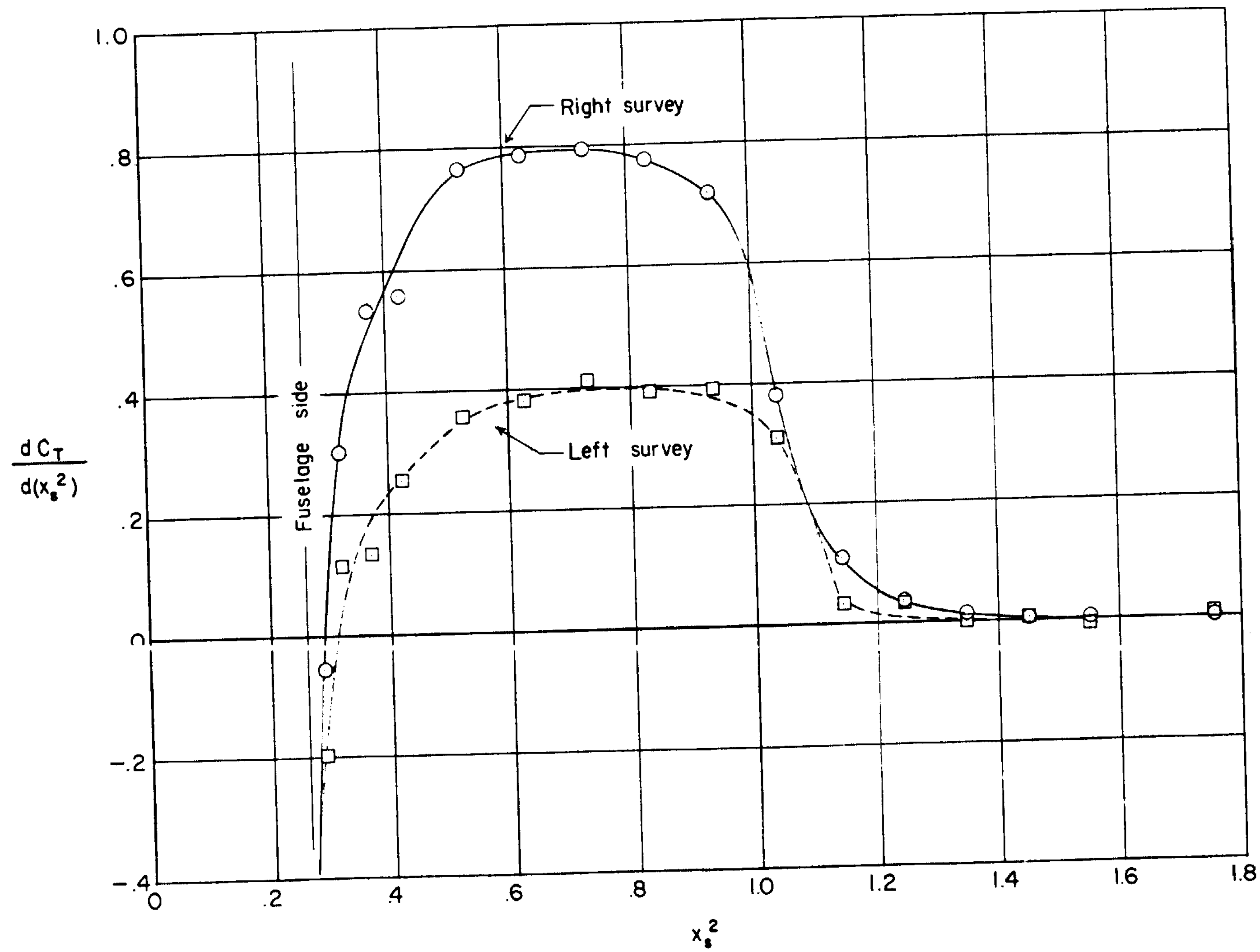
(a) $M_\infty = 0.658$; $J_\infty = 3.343$; $C_P = 1.597$; $M_t = 0.903$.

Figure 6.- Thrust distributions determined from survey rake.



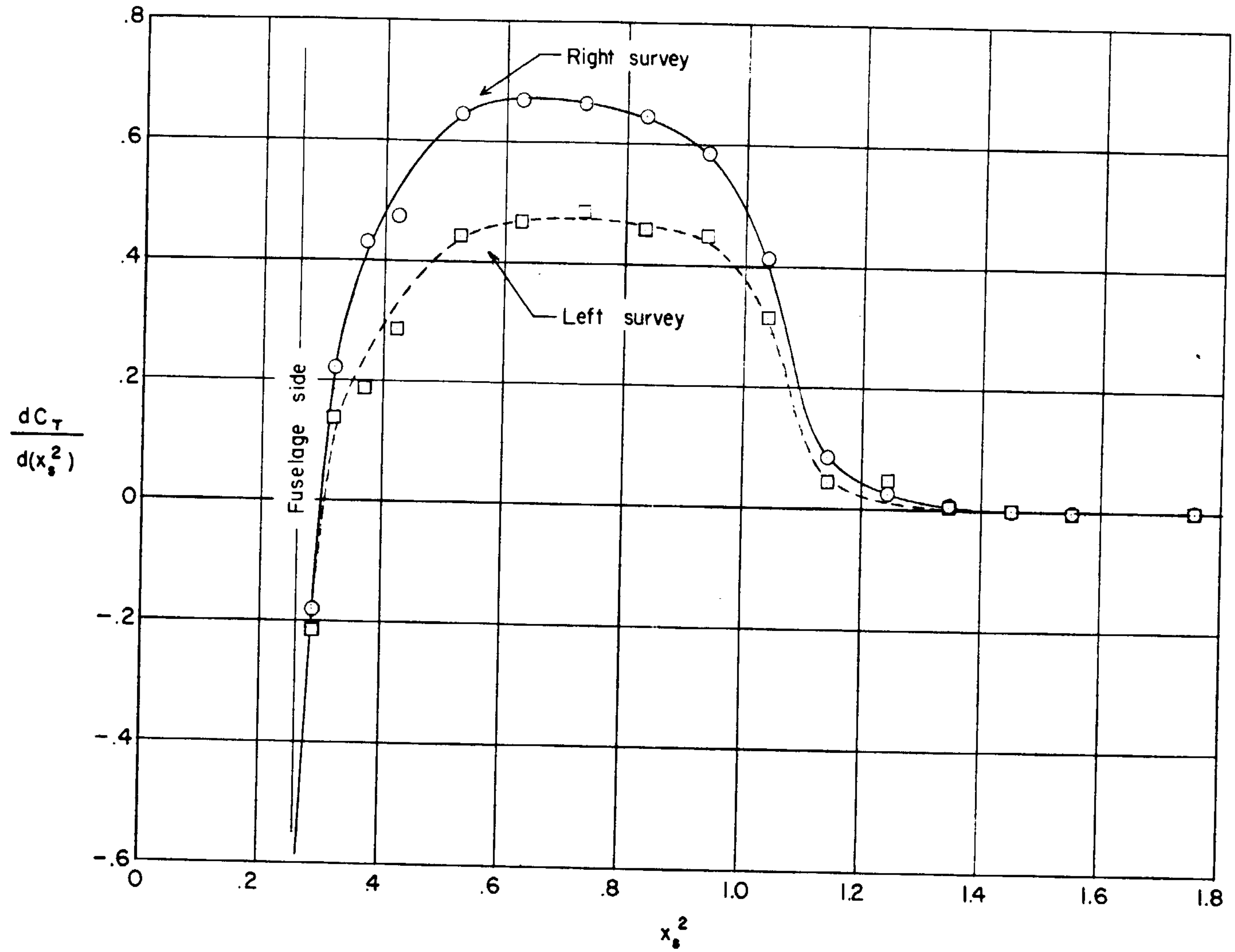
(b) $M_\infty = 0.700$; $J_\infty = 3.546$; $C_P = 1.658$; $M_t = 0.935$.

Figure 6.- Continued.



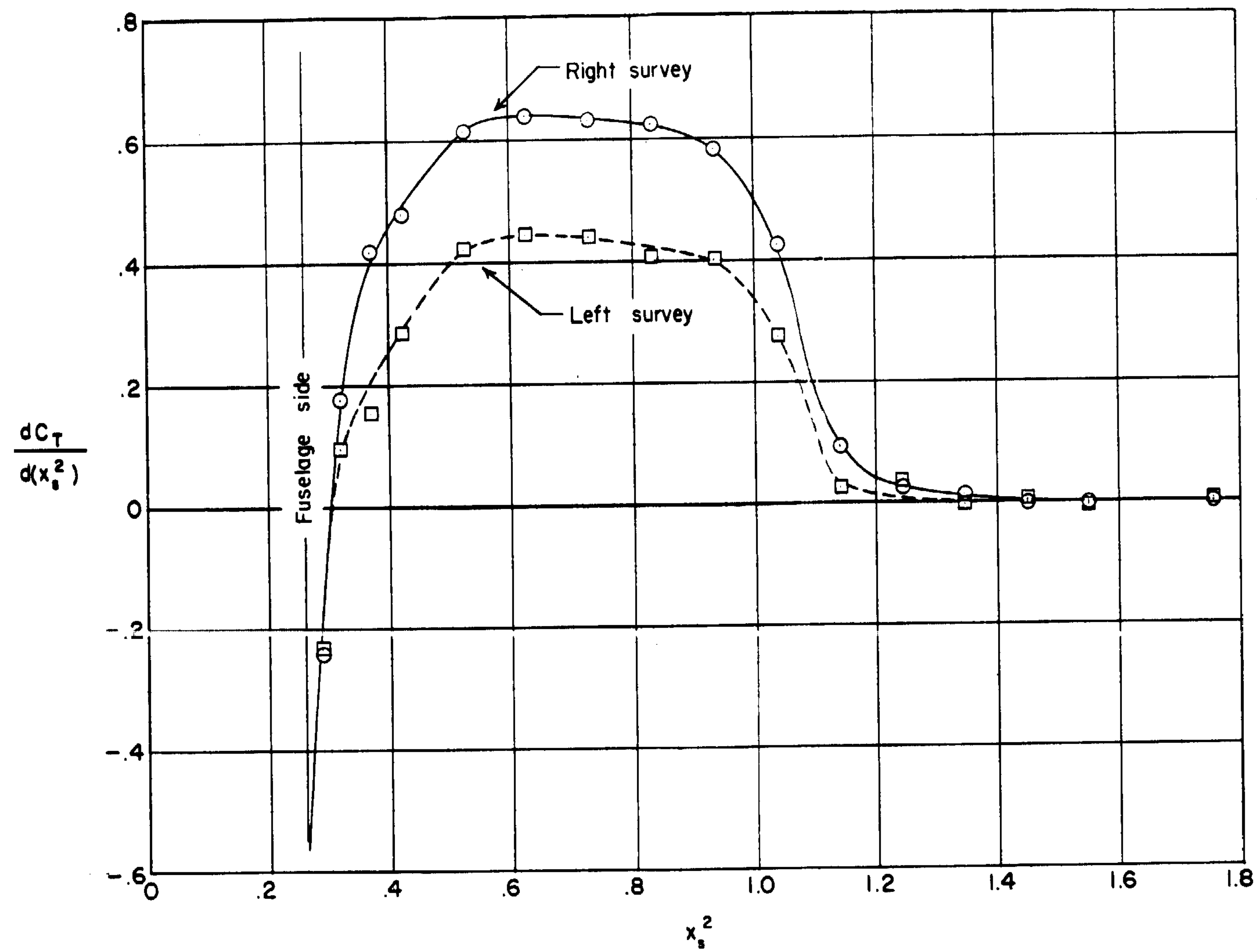
(c) $M_\infty = 0.750$; $J_\infty = 3.787$; $C_P = 1.719$; $M_t = 0.974$.

Figure 6.- Continued.



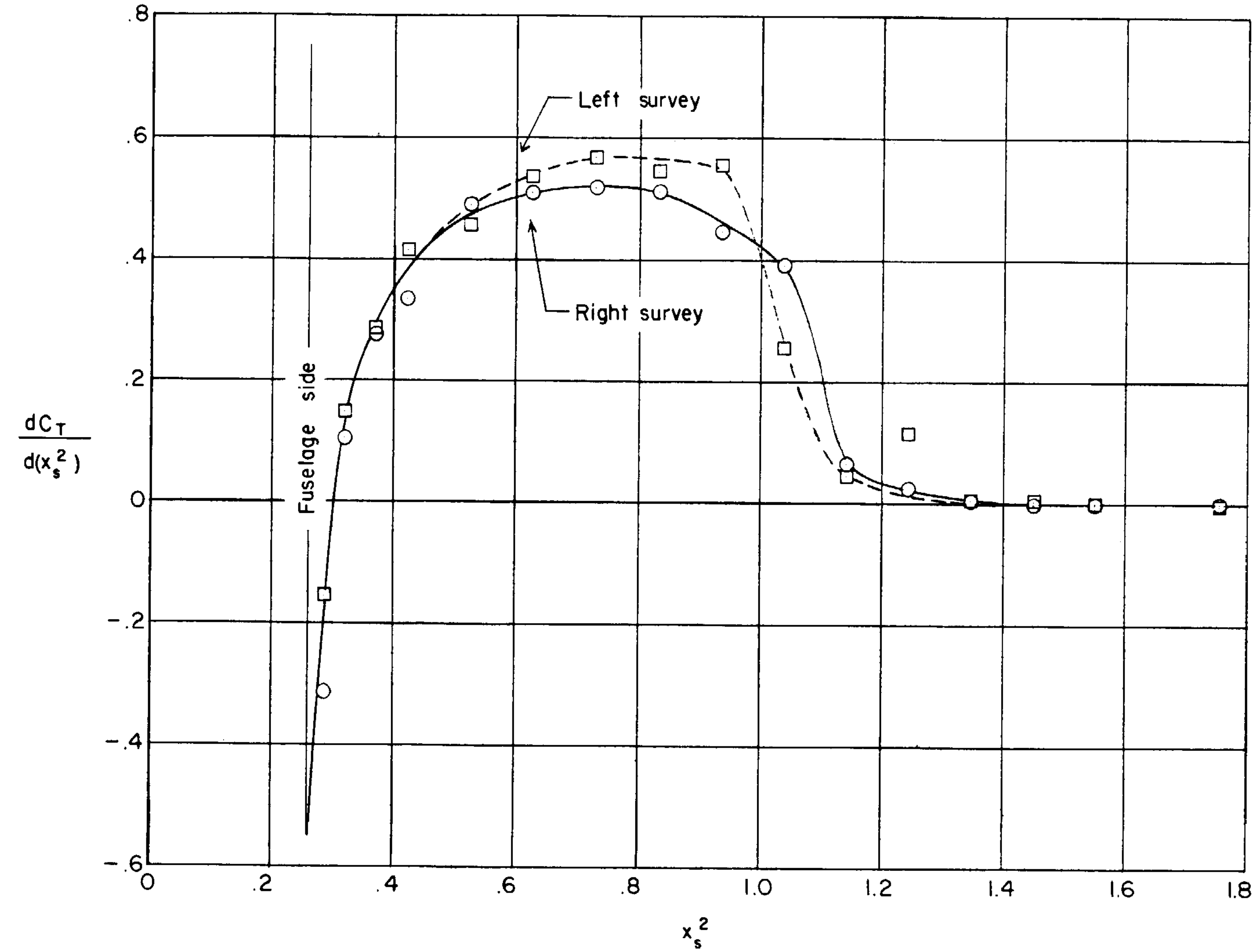
(d) $M_\infty = 0.800$; $J_\infty = 4.013$; $C_P = 1.752$; $M_t = 1.016$.

Figure 6.- Continued.



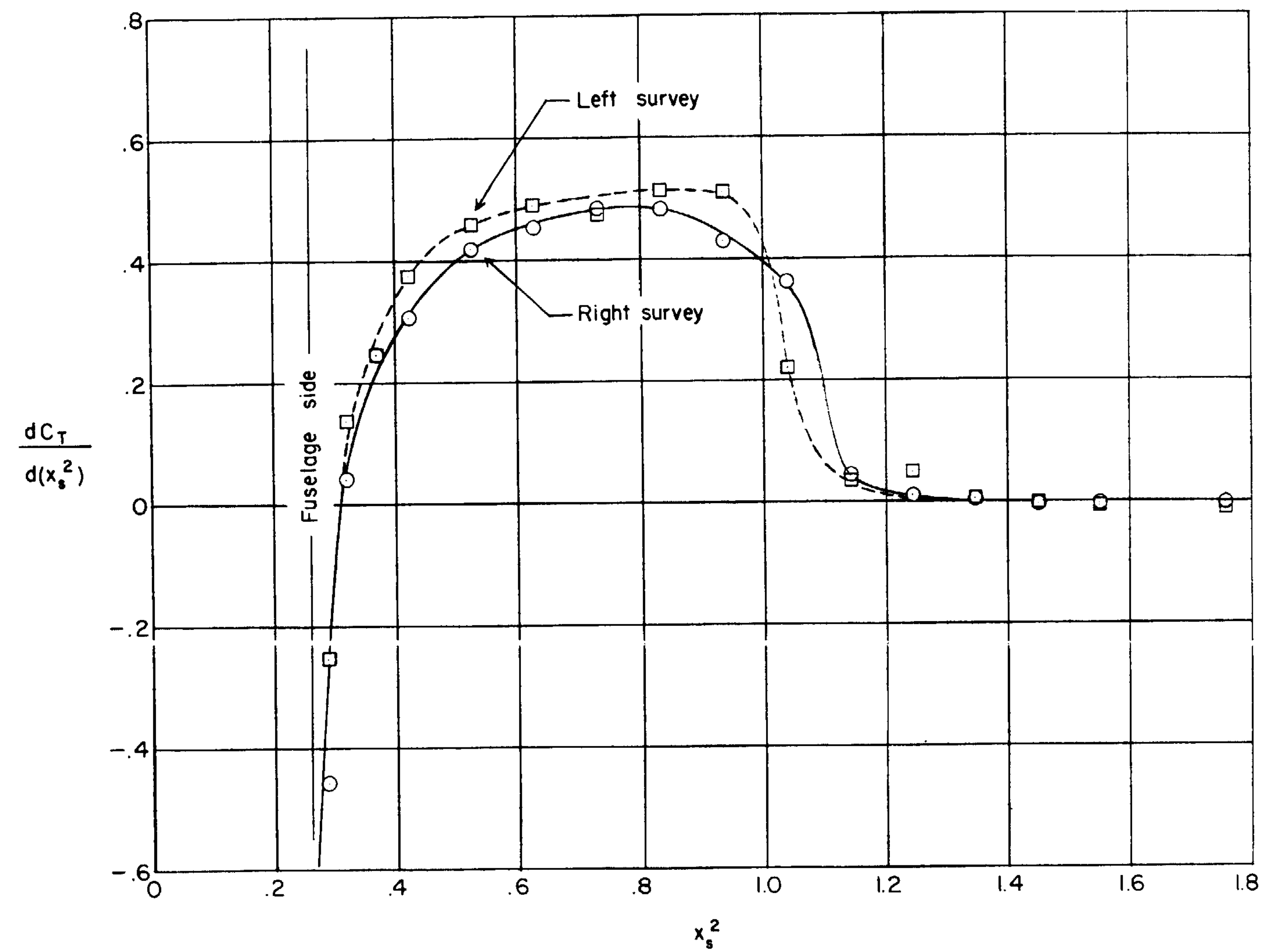
(e) $M_\infty = 0.831$; $J_\infty = 4.156$; $C_P = 1.747$; $M_t = 1.0416$.

Figure 6.- Continued.



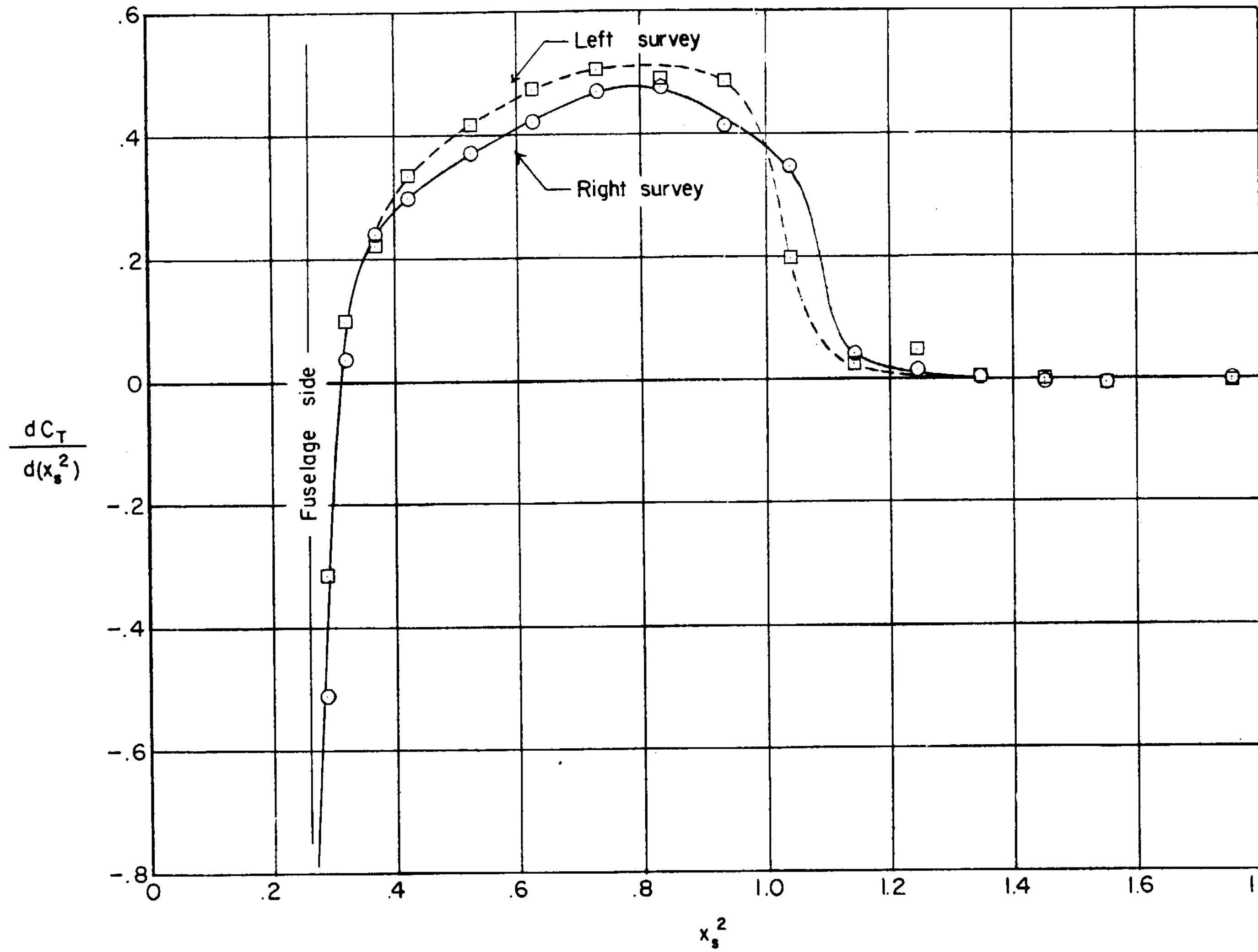
(f) $M_\infty = 0.850$; $J_\infty = 4.219$; $C_P = 1.790$; $M_t = 1.056$.

Figure 6.- Continued.



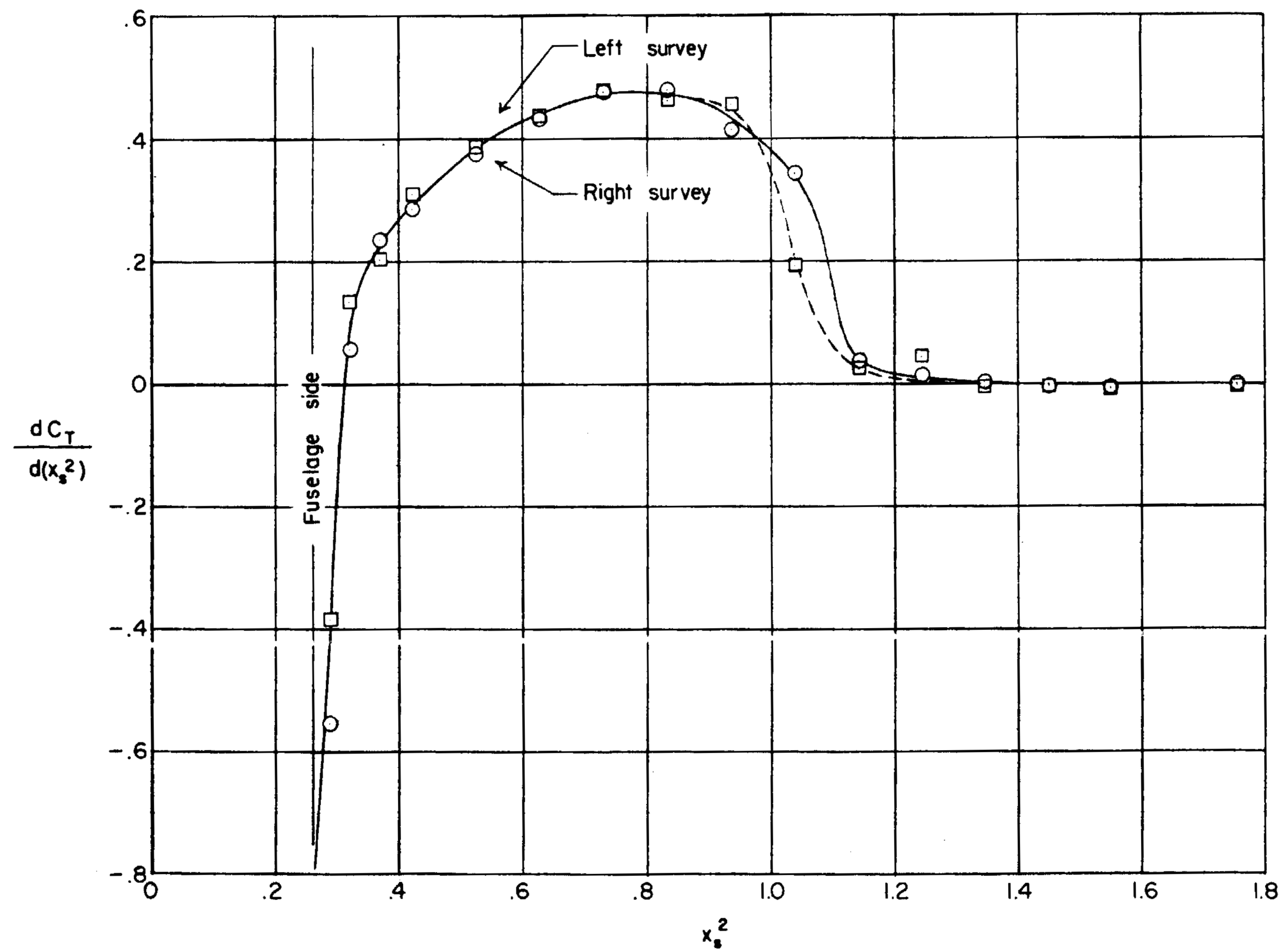
(g) $M_\infty = 0.901$; $J_\infty = 4.483$; $C_P = 1.852$; $M_t = 1.100$.

Figure 6.- Continued.



(h) $M_\infty = 0.951$; $J_\infty = 4.812$; $C_P = 1.935$; $M_t = 1.136$.

Figure 6.- Continued.



(i) $M_\infty = 0.956$; $J_\infty = 4.909$; $C_P = 1.972$; $M_t = 1.135$.

Figure 6.- Concluded.