Noise and Performance of Propellers for Light Aircraft

G. P. Succi
Project Manager

GT&PDL Report No. 154 July 1980

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Noise and Performance of Propellers for Light Aircraft

Final Report

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3 "Computed and Experimental Frequency Spectra for a Wing Mounted Microphone on a Light STOL Aircraft," G.P.Succi

4 "Sweepback as a Strategy for Noise Reduction," D.H.Munro

5 "A General Formulation of the Minimum Induced Loss Problem," D.H.Munro

6 "Practical Design of Minimum Induced Loss Propellers," E.E.Larrabee

7 "Design of Quiet Efficient Propellers," G.P.Succi

8 "Experimental Verification of Propeller Noise Prediction," Succi et al

9 "A Review of Propeller Discrete Noise Prediction Technology with Emphasis on Two Current Methods for Time Domain Calculation," Farrassat and Succi

10 "On Acoustic Intensity Measurements in the Presence of Mean Flow," Munro and Ingard

11 "Performances of Light Aircraft Propellers," P.B.Dunbeck

12 "Wakes and Performance of Light Aircraft Propellers," J.A.Zimmer

13 Selected Chapters from "The Production of Sound by Moving Objects," D.H.Munro

1.0 Introduction and Summary

The project "Noise and Performance of Propellers for Light Aircraft," Contract #NAS1-15154 between NASA Langley and MIT, has now been completed, and the main results obtained are summarized in this report and its appendices.

The primary practical objective of the study was to explore the possibility of reducing the noise from a general aviation type propeller without altering significantly its aerodynamic performance or the engine characteristics. After an extensive study of this question, involving aerodynamic and acoustic theory, design, construction and wind tunnel testing of model propellers, design and manufacturing of full scale propellers and, finally, flight tests, we are pleased to report that for one of the propellers tested an overall reduction of 4.8 dBA as measured in a flight test was achieved.

The theory deals with aerodynamics and acoustics of lightly loaded propellers with subsonic tip speeds and includes studies of the effects of sweeping the blades, altering the radial load distribution, and changing the number of blades. These studies lead to new insight into the general problem of sound generation from moving bodies. Of particular value are the algorithms, which are well suited for computer coding.

The wind tunnel tests involved three propellers, 1/4 scale, including a replica of a fixed pitch propeller used on a 150 HP single engine airplane. The other two propellers were designed to have the peak radial load distribution shifted inboard. The acoustic wind tunnel which was used in these tests enabled measurement not only of the radiated sound field but also the thrust and torque of the propeller. In addition, the load distribution was determined indirectly from wake surveys.

Sound pressure signatures were obtained at different locations and speeds (up to a tip Mach number of 0.75) and compared with theoretical predictions in which only the shape and motion of the propeller were needed as input parameters; no empirical adjustments were made. Agreement to within a few percent was obtained throughout except in the presence of a transonic "buzz" instability which was encountered within a narrow speed range.

On the basis of the theoretical analysis and its verification in the model tests, a two-bladed fixed pitch propeller was designed for a 150 HP single engine airplane. Flight tests with this propeller indicated about the same performance as the production propeller for that airplane, but the maximum sound level during a full power flyover at 1000 feet was found to be 4.8 dBA lower.

A second propeller, with three blades and fixed pitch, was designed for the Ohio State University 180 HP single engine airplane. Flight tests of this propeller have not yet been made at this time.

2.0 Report Organization

During the course of this project, in addition to the regular progress reports, a number of theses were written and several papers published with detailed accounts of the various aspects of the work. These documents are submitted in the form of appendices and the reader is referred to them for details. The documents are listed below and reviews of their content are presented under the headings Theory, Wind Tunnel Tests, and Flight Tests in sections 3, 4, and 5. Copies of these documents are available on request, for a charge to cover the cost of reproduction and mailing.

2.1 Selected Interim Reports

"Noise and Performance of the MIT and Production Propellers for a 150 HP Single Engine Aircraft,: G.P.Succi -- Appendix 1 (11 pages)

"Computed and Experimental Pressure Signatures from Two 1/4 Scale General Aviation Propellers," G.P.Succi -- Appendix 2 (69 pages)

"Computed and Experimental Frequency Spectra for a Wing Mounted Microphone on a Light STOL Aircraft," G.P.Succi -- Appendix 3 (119 pages)

"Sweepback as a Strategy for Noise Reduction" D.H.Munro -- Appendix 4 (65 pages)

"A General Formulation of the Minimum Induced Loss Problem," D.H.Munro -- Appendix 5 (7 pages)

2.2 Papers

"Practical Design of Minimum Induced Loss Propellers," E.E.Larrabee -- Appendix 6 (reprint)

"Design of Quiet Efficient Propellers," G.P.Succi -- Appendix 7 (reprint)

"Experimental Verification of Propeller Noise Prediction," Succi, Munro and Zimmer -- Appendix 8 (reprint)

"A Review of Propeller Discrete Frequency Noise Prediction Technology with Emphasis on Two Current Methods for Time Domain Calculation," Farassat and Succi -- Appendix 9 (46 pages)

"On Acoustic Intensity Measurements in the Presence of Mean Flow," Munro and Ingard -- Appendix 10 (6 pages)

2.3 Theses

"Performance of Light Aircraft Propellers," P.B.Dunbeck -- Appendix 11 (68 pages)

"Wakes and Performance of Light Aircraft Propellers," J.A.Zimmer -- Appendix 12 (344 pages)

Chapters from "The Production of Sound by Moving Objects," D.H.Munro -- Appendix 13 (263 pages)

3.0 Theory

The theoretical analysis included both the aerodynamics and acoustics of the propeller. In our formulation the aerodynamic calculation is an essential part of the noise prediction scheme since it yields the load distribution on the blades from a given propeller shape and motion.

3.1 Aerodynamic Theory -- The aerodynamic theory addresses two questions. First, given a set of operating parameters, what is the most efficient propeller shape? Second, given the propeller shape and motion, what is its load distribution?

Larrabee[1] explores the aerodynamic problem using a lifting line theory with induced velocities supplied by a helically convoluted trailing vortex sheet. The essentials of this theory, with regard to the design of optimum propellers, were published in 1919 by Betz and Prandtl.[2] A more accurate description of the circulation distribution for lightly loaded propellers of minimum induced loss, which accounts for vortex sheet curvature, was given by Goldstein.[3] We used the Betz-Prandtl approximation which is adequate for low advance ratios. The design of a minimum induced loss propeller is analogous to determining the planform and twist distribution of a wing which will develop an elliptical span loading.

In addition to the optimum design it is also necessary to determine the performance of arbitrary propellers. Larrabee[1] deals with arbitrary propellers by means of a radially graded momentum theory, which, however, requires an iterative calculation to yield the radial load distribution. Munro[4] was able to restructure the calculation so that a closed form analytic expression is obtained.

3.2 Acoustic Theory -- Given the shape and motion of the propeller, it is possible to calculate the sound it produces by subdividing it into many small elements, represented by acoustic sources (Succi[5]). Each source contains force load and volume associated with each element. Each source spirals forward along a helical path. The effect of each is calculated independently and the various contributions are then summed to find the sound radiated by the entire propeller. The power of this technique lies in the fact that there is an exact analytic expression for the sound emitted from each point. This greatly simplifies the computation. The derivation of this technique from the Ffowcs Williams Hawkings equations is discussed in Ref 5 and a comparison with Farassat's method is given in Ref. 8. A good description of the relation of this technique to other computation methods may be found in a review by Farassat.[7]

Munro[4] approached the problem by generalizing the Kirchoff formula for the solution of the wave equation in terms of its boundary values. The generalization, which is originally due to Morgan,[9] allows for the motion of the boundary surface. Munro ultimately reduced the formulas to an array of point sources like those above and made several interesting observations. The "thickness" term was identified as a couplet of mass sources with a time-like separation rather than a spatial separation, and he noted that the induced drag forces must be treated differently from the profile drag source. These two types of source, however, are identical in the limit as M^2 is negligible. Additional terms due to the radial contraction of the shed vortex sheet and the rollup of the shed vortex sheet were derived but not implemented on the computer. These terms cannot be treated until improvements in the aerodynamic theory are made so as to accurately predict the time-dependent structure of the wake. For lightly loaded subsonic tip speed propellers the distinction between Munro's and Succi's source models is negligible.

3.3 Numerical Parametric Studies -- A series of noise reduction schemes was explored with particular application to a 150 HP aircraft, with the objective of minimizing the peak dBA levels recorded by a ground observer as the aircraft flies along a level path at an altitude of 304.8 meters, in accordance with FAA advisory circular #36-1A[10] which states "Overflight must be performed at rated maximum continuous power, stabilized speed...and with the aircraft in cruise condition." In the numerical studies only the propeller parameters were varied; we did not explore noise reductions that are possible by changing engines or introducing a gear box.

The bulk of the studies are presented in Ref. 5 in which both the aerodynamic penalties and acoustic gains are discussed. For example, we found that if the propeller radius was reduced by 20%, the sound level decreased 4 dB or 8 dBA, and the efficiency dropped by $4^1/2$%.

In studies of the role of radial load distribution, the idea is to start with an aerodynamically optimum load pattern and then perturb it. Since the original distribution is an aerodynamic extremum, the load perturbation causes only second order changes in the efficiency. However, such load changes will alter the acoustic field to first order since the aerodynamic optimum differs from the acoustic optimum. A family of load curves was explored and it was found that moving the load inboard 20% decreased the sound level by 1.4 dB, 4.2 dBA, but reduced the efficiency by only 1%.

The role of the number of blades was also explored as well as the blade sweep. In regard to sweep our simple aerodynamic model could not accurately predict the efficiency changes. However, we did estimate the sound level changes and two families of swept blades were explored. In the first the rate of sweep per unit radius was fixed and the maximum sweep angle was increased. In this scheme it was possible to reduce the noise without limit, as, in the limiting case, the propeller occupied the entire disk plane and became a noiseless actuator disk. This strategy, of course, is impractical. A second family of swept curves was explored. Here the maximum sweep angle was fixed and the rate of sweep was altered. In this instance there was an acoustically optimum distribution.

Munro[11] performed a detailed study of the aerodynamic, structural and acoustic problems associated with swept blades. The program resulted in a design procedure which was the basis for the design of a series of three swept propeller blades for a Cessna 172. The blades cannot be fabricated from aluminum, but they are well within the range of carbon-epoxy construction technique. The quietest of these blades is swept forward 5° from the hub to the 50% radius, then swept back 45° from the 50% radius to the tip. It offers a noise reduction of approximately 1.3 dB and 3.4 dBA over a similar straight blade. Acoustics play a minor role in the actual design process. This is due to the constraints dictated by the extremely large centrifugal forces.

3.4 Sample Calculation -- Before carrying out the wind tunnel tests, we tested our computational scheme in a comparison with data given by Magliozzi[12] in his report on the influence of forward flight on propeller noise. It involved a light twin engine STOL transport aircraft with three bladed propellers which was operated under a variety of flight conditions for a range of propeller tip speeds and powers. A boom was installed on the wing tip and used to support two microphones, one in the disk plane and one slightly aft. In flight, the tone noise was found to be thickness and steady loading noise.

In comparing these results with our computational procedure, rather than to calculate the exact load distribution we made the approximation that, for each flight condition, the propeller loading minimized the induced losses for that RPM, power, blade number, radius and forward velocity. We also made an estimate of the unsteady loading due to flow blockage by the engine nacelle. Calculations were carried out for all flight tests where only one propeller is powered. The Fourier amplitude spectra, which we derived from the pressure time signature, were compared with the observed spectra and good agreement was found, even out to the twentieth harmonic (Ref 5). The one instance of poor agreement occurred for flight tests at altitudes described as "low." We assume that the reason for the disagreement is non-uniform inflow to the propeller. Sample calculations from Ref 5 are provided in figures 1 and 2.

Besides providing the experimental comparison, we took great care to document the input used for each test case (see "Computed and Experimental Spectra for a Wing Mounted Microphone in a Light STOL Aircraft"[13]). Hopefully, this tabulation will be of some use to those who would write their own computer programs and are searching for detailed comparisons with an existing program.

4.0 Wind Tunnel Tests

The purpose of the wind tunnel tests was to provide a detailed test of our computations. Three propellers were constructed and were operated in front of three nacelles. A variety of operating conditions were explored and the data obtained have been digitized and stored on magnetic tape. The best summary of our results is contained in "Experimental Verification of Propeller Noise Prediction,"[14] and the description of the test facility and instrumentation can be found in the theses by Munro,[4] Zimmer,[15] and Dunbeck.[16]

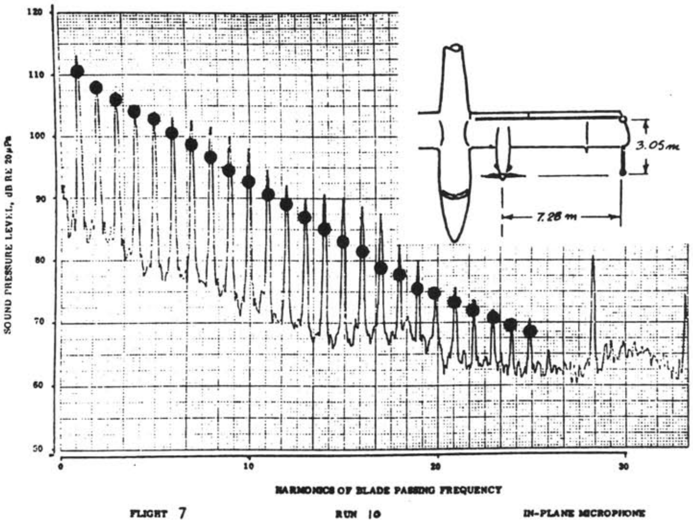


Fig. 1--Experimental and computed aft microphone spectra. rpm 2145, power 262 KW, velocity 50 m/s.

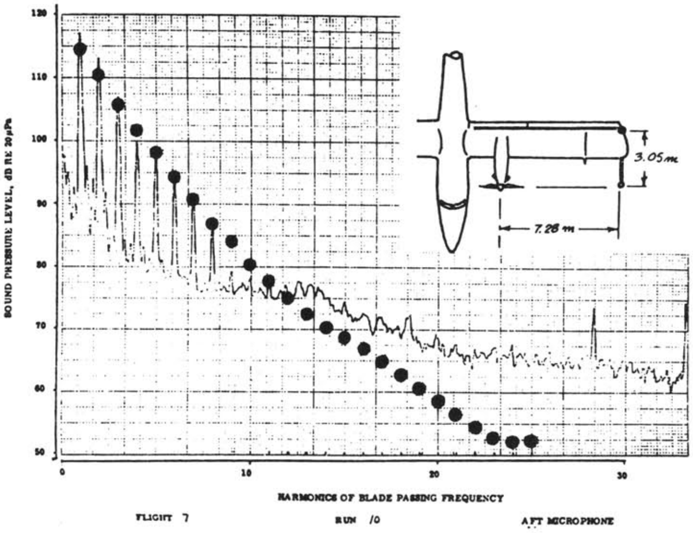


Fig. 2--Experimental and computed fore microphone spectra. rpm 2145, power 262 KW, velocity 50 m/s.

The tests were made in the anechoic wind tunnel at MIT as indicated in figure 3. The major piece of equipment constructed for the experiment was the thrust stand, the support apparatus for the motor used to drive the propellers. This stand was instrumented to measure thrust, torque, rotation rate and propeller position. The propeller blades were attached to the hub so as to allow the blades to be rotated to different pitch settings.

The radial load distribution was explored with a probe moved radially through the slipstream by a motorized traverse. The sound field was explored with a microphone mounted in the airstream so as to avoid scattering and refraction effects in the tunnel jet shear layer. The rack position was set by a small motor so as to allow continuous angular surveys of the propeller without entering the tunnel.

All signals were digitized using an Explorer III oscilloscope. Temporary storage was done on the oscilloscope floppy disk; the data were ultimately transferred to magnetic tape on a VAX and IBM 370. In our tests it was important to keep the tip Mach number similar to full scale and since the propeller was 1/4 scale, its rpm had to be 4 times the full scale value. Similarly, to cover adequately a 20 KHz full scale frequency range, we had to make measurements up to 80 KHz and sample at 160 KHz. A 1/8" B&K microphone signal digitized with an Explorer III oscilloscope was sufficient to meet these requirements.

4.1 Aerodynamic Measurements -- The aerodynamic measurements were made to test the validity of our version of lifting line theory for these general aviation propellers. We were particularly concerned with verifying the predicted load distributions as alterations in this distribution can be used as a noise reduction strategy.

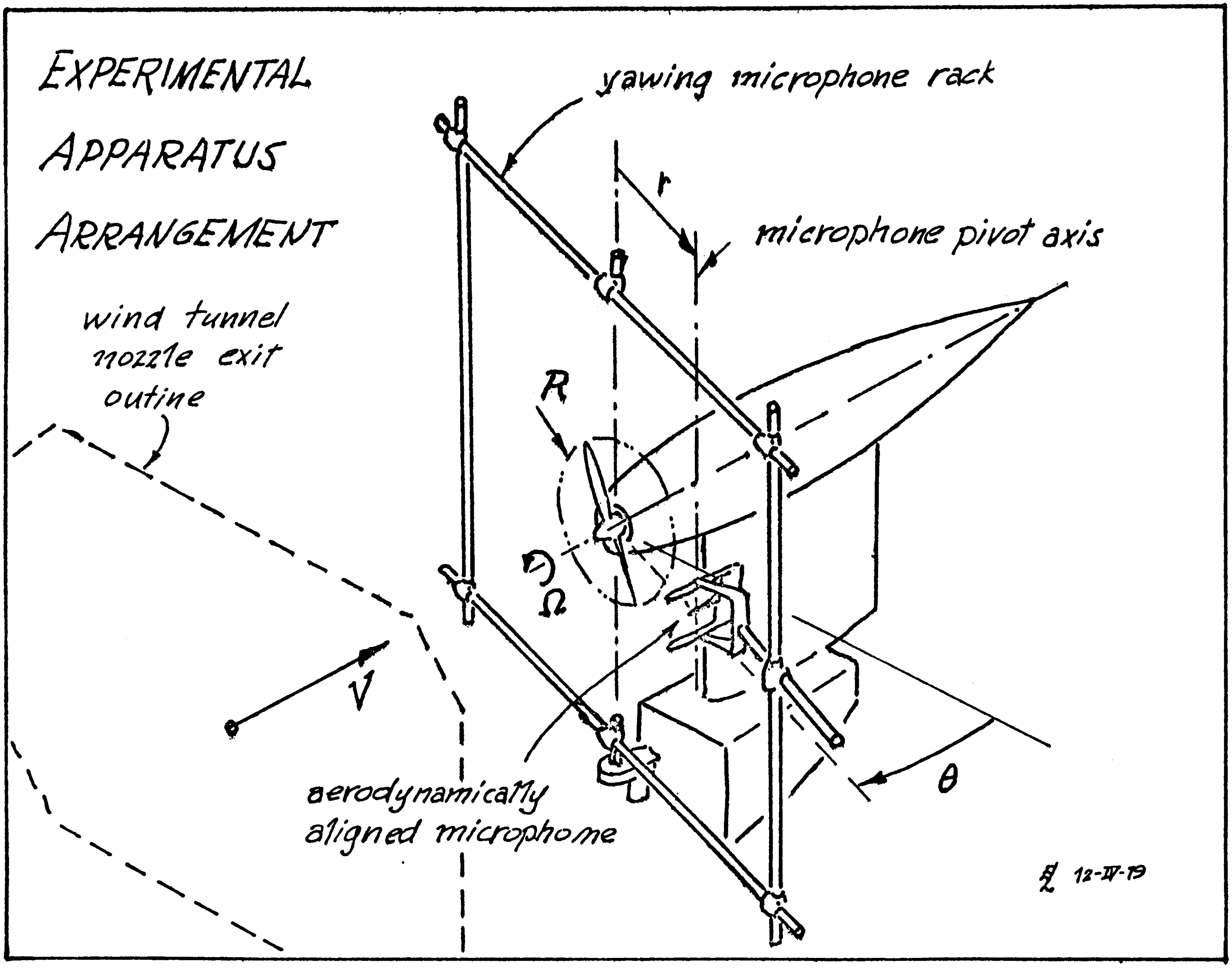

EXPERIMENTAL APPARATUS ARRANGEMENT
yawing microphone rack
r
microphone pivot axis
wind tunnel nozzle exit outine
R
Ω
V
aerodynamically aligned microphome
θ
12-IV-79

Figure 3

The first tests measured the power and thrust coefficient as a function of advance ratio ($\lambda = v/\Omega R$). Since the flow in our tunnel had a maximum speed of 30 M/S, advance ratio was increased by reducing RPM at fixed maximum tunnel velocity. When the propeller speed was reduced below 7000 RPM to go to values of λ in excess of .17, the experimental values of thrust and power absorption fell below the predictions. This was most likely due to a degradation in airfoil section characteristics with decreasing Reynolds number. This discrepancy did not affect our acoustic results as the propeller noise could be measured above the background noise only at rotation rates greater than 7000 RPM.

The radial load distribution was examined by measuring the wake behind the propeller. Two probes were used--a three hole pressure probe which gave adequate response when the radial component of velocity was small, and a hot wire velocimeter which was useful under all flow conditions.

Three bodies were used in conjunction with each propeller:

Minimum Body: the smallest fairing that could fit around the motor

Symmetric Body: a large axially symmetric body with a cross area distribution similar to a light airplane.

Asymmetric Body: a variation of the symmetric body wherein the upper portion of the body was modified to be a 2:1 axis ratio ellipse and then was transformed into a conical "windshield" region which was faired into the symmetric afterbody.

The wake measurements with the minimum body were used as a reference simulating the operation of the propeller in a uniform flow. In this instance the wake was distorted only by a small contraction. It was possible to relate the momentum in the wake to the radial blade loading by assuming a one to one correspondence between percentage radii of the blade and wake.

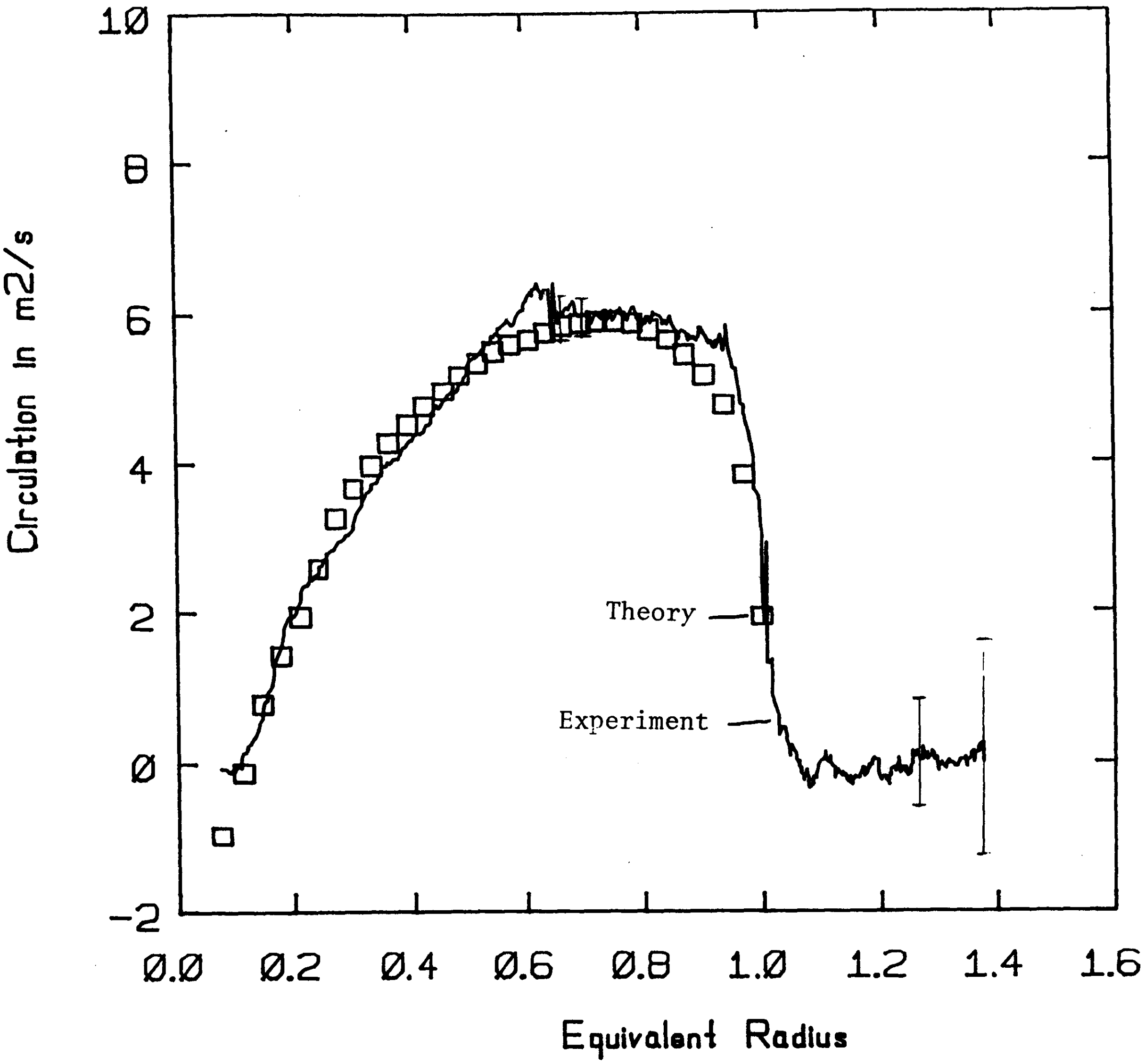
This procedure didn't work when the wake was distorted by a large body. The search for a proper interpretation of the wake measurement made with the large synmetric body resulted in a data reduction procedure wherein measurements were compared directly to theory. The procedure was to calculate the circulation from the measured swirl velocity and relate it to the appropriate propeller by mapping out the lines of equal mass flux. The distortion of the vortex sheet by the nacelle did not alter the conservation of vortex lines. All vortex lines originated in the bound vorticity on the blade. As the load distribution varied, the vortex lines were shed into the flow. For a lightly loaded propeller the shed vortex lines followed the stream surfaces, which were measured by constructing the mass flux. Zimmer[15] reduced his measurements in this manner and obtained a consistent description of propeller performance.

In figure 4, a comparison between theory and experiment is made for the production propeller operating in front of the minimum body. In figure 5 a similar comparison is presented for a propeller with an inboard load peak operating in front of a large symmetric body.

Of the three propellers studied, two were designed to have the peak loading moved inboard and the wake measurements verified this design objective. This strengthened our reliance on the aerodynamic theory as a sufficiently accurate tool in the design of low noise propellers.

4.2 Acoustic Measurements -- Angular surveys of the sound pressure were made at constant propeller rpm as well as at a constant advance ratio and in each case the various propeller-body combinations were used.

The results of these measurements for the symmetric body with production propeller and the MIT propeller designed to replace it are given in "Computed



Propeller: Cessna

Blade Angle: Nom.

Nacelle: Minimum

RPM: 10000

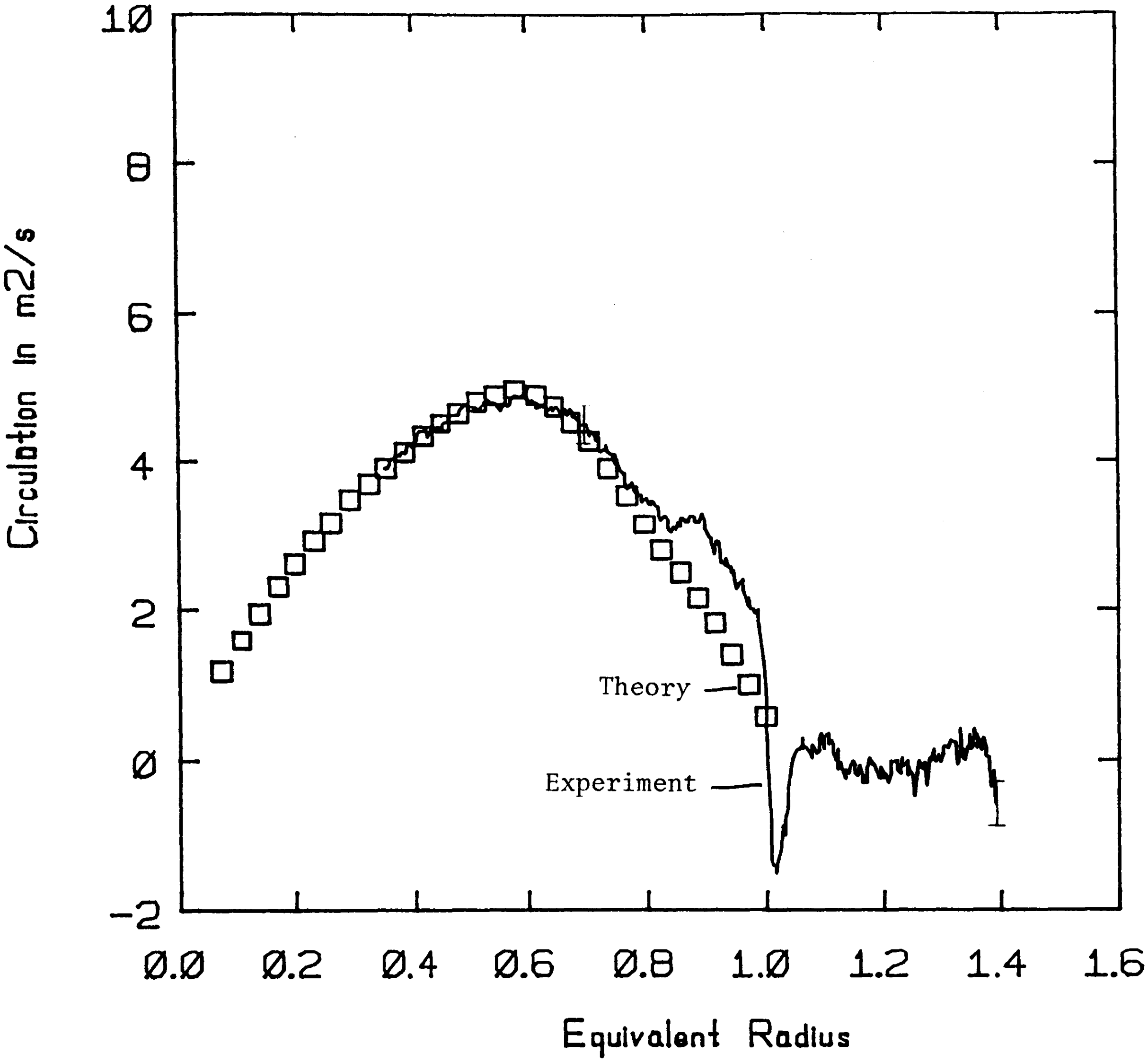
Tunnel Speed: 29.3 m/s

Axial Location: 0.41R

Probe: Hot Wire No. 2

Air Density: 1.16 kg/m^3

Figure 4--Circulation



Propeller: Windsong	Tunnel Speed: 29.3 m/s
Blade Angle: Nom.	Axial Location: 0.13R
Nacelle: Symmetric	Probe: Hot Wire No. 2
RPM: 7000	Air Density: 1.16 kg/m^3

Figure 5--Circulation

and Experimental Pressure Signatures from Two 1/4 Scale General Aviation Propellers."[17] These early results showed that the theory was quite accurate.

For a detailed comparison between experimental and theoretical curves we needed to improve the experimental pressure signatures so as to extract that part of the trace with a period equal to the blade passage period. (It was only this part that was obtained from the theory.) To do this the raw signal composed of several pressure pulses, was Fourier transformed and the average "cleaned" signal was produced by inverse transforming the first 64 harmonics of the blade passing frequency. This procedure was used by Munro[4] (Chapter 5), who also gave sample results for other propeller body combinations. In all cases the agreement between prediction and theory was good. A sample calculation for the production propeller mounted in front of the symmetric body is presented in figure 6.

An unexpected phenomena was uncovered in measurements made with production propellers over a narrow range of operating conditions. At a tip Mach number of 0.7 extremely intense coherent bursts of high frequency sound were produced from the region near the tips of the blades where the airfoil chords were roughly 2 cm. The measured (Doppler shifted) frequency within the burst was 38 KHz near the disk plane, which indicated a frequency of 13 KHz in the frame of the blade. The flow instability responsible for the sound has not been positively identified, but most likely is related to a transonic shock instability (see Munro,[4] Chapter 5).

5.0 Flight Tests

The flight tests on the low noise propeller for the Cessna 172 are documented in "Noise and Performance of the MIT and Production Propeller for a Cessna 172."[18] During a level flyover at 1000 feet the maximum sound level for the MIT propeller was found to be 4.8 dBA lower than that of the production propeller at essentially the same aerodynamic performance of the two propellers.

The MIT flight test propeller was a variation of the propeller No. 3[14] used in the wind tunnel. It was designed to match the power absorption of the production propeller, at the design flyover condition, and have the peak radial load moved inboard. However, off-design calculations indicated

TABLE 1

Runs	Standard Propeller (dBA)	MIT Propeller (dBA)	Level Difference (dBA)
		1000' Flyover	
6	77.1 ± .7	72.0 ± .4	- 5.1
6	77.9 ± .3	73.8 ± .2	- 3.5
6	77.3 ± .2	72.1 ± .8	- 5.2
36	77.4	72.6	- 4.8
		500' Flyover	
6	84.5 ± .7	78.0 ± .6	- 6.5
6	83.7 ± 1.0	80.8 ± .5	- 2.9
6	83.1 ± .7	79.5 ± .7	- 3.6
36	83.8	79.4	- 4.4

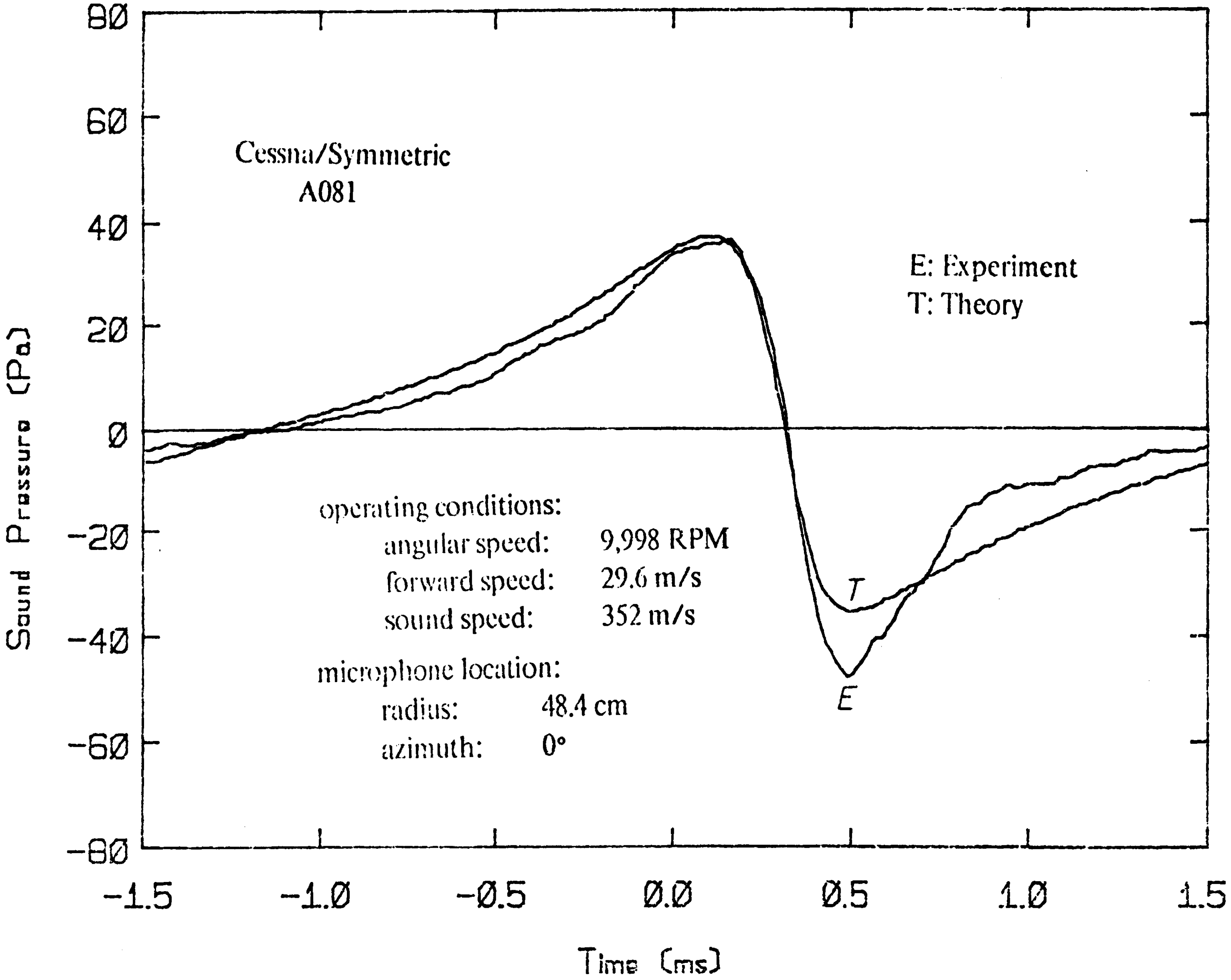


Figure 6--Cessna Blade: 10KRPM, 29 m/s, 0°

that this propeller absorbed too much power at low speeds. To mitigate this effect the radius was reduced to 92.5% of that of the production propeller. This had little change on the high speed performance, since the tips were already unloaded, but significantly improved the low speed performance. Another factor to consider was the danger of overspeeding the engine. To avoid this problem the propeller was designed conservatively so that it turned 100 RPM slower than the production propeller at full engine throttle.

Performance

Comparisons of the MIT and production propellers installed on a 150 HP Cessna 172 are indicated in figures 7 and 8. These data are for an average altitude of 2000 feet MSL, taken under similar atmospheric conditions and are not corrected to a standard day. Figure 7 indicates the power absorption is similar except at the high speed point. Figure 8 shows the rate of climb, which indicates propeller efficiency if the power input is identical, is also similar. Thus, noise was reduced with a minimal alteration of performance.

Each of the modifications contributed to the noise reduction. However, the basic strategy of moving the load inboard (when the thickness noise does not dominate) was the most important in reducing the flyover noise and it represented a rewarding demonstration of the usefulness of the aero-acoustic computational procedure which we used.

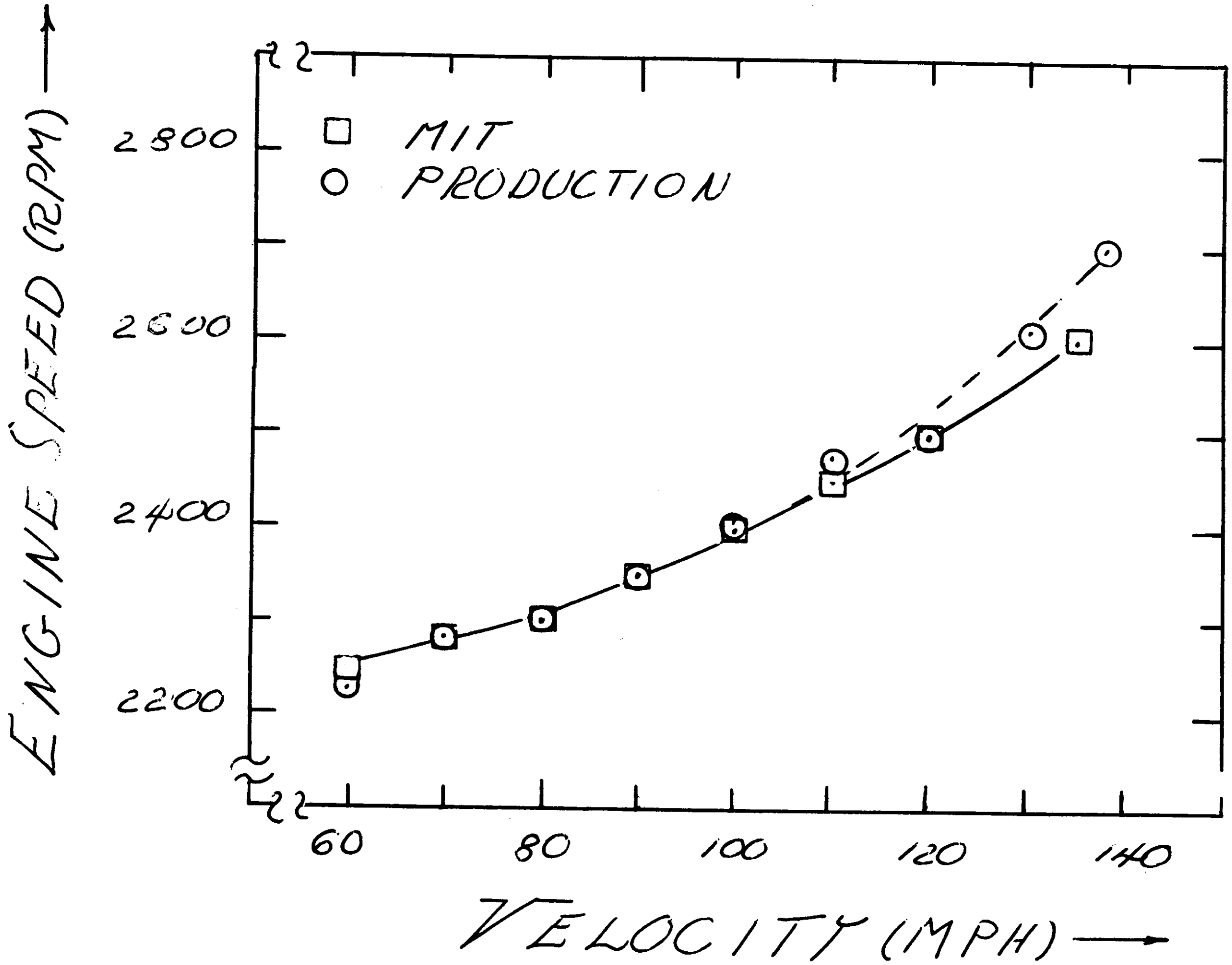

□ MIT
○ PRODUCTION
ENGINE SPEED (RPM)
2800
2600
2400
2200
60
80
100
120
140
VELOCITY (MPH)

Figure 7

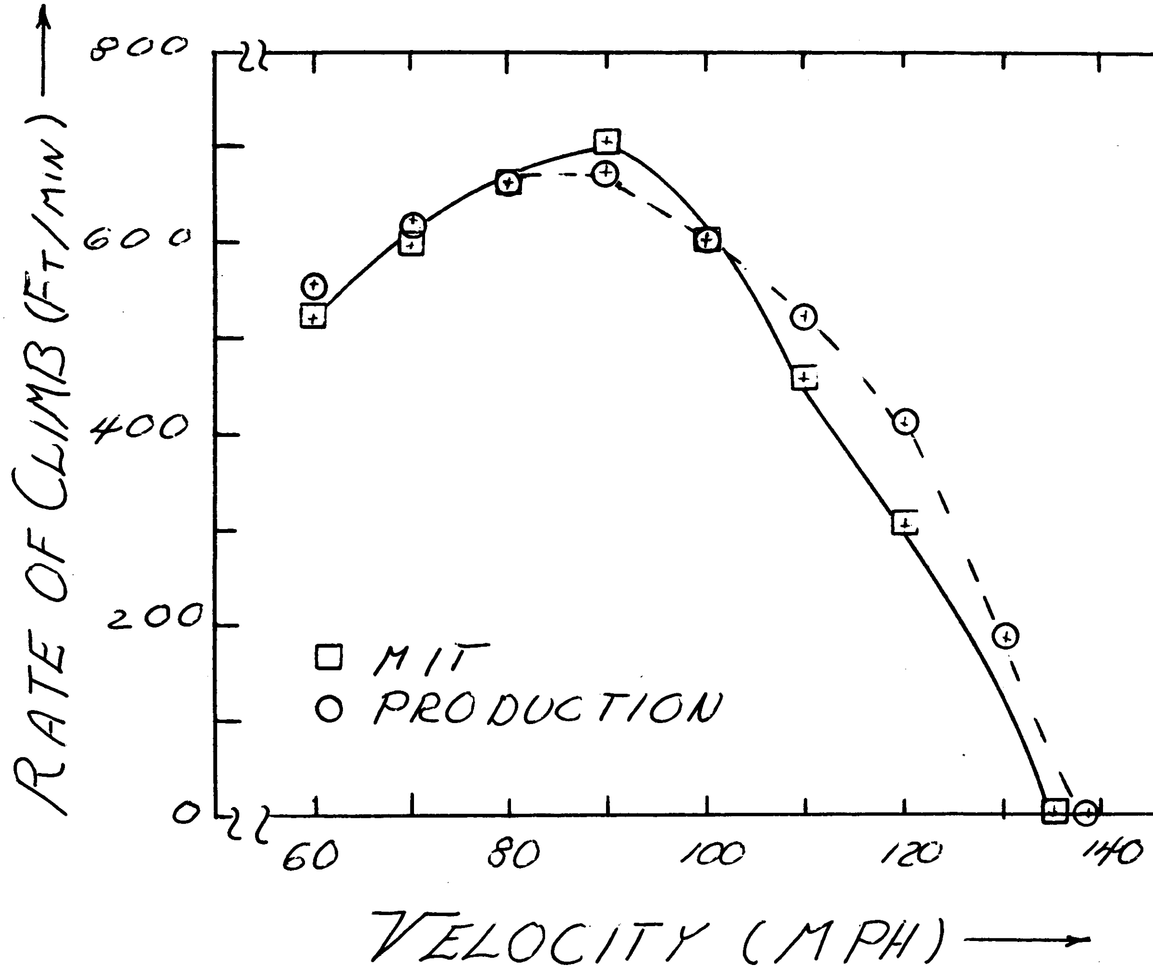

RATE OF CLIMB (FT/MIN) →
800
600
400
200
0
60
80
100
120
140
VELOCITY (MPH) →
□ MIT
○ PRODUCTION

Figure 8

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