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# **STUDIES IN A TRANSONIC ROTOR AERODYNAMICS AND NOISE FACILITY**

**S. E. Wright, D. J. Lee, and W. Crosby**

## **1. INTRODUCTION**

This report describes the philosophy, design, construction, and initial test of a rotating arm blade element support facility, designed to investigate rotor aerodynamics and noise mechanisms, from windmilling speeds through to transonic velocities.

## **2. PHILOSOPHY OF APPROACH**

The experimental technique provides a method of rigidly supporting and rotating blade elements using a "quiet" support arm in good anechoic conditions.

This approach provides a research capability between the conventional stationary element in a moving flow (wind tunnel approach) and a complete rotating blade system (rotor).

The philosophy is that blade elements contain, and therefore allow, the basic aerodynamic and rotor noise mechanisms to be studied.

The approach avoids acoustic problems associated with wind tunnel measurements (flow gradients, reflecting surfaces, tunnel noise) and allows rotational noise to be studied.

It enables the acoustic properties of blade elements to be studied in isolation, rather than try and understand the complex acoustic signature of a complete rotor.

The method provides an inexpensive way of obtaining high speed aerodynamic research, and effecting blade geometry changes simply (without constructing a new rotor).

## **3. ROTOR DESCRIPTION**

Figures 1, 6 and 7 illustrate the main features of the rotor system. The frame is constructed from 3" x 2" steel box channel, the center of which can be filled with lead shot to dampen any residual structural vibrations. Each structural member is of a different

length to avoid resonances. The drive shaft is short to reduce shaft vibrations and is supported by large sleeve bearings rather than ball or roller bearings, for quietness.

The motor is an extremely quiet AC motor, the quietest U.S. motors make for the power rating required. An AC motor was selected as it eliminated brush and commutator noise associated with D.C. motors. The speed of the motor is changed through varying the frequency of the supply. The power unit which supplies the variable frequency utilizes the latest solid state technology which has recently become available at these horsepower (30 HP).

The element support arms are rigid, tapered, airfoil sections (NACA 0024), with boundary layer trips. The taper is essential to provide rigidity towards the root, but less volume displacement towards the tip. The boundary layer trip is necessary to remove laminar boundary layer noise from the inner parts of the arm. This noise can dominate the noise from the faster moving turbulent boundary layers associated with the outer regions of the rotor.

Detachable mechanical couplings for the blade elements have a strength-to-weight ratio problem. At speeds approaching Mach one, on a 6 feet diameter rotor, the centrifugal force is approaching  $10^4$  times that of gravity. Thus for heavy elements, the centrifugal force is large. The solution in this study was to use a light weight material such as balsa wood for the elements and glue them to a protruding tongue at the end of the support arm. This method provides a large contact area over which to distribute the strain.

Only one arm supports an element; the other provides the balance. Fine balancing is achieved through inserting or withdrawing radial grub screws through the end of the "dummy" arm. This arm also provides an acoustic signature of arm alone noise to compare with the arm plus element in the high speed noise studies.

The rotor system can be operated either in a propeller configuration (vertically), or it can be turned on its side for the helicopter mode (horizontally). From a safety point of view the vertical operation is more convenient, as only a short safety wall need be built

across the plane of rotation.

The whole rotor assembly is housed in an enclosure acoustically lined with 4" thick surface treated fiber glass. This material has a surprisingly high-low frequency asorption (99% at 125 Hz). The ease with which this material is installed, and its low cost, make it an attractive material for acoustically treating large scale enclosures.

#### **4. FACILITY SPECIFICATION**

##### Acoustic Chamber:

chamber size - 24' × 24' × 12'

acoustic treatment - 4" faced fiber glass

acoustic absorption - 0.99 at 125 Hz

##### Variable Frequency Supply:

type - solid state AC-DC-AC converter

frequency range - 6Hz - 60Hz

power - 30 HP

drive motor - AC electrical

##### Rotating Arm Element Support:

operation - both helicopter and propeller mode

height - 5' × 5'

speed - 100-1000 ft/sec

##### Analysis Equipment:

online - B & K (2033) high resolution analyzer

on campus - Nicolet (660B) 2 channel analyzer used in conjunction with Nagra 2 channel tape recorder

## 5. LIMITATIONS OF APPROACH

### (a) Hover Facility

As the rotor rig is housed in a closed chamber, no forward flight studies can be made. However, many of the forward flight unsteady aerodynamic processes can be simulated in hover by passing the blade elements through well defined disturbances, see Section 7(b). Also, the rig is portable and can be moved to an 8' × 10' wind tunnel or bigger for actual forward flight work.

### (b) Large Angles of Attack

For large elements at high speeds, there are problems at large angles of attack.

(i) Large circulation is produced around the chamber. For moderate speeds this is not a problem, as the circulation time is large. Thus, it is possible to operate the rotor in "clean" or circulated air. At high speeds there is little interest at large angles of attack.

(ii) An inboard vortex is generated. In hover this vortex appears to have little effect on the noise generation processes. This can be demonstrated by altering the element chord to span aspect ratio (including a complete span). Note at zero angle of attack the arm requires a small but nonzero pitch angle so that the element does not move through its own wake.

## 6. ADVANTAGES OF APPROACH

### (a) Low Ambient Noise

The main point of rotating elements in an anechoic chamber is that very low blade element noise can be detected in a very low ambient noise environment. This is difficult to achieve in wind tunnels or open jets.

### (b) Rotational Noise

Rotational noise can be studied only on rotating elements. Rotational noise cannot be studied on fixed elements in a wind tunnel or an open jet.

### (c) Why Elements?

(i) Elements have a small radial speed variation and therefore a small Reynolds number range associated with them, compared with a complete span. This results in a higher resolution of the noise generating processes acoustically, as the microphone hears only the total noise radiated.

(ii) Blade elements are inexpensive to make and allow blade geometry to be changed and investigated readily.

## 7. RESEARCH TOPICS

The blade element approach is particularly suitable where detail noise processes need to be studied as a function of blade geometry. Topics of interest include:

### (a) Broad Band Noise

(i) Here blade self noise, generated by laminar and turbulent boundary layers moving over the blade surfaces, can be studied as a function of chord length, thickness, distribution, chamber, angle of attack, velocity, etc.

(ii) Externally induced noise produced by oncoming turbulence. Here relations between self and externally induced noise can be established, including levels and nature of oncoming turbulence required to dominate blade self noise.

### (b) Discrete Noise

Here, unsteady aerodynamic noise generated by passing blade elements through well defined disturbances (jet profiles) can be studied. The response of the elements to disturbances as a function blade geometry, speed, disturbance shape and duration corresponding to

(i) tip vortex/blade interaction,

(ii) main rotor/tail rotor interaction, and

(iii) forward flight disk loading asymmetry may be investigated



### **(c) High Speed Noise**

Here the acoustic characteristics of blade elements moving at high speed need to be established as a function of blade geometry (chord length, thickness, profile, planform, tip shapes).

Also investigated are the precise conditions (speed and geometry) at which nonlinear wave steepening occurs, and to establish the accuracy of theoretical prediction over a wide range of geometry changes.

The data and theoretical developments could then be used to suggest minimum noise airfoils without loss of aerodynamic performance.

Initially, interest was in research topics (a) and (b) above, but had changed to (c) by the time the facility was completed. The measurements given in Section 10, therefore are those of the high speed noise problem.

## **8. CONSTRUCTION OF ROTOR**

(i) The main frame was set up in a jig for accuracy, and arc welded.

(ii) Provision was made in the frame to house two types of shaft bearings. Floating sleeve bearings for quietness (but unfortunately these bearings can be used only in horizontal operation) and roller bearings for vertical operation.

(iii) Center plates on the rotor arms were arc welded to the leading edge spars and Xrayed for weld quality.

(iv) Rotor arms were constructed of mild steel (1" diameter at root) having a tensile strength of 75,000lbs/in<sup>2</sup>. In retrospect, it would have been better to have used a higher grade steel, with 2 or 3 times this strength, for tip speeds greater than Mach 0.9.

(v) Arms were held in position in the hub with steel blocks, whose shoulders tended to flow and jam at the higher speeds. Two new blocks were added to reduce the strain on the shoulders, giving a safety factor of two at Mach 0.9.

(vi) Because of the high accelerations at the tip, blade element detachable couplings

had a strength/weight ratio problem. For  $r_{tip} = 3$  ft,  $v = 1000$  ft/sec,  $g = 32$  ft/sec<sup>2</sup>,  $\omega = 2\pi f$ ,  $f = 50$  Hz,  $a = v^2/r = \omega^2 r$ , the acceleration compared to gravity was approximately  $10^4$ .

For safety the blade elements were made of high grade balsa wood (for lightness) and painted to give a hard surface. To distribute the strain the elements were glued to a protruding tongue at the end of the rotor arm.

## 9. INITIAL TESTS

(i) The rotor was fitted with a shaft frequency counter to calculate the tip speed, and a vibration transducer to monitor the structural vibration levels.

(ii) Because of the short shaft and stiff structure, vibration problems were minimal. Balancing the rotor for 2 arm operation, in the propeller (vertical) mode, gave no problems. But single arm operation in the vertical mode with a counter balance weight gave many problems and was abandoned.

(iii) The acoustic treatment of the enclosure was checked to be effective by measuring the reflected acoustic signature from the rotor, with and without the treatment on the floor. The near zero reflected image can be judged in comparing Figures 2, 3(a) and 3(b).

(iv) The recirculation in the chamber was high only at high rotor speeds, and high angles of attack. This combination was not of interest in this study. Recirculation, if it occurred, could be detected, acoustically, through large low frequency fluctuations in the acoustic signal.

(v) Acoustic measurements, at high speed, showed that the drive system noise was many dB below that of the blade element noise. At low speeds (below 200 ft/sec), the electric motor/power unit "hunted", making considerable noise. The problem arose because insufficient power was being taken from the power unit at these low speeds, making the unit unstable. The problem was removed by increasing the electrical load on the power unit, by adding resistance (room heaters) in parallel with the motor. The increased power

stabilized the unit.

(vi) With the present 30 HP P.U., 20 HP motor and 6ft diameter rotor at near zero angle of attack, a maximum tip Mach number (adjusted for temperature) of 0.93 could be achieved. Replacing the 20 HP motor (which was selected for quietness and lightness) for 30 HP should give something like an additional 50% increase in power. The notion that changing the upper frequency limit of the power unit from 60 Hz to 120 Hz and changing the pulley ratio to give the same tip speed, but more power, proved to be fruitless.

(vii) Initial acoustic tests, showed that the blade element noise was characteristic of rotor noise, having the broadband excrescence and discrete noise at low speeds, and radiating the classical compressibility signature at high speeds.

## 10. MEASUREMENTS

All data, unless otherwise stated are measured in the plane of rotation at a distance of 10' ( $\approx$  3 meters) from the center of the rotor. The rotor diameter is 6 feet (to tip of element), the element is a NACA .0012, planform 8cm chord by 12cm span and 0.96cm thick.

Also, unless otherwise stated, the element tip speed is Mach 0.89 (rotational frequency 52.8 Hz, periodic time  $T = 19\text{ms}$ ) and angle of attack near zero. When working to the second significant figure in Mach number, allowance should be made for the variation of the speed of sound with temperature, given by

$$c = c_o \sqrt{1 + \frac{t}{273}} \approx 331.6 + 0.6t$$

where  $t$  is in centigrade and  $c_o = 331.6$  meters/sec at  $0^\circ\text{C}$ . For example, a  $10^\circ\text{C}$  ( $\approx 20^\circ\text{F}$ ) change gives 2% change in the Mach number, which can be critical at high speeds.

The data is illustrated in the form of photographs of time histories displayed on a B&K 2033 high resolution analyzer. The first number at the bottom of each photo indicates the vertical scale sensitivity (pressure in volts per division). Up is negative pressure, where

84.6mv  $\equiv$  (94 + 3) dB peak pressure relative to .00002 newtons/m<sup>2</sup>. The second number indicates the horizontal scale time sensitivity (doubling the frequency halves the time).

## 11. DATA

Figure 2 shows the characteristic high speed "compressibility" signature of the arm plus element and the arm alone signature, following half a period later. In figure 2(a) the arm alone includes the element support tongue extension enclosed in an aerodynamic cover. In figure 2(b) the tongue has been removed making both arms identical in length, and therefore easier to assess the contribution from the element alone.

Note in figure 2(b), the vertical sensitivity has been changed, and the smaller image between traces is that reflected from the machine structure. This reflection can be removed, if bothersome, by acoustically treating the structure. Note also, the intense peak sound pressure levels  $2.5 \times 8.9v \equiv 20 \log \frac{22.2}{0.846} + 97\text{dB} = 145\text{dB}$ .

However, the main point to note here is that the total arm contribution to the acoustic signature is small compared with that from the element. This is because the acoustic weighting function is very sensitive to speed, and therefore to elements toward the rotor tip.

According to theory the effective span length based on the rotor tip speed is approximately 6%, 3%, 1.5% of the rotor radius, for tip Mach numbers 0.8, 0.9, 0.95, respectively. This indicates that the aerodynamics associated with the inner parts of the rotor are not important, acoustically.

Figure 3 shows the effectiveness of the surface acoustic treatment. Figure 3(a) shows the reflected image from the hard floor (without acoustic treatment). Figure 3(b) shows the effect with acoustic treatment. In this case the reflected image is negligible.

Figure 4 shows the interesting effect of microphone distance from the element tip. It can be seen that apart from amplitude changes, the general shape of the signature does not change appreciably from 3 meters (10 ft) from the center of the rotor, down to 15cm (6

in.) from the tip. Around 7cm (3 in.) the signature changes dramatically to the signature shown in 4(b).

Figure 5 illustrates the speed characteristics from Mach 0.3 to 0.93. The full line shows the peak sound pressure level in the plane of rotation and how the signature changes its shape with increasing speed (amplitude and time scales have been changed to give similar sized traces).

Below Mach 0.7 the signature is a smoothly changing once per revolution characteristic. In the absence of excessive noise mechanisms (large inlet flow distortions), this signature is presumably a result of weak, residual, cyclic variations in the rotor aerodynamic loading.

Above Mach 0.7 the rate of increase in sound pressure with increase in speed changes abruptly. Here the high speed impulsive signature, generated by the steady displacement (blade thickness) effect, starts to emerge above the unsteady aerodynamic noise. Above Mach 0.8, the blade thickness noise completely dominated the acoustic signature. At speeds above Mach 0.9 the acoustics signature steepens rapidly, as the wave turns into a shock wave in the far field.

Between Mach 0.8 and 0.93 the data is in good agreement, both in shape and magnitude, with that taken by Schmitz et al. on a complete rotor, reference (1). This gives further confirmation of the validity of the blade element approach.

On the axis of rotation, the acoustic characteristic is quite different. Here the noise is basically broadband over the entire speed range, from Mach 0.3 to 0.93. Note there is no evidence, on the axis of rotation, the intense impulsive noise being reflected from the plane of rotation via the chamber walls, again confirming the effectiveness of the acoustic treatment.

## 12. CONCLUSION

A research facility has been described, which enables high quality noise measurements to be made on blade elements moving in a circle over a wide range of blade speeds.

The philosophy is that useful information can be obtained by studying the more basic blade element, rather than a complete rotor. Initial measurements indicate that this approach is valid.

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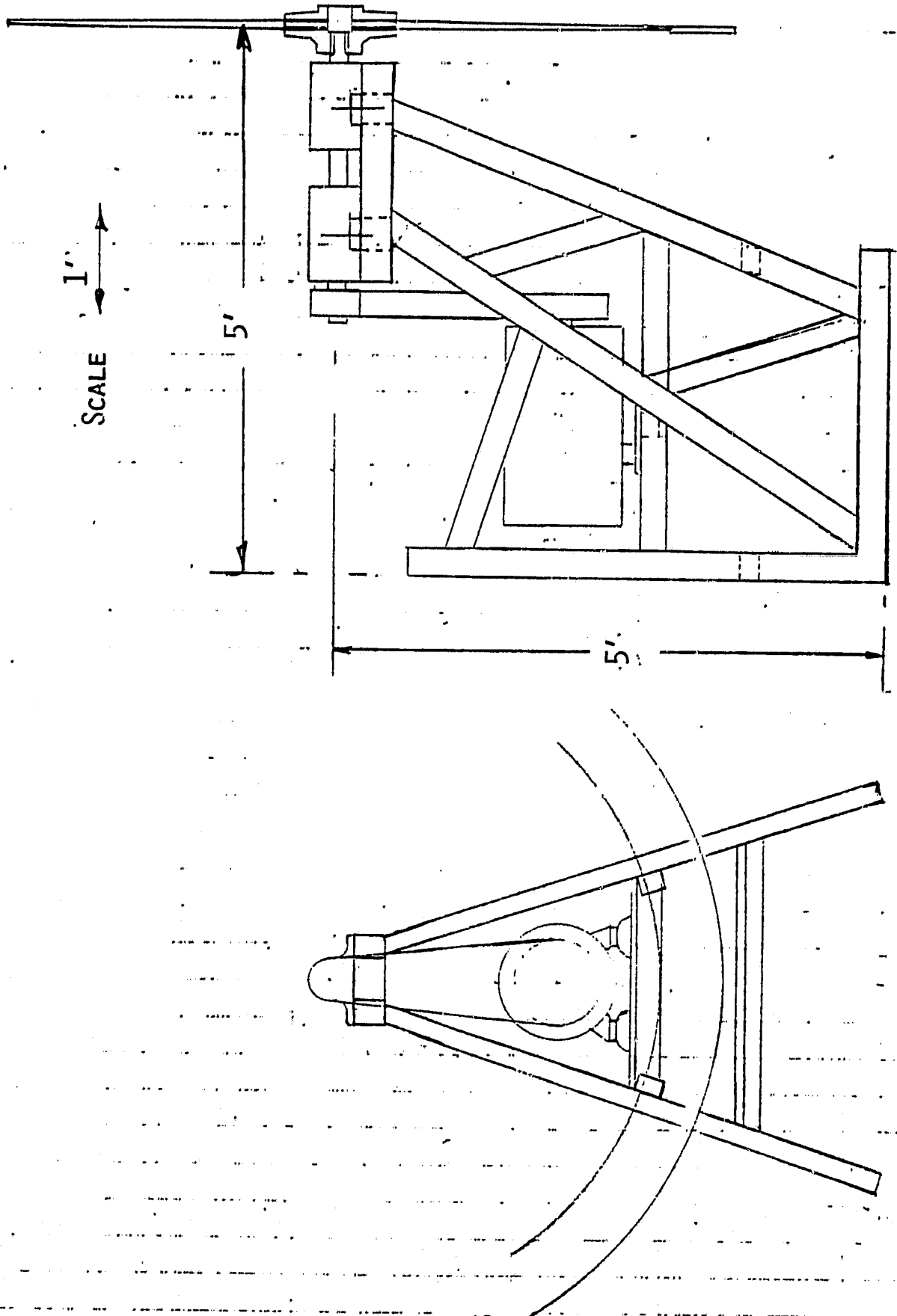
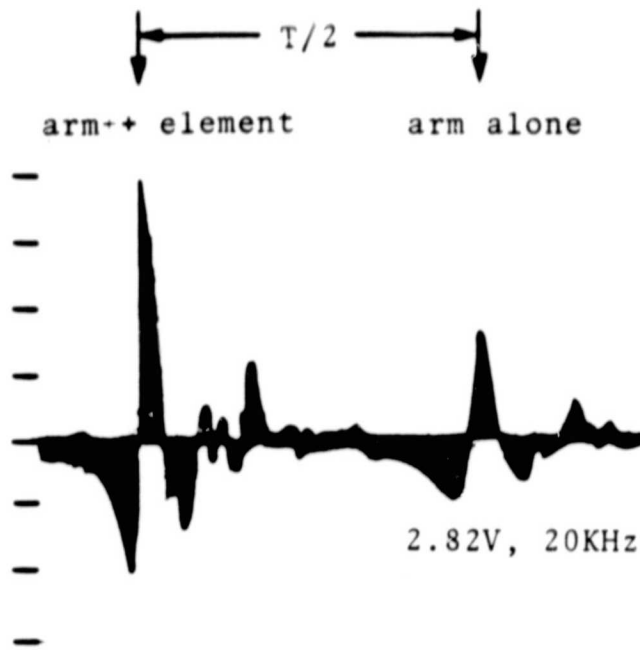
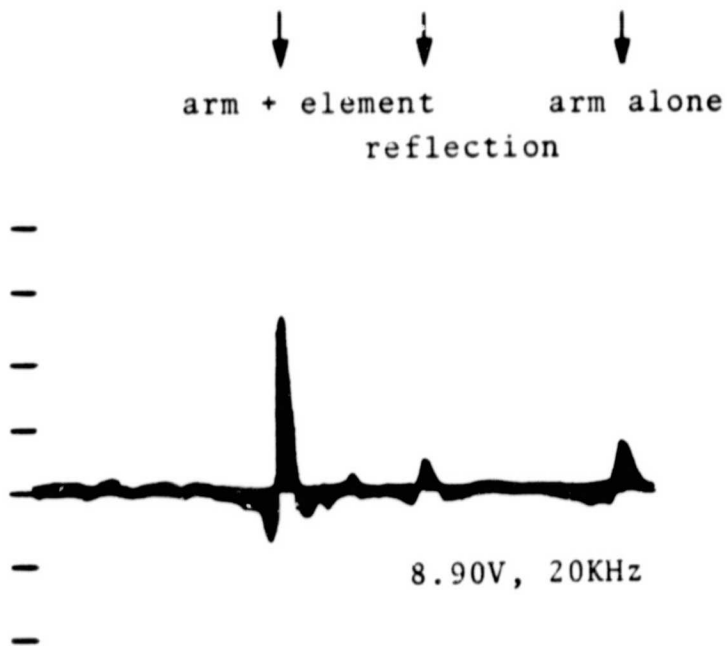


Figure 1. Rotating arm element support (RAES) equipment.





(a) Arm alone with extending tongue.  $M=-0.87$ .



(b) Arms of equal length.  $M=0.89$ .

Figure 2. Contribution of Arm and Element

ORIGINAL IMAGE OF POOR QUALITY

↓ ↓  
direct reflected ↓



(a) hard surface

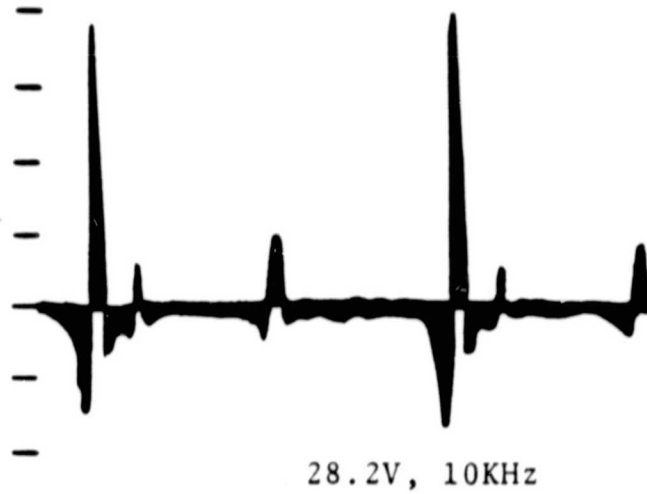
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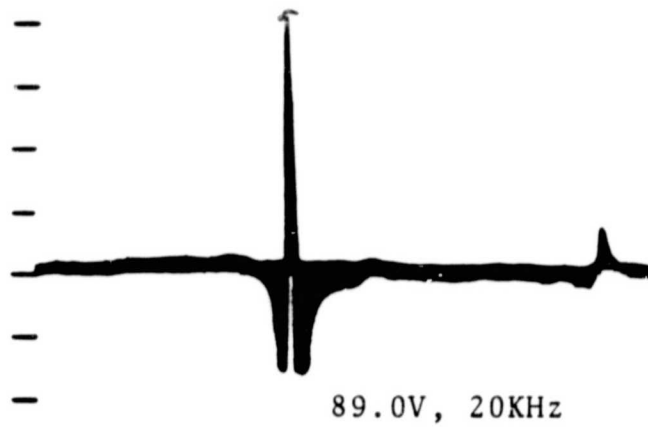
(b) treated surface

Figure 3. Effect of Acoustic Treatment

ORIGINAL COPY  
OF POOR QUALITY



(a) microphone distance.  $R=6''$  (15cm).



(b) microphone distance.  $R=1''$  (2.5cm).

Figure 4 Effect of Distance

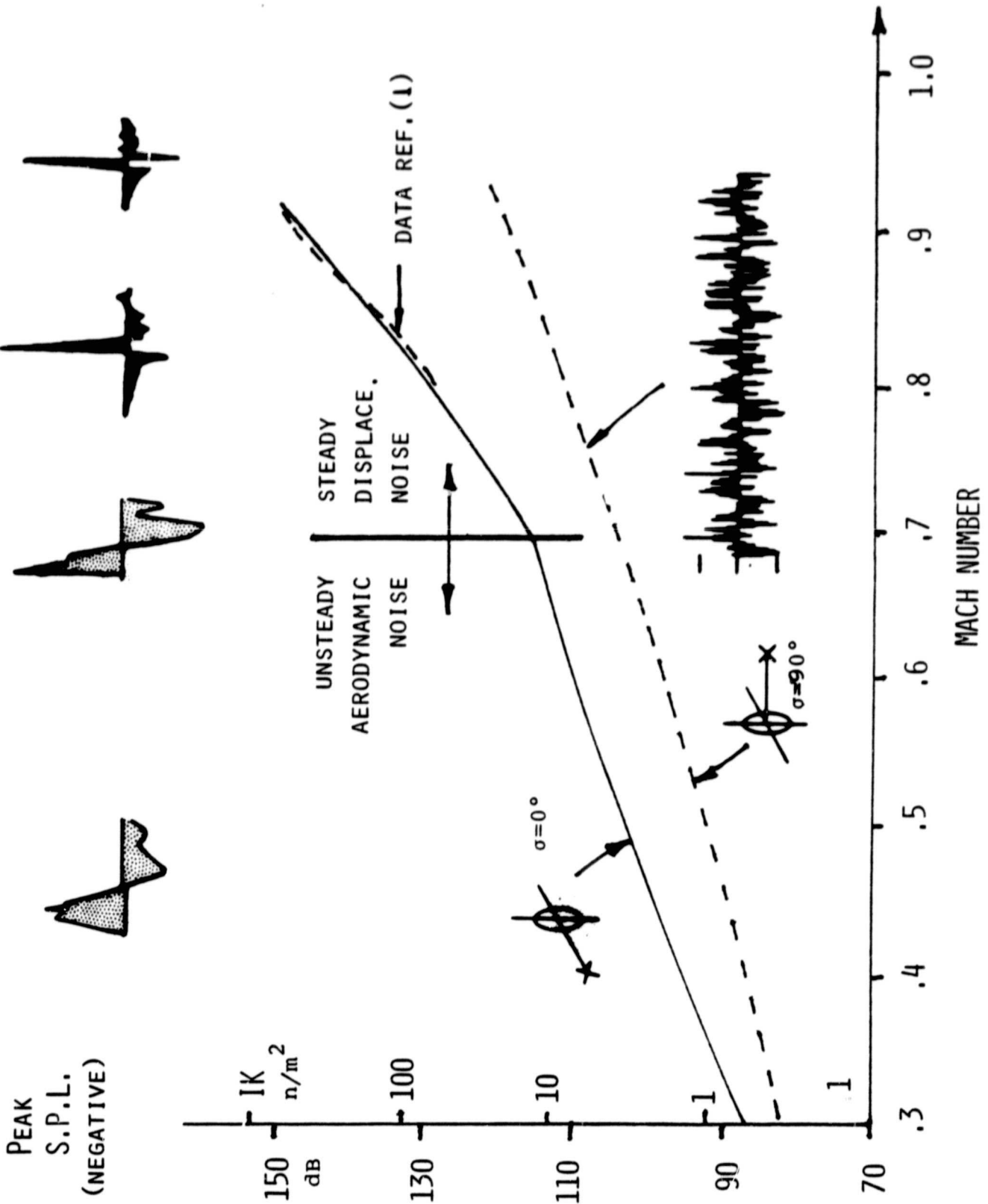




Figure 6. RAES showing arm detail.

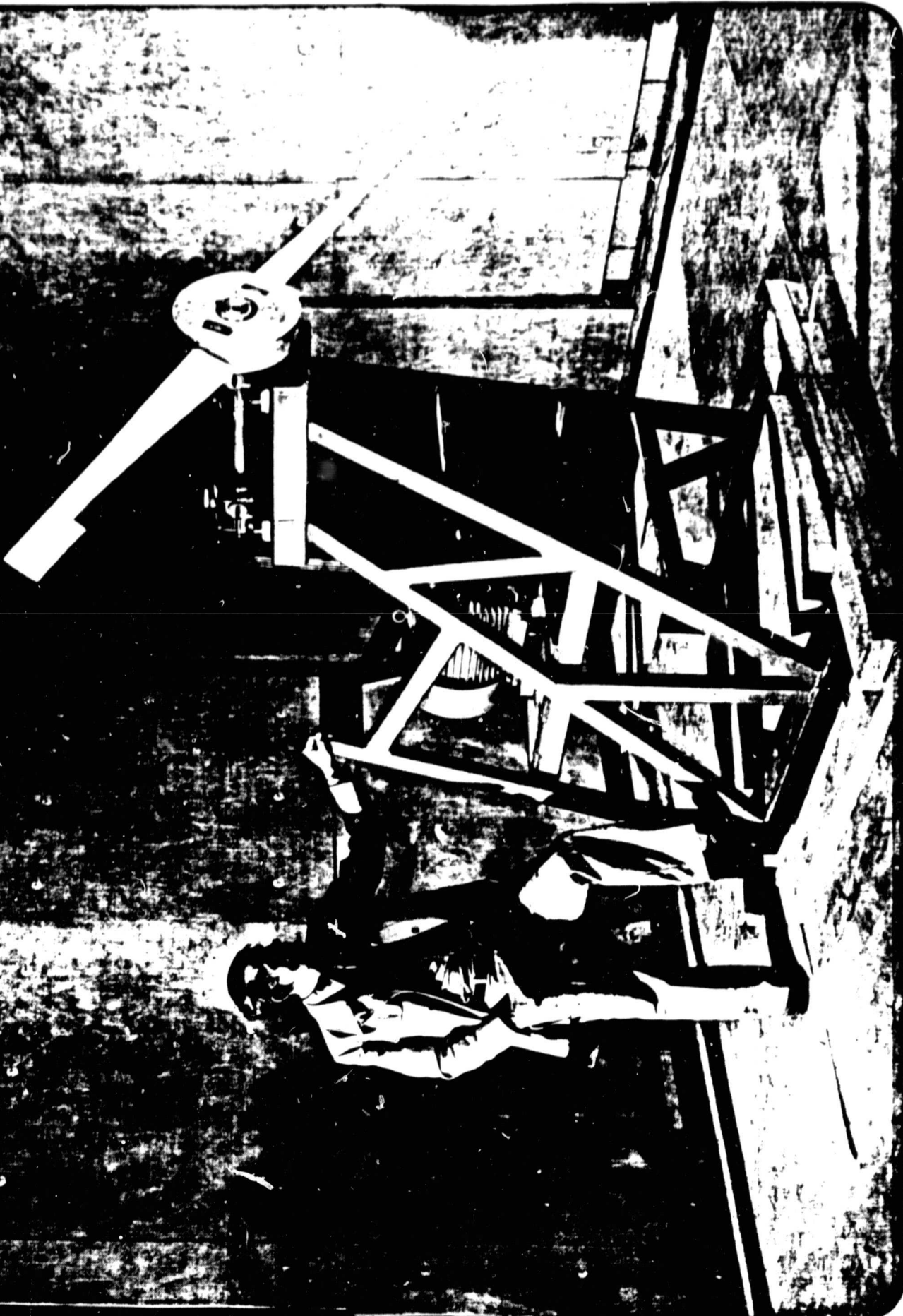


Figure 7. Rotor situated in anechoic chamber.