FLOW GENERATED NOISE OF ACOUSTICAL DUCT LINERS

by

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ABSTRACT

Noise generated by flow over acoustic duct liners is studied with main emphasis on discrete tones produced by flow instabilities over perforated metal liners in conjunction with Helmholtz resonator arrays. Specific experiments are designed to determine the noise source mechanisms. In addition, the noise generated by duct inlet and exit configurations and its comparison to broadband foam liner noise is investigated.

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CHAPTER I

INTRODUCTION

To attenuate unwanted sound in ducts with flow acoustical linears are widely used. This absorbing liner provides the duct boundaries with a finite acoustical impedance thus attenuating the acoustical energy traveling through the duct. Acoustical impedance is defined as:

$z = p/u$ where p and u are the total pressure at the boundary and velocity amplitude normal to the boundary.

An ideally rigid duct boundary with velocity amplitude at the boundary equal to zero would have an infinite impedance, therefore a reflection coefficient $R = 1$ where:

$p_r(0) = R\, p_i(0)$

r - reflected
i - incident
(0) - at boundary

These so-called soft boundaries dissipate acoustical energy, thus attenuating sound.

Many types of methods and materials are used for acoustical liners such as foams, glass wool, screens and perforated plates with and without honeycomb or cavity type backing. The perforated plate backed with individual cavities can be regarded as a Helmholtz resonator array, providing the cavity depth is smaller than $\lambda/4$, where λ is the wavelength, which is true for the range of values used here.

An advantage of the Helmholtz resonator is that, depending on hole and cavity size, the system has a particular resonant frequency. The sound attenuation is usually quite high in the vicinity of this frequency, because the forcing frequency of the input signal matches the resonant frequency. Unfortunately, the attenuation is usually much lower at lower and higher frequencies, making the Helmholtz resonator an effective sound absorber only in relatively small frequency bands. These resonators are frequently damped by filling the cavities with porous materials, thus extending the range of attenuation somewhat, but lowering the magnitude of attenuation.

Most sound absorbers such as the Helmholtz resonator can be classified as a boundary with a local reaction. A locally reacting boundary as opposed to an extended reacting boundary has the feature that each point is decoupled from the rest of the boundary, thus its motion is virtually unaffected by any reaction occurring at another area. The case of the locally reacting boundary makes predicting and analyzing the characteristics of the boundary much simpler.

Other liners not using resonant cavities are commonly used. An example includes a simple lining of foam or another type of porous material along the duct walls. Sometimes screens or perforated plates are used as protective coverings for the foam. These foam linings don't normally attenuate sound at the magnitude of the Helmholtz resonator, but the range of attenuation is much larger.

The problem to be discussed in this thesis is not one of attenuation characteristics of liners, but one of the adverse qualities exhibited by some liners at certain conditions. A typical liner in the presence of grazing flow produces a highly turbulent flow near the boundary thus producing a liner self-noise. Depending on the conditions, these liners may produce more noise than is attenuated, thus limiting the liner length to an optimum value.

Undamped and lightly damped Helmholtz resonators and also perforated liners alone are shown to produce a discrete tone or tones with a significantly high amplitude, similar to the edge tone[1,2,3]. In all cases, though, the source of the problem seems to be that of vortex production at the holes[4,5,6]. The screech tone seems to be a complex combination dependent upon duct modes, flow velocity, damping and the like. Mechel et al.[7] along with his theory on signal amplification, observed these discrete tones that he calls pfeife-tones. His observation of the maximum intensity of the tone to be at a frequency equal to the product of the flow velocity and the number of holes per unit length seems to be an oversimplification. Screech tones such as these are the subject of discussion and experiment in Chapters II, III, and IV.

A simple lining of foam, for example, will produce noise also, but by a different mechanism[8,9,10]. This noise is generally of a lower amplitude than that of the discrete whistle of the perforated plate and it is generally of a broadband nature. Chapter V is a discussion with experiment of this broadband noise in comparison to the noise produced by the duct inlet and exit. This inlet and exit noise is believed to be more significant, in many cases, than the broadband liner noise.

Chapter VI discusses future investigations and what are the important directions of research on this subject.

CHAPTER II

APPARATUS AND EXPERIMENTAL METHODS

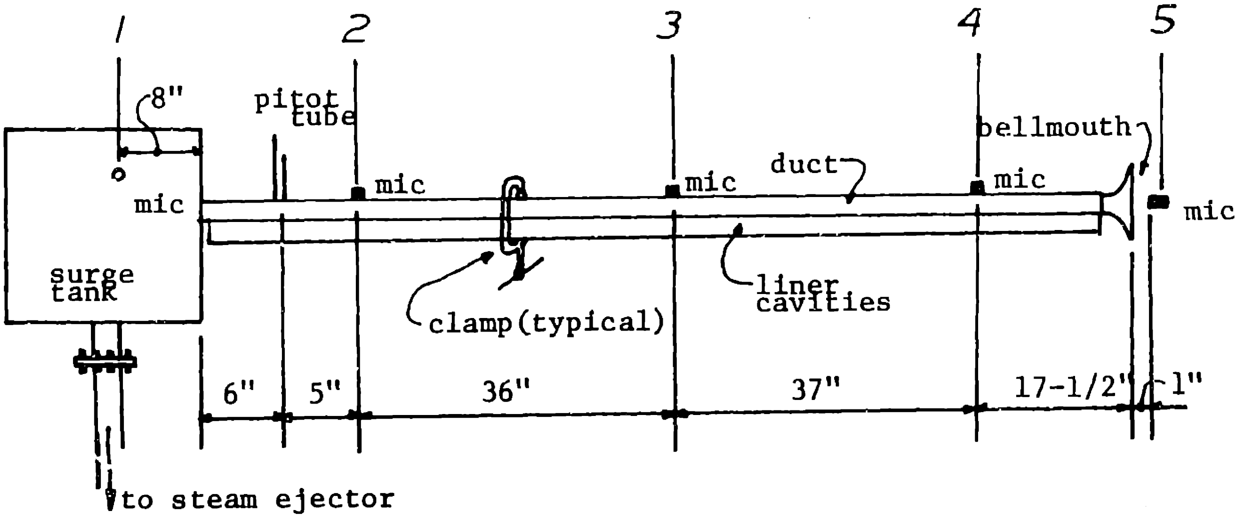
2.1 Apparatus for Chapters III and IV

The apparatus used in Chapters III and IV is shown in Figure 1. The duct and cavity sections were constructed using 3/4 inch by 7/8 inch aluminum channels with the specific liner to be studied sandwiched between the two as shown. The total duct length was approximately 8 feet.

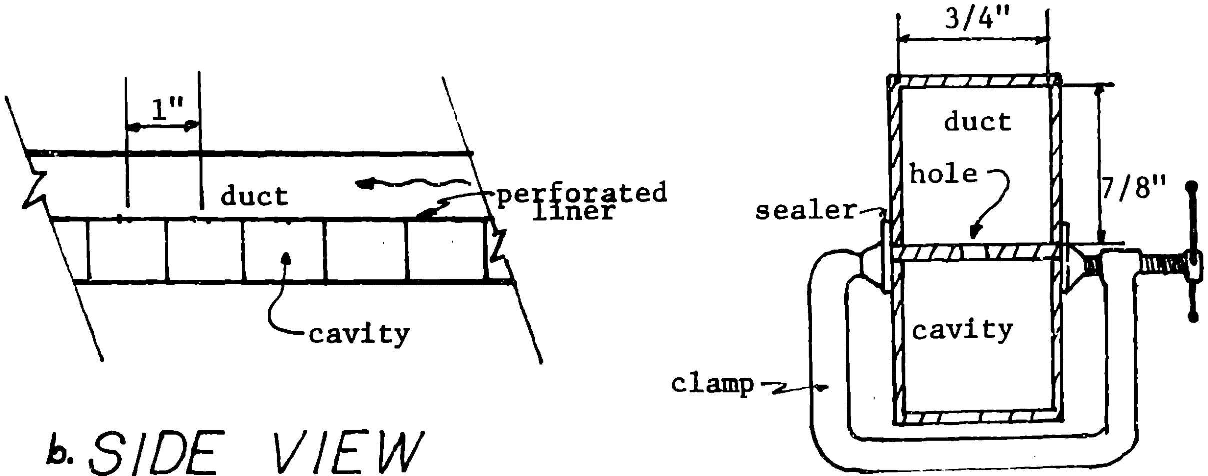
In Chapter III each cavity was 1 inch by 7/8 inch by 3/4 inch, and a combination of tape and metal strips with clamps, as shown in Figure 1-C was used to seal the duct from leakage. For the work in Chapter IV, the cavity geometry was changed accordingly by removing the cavity divisions and raising a plate to various depths. The cavity divisions were constructed using securely glued plastic pieces. Static pressure taps were placed next to microphones 2, 3 and 4 and a pitot tube was placed as shown.

After experimenting with the internal microphones (2,3, and 4) it was soon decided that the inlet microphone (#5) outside the duct was sufficient and best suited for the remaining experiments. The microphones used were Primo-Electret Condenser microphones with a nearly flat response up to 10 KHz. A bellmouth was placed at the inlet to minimize separation problems and inlet noise.

APPARATUS

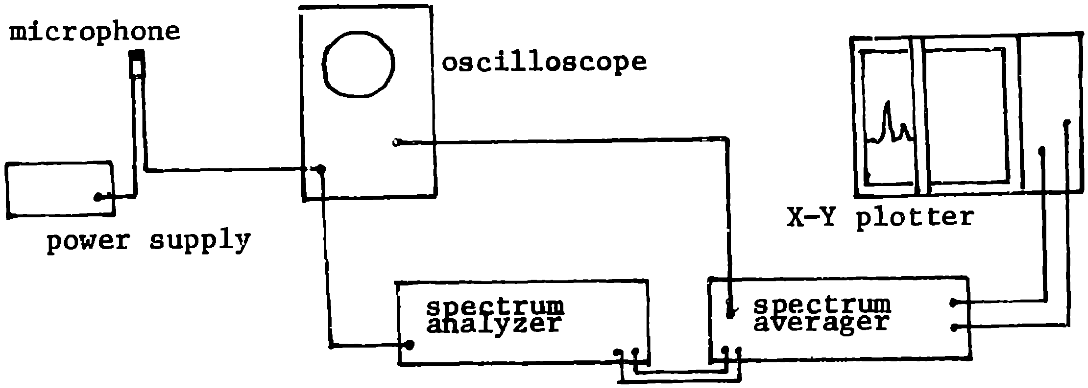


a. DUCT ARRANGEMENT



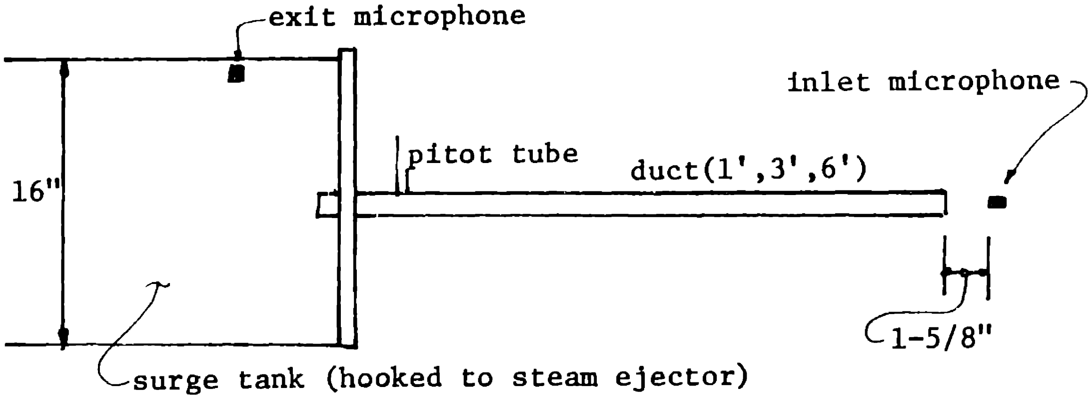
b. SIDE VIEW

c. CROSS SECTION

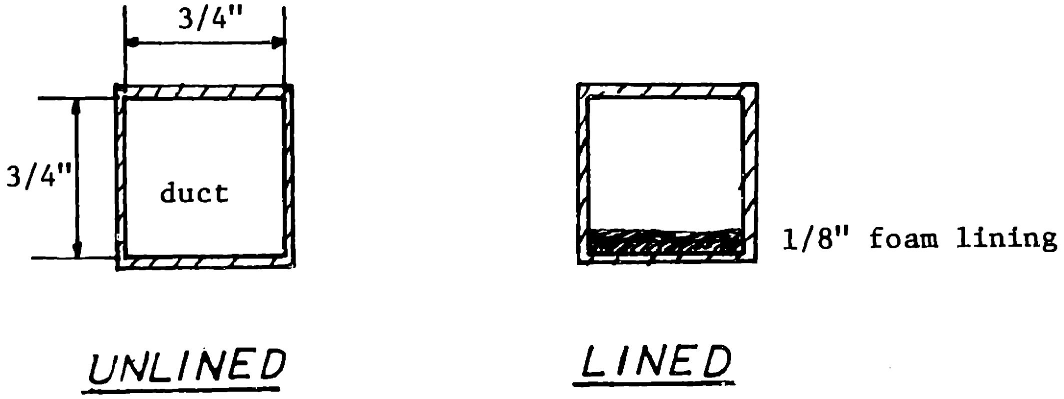


d. ELECTRONICS

FIGURE 1



a. APPARATUS
INLET & EXIT NOISE



b. DUCT CROSS SECTION

FIGURE 2

The duct was then mounted to the surge tank, which was hooked to the steam ejector to provide suction with the suction source being an ample distance away, as not to cause any noise problem.

The electronic equipment was set up as shown in Figure 1-D, using the oscilloscope as a visual monitoring device. The instruments used included a Federal Scientific UA-14 Ubiquitous Spectrum Analyzer and a model 1014 Spectrum Averager. The Hewlett Packard 7035B X-Y plotter was calibrated for sound pressure level using an Advanced Acoustical Research Corporation Sound Level Meter and a 1 KHz sound source. Perfect calibration was not necessary since our prime concern here is the frequency of excitation and the relative not absolute magnitude.

In a typical run for a specific liner case, the flow speed was adjusted and the microphone output was plotted. Typically 5 to 10 different flow speeds were taken, except for the section of Chapter III where many more data points were taken. The description of specific configurations used are presented in each individual section.

2.2 Pressure Drop in the Eight Foot Duct

For the 8 foot duct, the pressure drop was examined for the different liners and a comparison to analytical results is made. To get an idea of the static pressure variation for the 3/16 inch hole liner with one inch spacing at

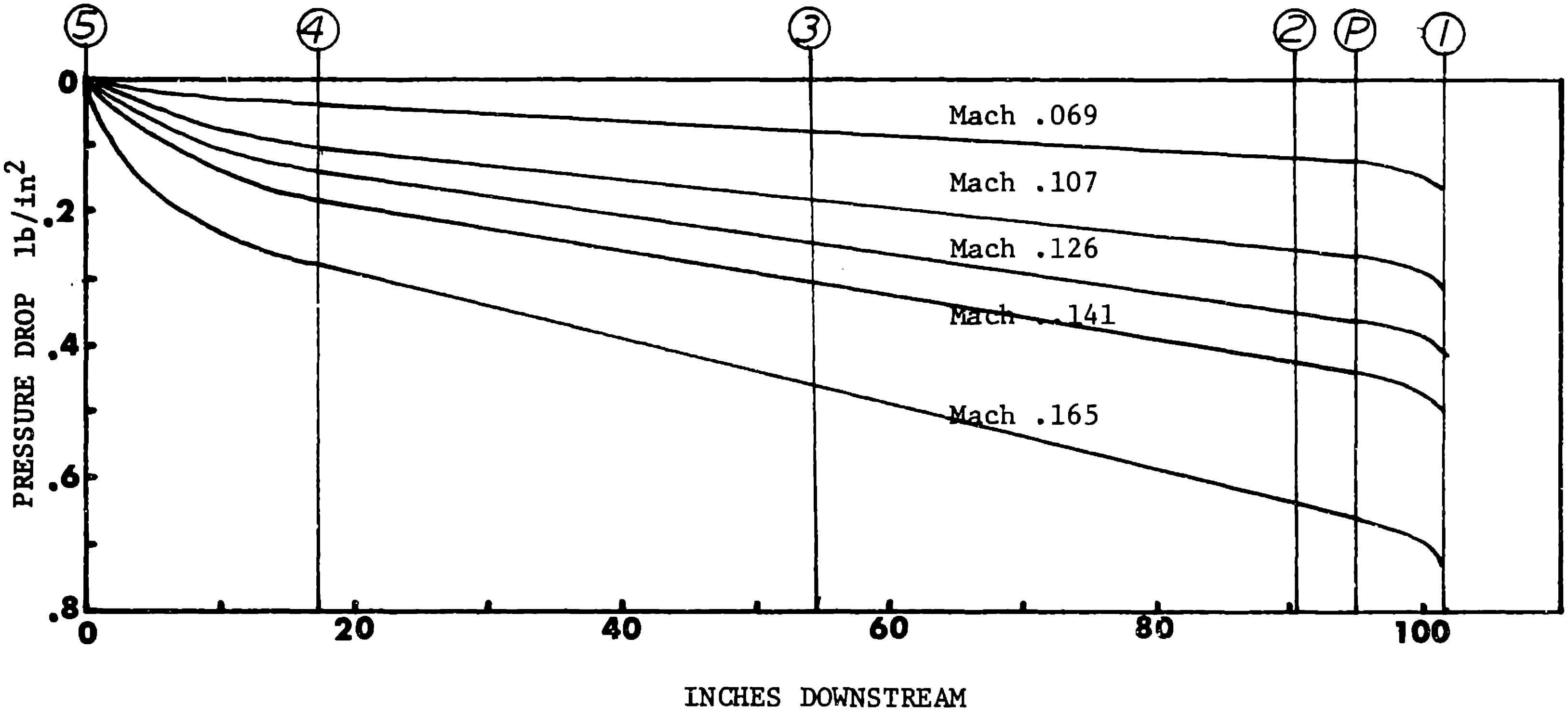


Figure 3: Static Pressure variations for 3/16" hole liner at one inch spacing for various Mach numbers.

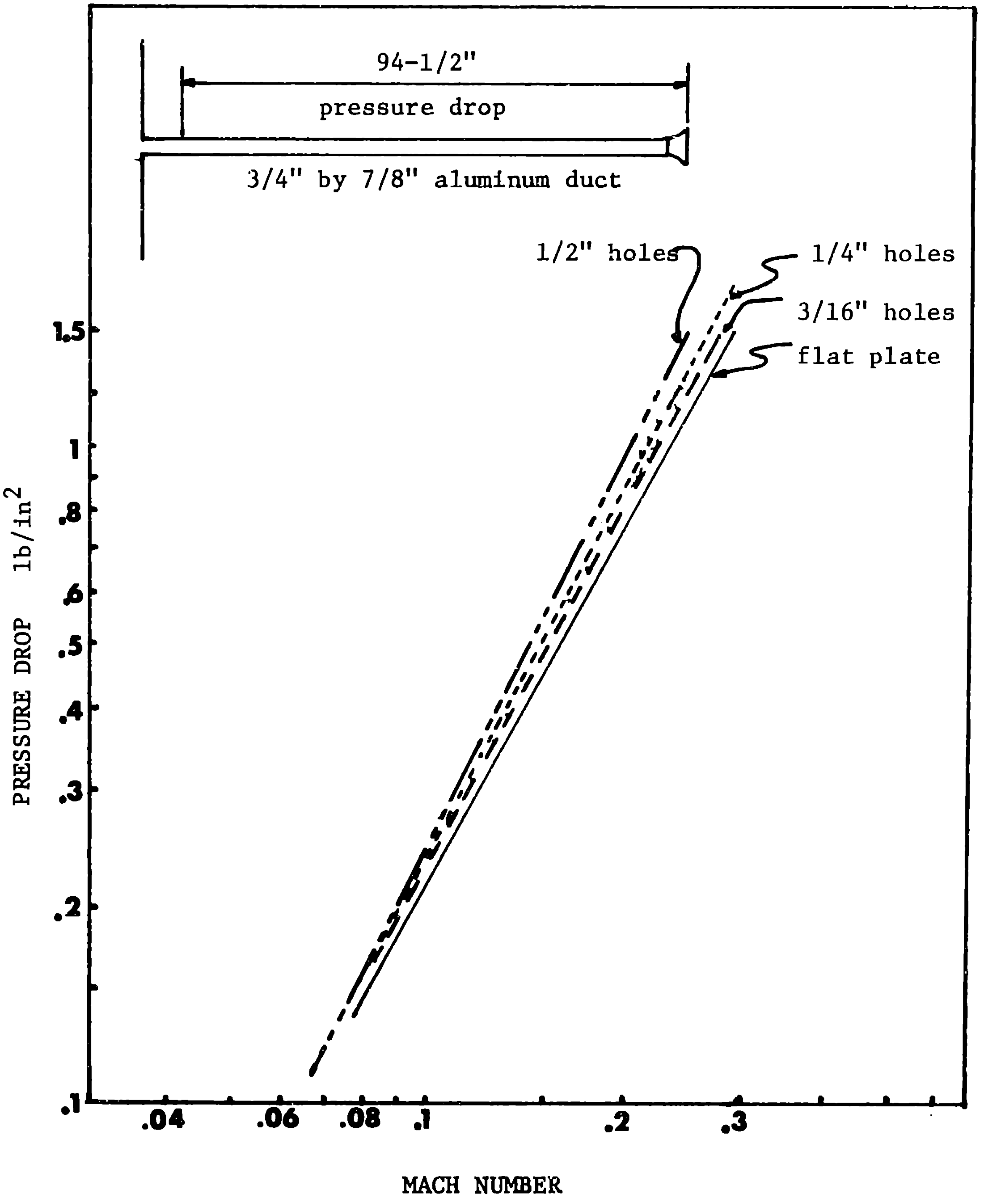


Figure 4: Pressure drop vs. Mach number for liners with various hole sizes (one inch hole spacing).

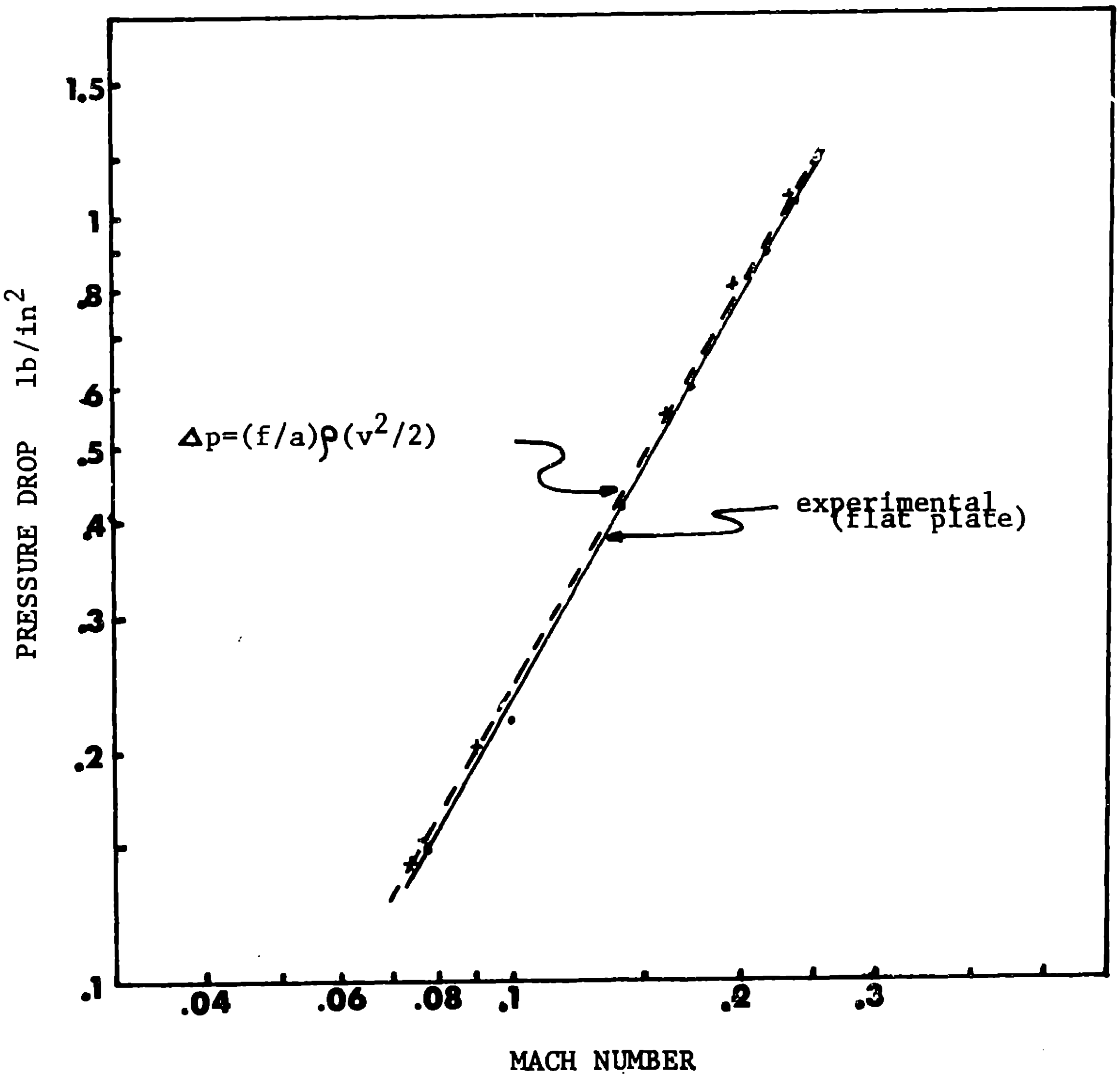


Figure 5: Comparison of formulated pressure drop with experimental for smooth wall liner(no holes).

various Mach numbers, it is plotted as a function of distance downstream of the inlet in Figure 3. The curve shapes compare qualitatively with the results of Shapiro[11].

Next, the pressure drop vs. Mach number is shown in Figure 4 with the expected results of increasing pressure drop with hole size being confirmed. To check the validity of these measurements, the flat plate (no holes) result is compared to analytical results with good agreement, as shown in Figure 5. These relations, as shown by Ingard et al[12], are that the pressure drop per unit length of duct is $(f/a)\ \rho(V^2/2)$ where a is the ratio between the area of the duct cross-section and its perimeter, and f is the friction factor given in Moody Diagrams. V is the velocity and ρ is the density.

2.3 Apparatus for Chapters V and VI

The apparatus and experimental methods were very much similar for Chapters V and VI, except that the ducts used were somewhat different. Chapter VI ducts were all of one foot length (3/4 inch by 7/8 inch) with a change of liner configuration from a one hole-resonator liner to a two hole-two cavity liner to a 3 hole-three cavity liner with all resonant cavities 3/4 inch by 7/8 inch. A microphone was placed 1-5/8 inches in front of the inlet.

Chapter VI ducts were of varying lengths (one foot, 3 feet, and 6 feet) with a 3/4" by 3/4" cross-section without

Helmholtz liners, but a foam liner was inserted for some experiments. The set-up is shown in Figure 2.

2.4 Future Experimentation

For future experimentation in this same field a few suggestions can be offered. For long ducts (L/D > 40) it is wise to take two pitot measurements and take an average because the change in flow velocity may be significant. Also it is wise to plan ahead of time a convenient modular construction for a particular experiment to fascilitate easy duct geometry change without excess flow disturbance. The configurations in this investigation were not quite as convenient as could have been expected.

Another important consideration is the placement of the microphones. First of all it should be far enough from the inlet as not to be disturbed by the turbulent fluctuations of incoming flow. Also, when using a bellmouth, one should be careful if the placement of the microphone is too close because the near field behavior of a horn or bellmouth is different than the far field. Placing the microphone in an enclosed area such as in the surge tank is also a problem, because depending on the placement, the response could be affected by modes of the enclosure, thus giving a specific response.

CHAPTER III

EFFECT OF LINER SURFACE GEOMETRY CHANGE

3.1 Changing Liner Configurations

This chapter concentrates on the effect of changing the liner plate geometry and not the cavity geometry except for that investigated later in the chapter where cavity damping is employed. The basic purpose of this chapter is to note the effect of hole size and hole spacing on the frequency and magnitude of screech. The last two sections of the chapter are specific studies of: 1) an in-depth study of several specific liner configurations with many data points; and 2) a look at the screeching characteristics of a highly perforated liner.

The experimental arrangement was that of Figure 1 as described in Chapter II. Liners of 1/16 inch, 1/8 inch, 3/16 inch, 1/4 inch, and 1/2 inch holes were tested with one-inch hole spacing on all of them, two-inch spacing on the 3/16 and 1/4 inch, and three- and four-inch spacing on the 1/4 inch liner.

3.2 Cavity Resonances

Before starting with the results of self-excitation, the cavity resonances are calculated for the 3/16 inch, 1/4 inch, and 1/2 inch liners with the validity of the 1/2 inch hole-cavity resonance in question as a result of the mass end correction of the holes valid for the diameter of the hole being much less than the cross-dimension of the cavity. From the relation of cavity resonance with end correction given by Ingard[13]:

$$\nu_o = \frac{c}{2\pi}\left[\frac{A}{V(t+\delta)}\right]^{1/2}$$

$\delta = .96\ (A)^{1/2}$ (end correction)
A = Hole area
V = Volume of cavity

Results:

$\nu_{3/16}$ = 807 Hz
$\nu_{1/4}$ = 989 Hz
$\nu_{1/2}$ = 1142 Hz

In taking data for the first few times, it was concluded that the data from microphone number 5 was sufficient for the study of this phenomenon. The other microphones were simply redundant and placement of microphones in the duct can lead to duct mode problems.

3.3 Liners with 1-inch Hole Spacing

Each liner was tested with undamped resonator backings. Each liner consisted of 68 holes spaced at 1 inch and had a thickness of 1/8 inch. The 1/16 inch and 1/8 inch holes did not screech at all, which shows that there must be a critical hole size for a given plate thickness of which these instabilities occur. The 3/16 inch, 1/4 inch and 1/2 inch holes did screech and these are plotted on Figure 6 with frequency as a function of Mach number. It is seen from the $f = CM^n$ relation-

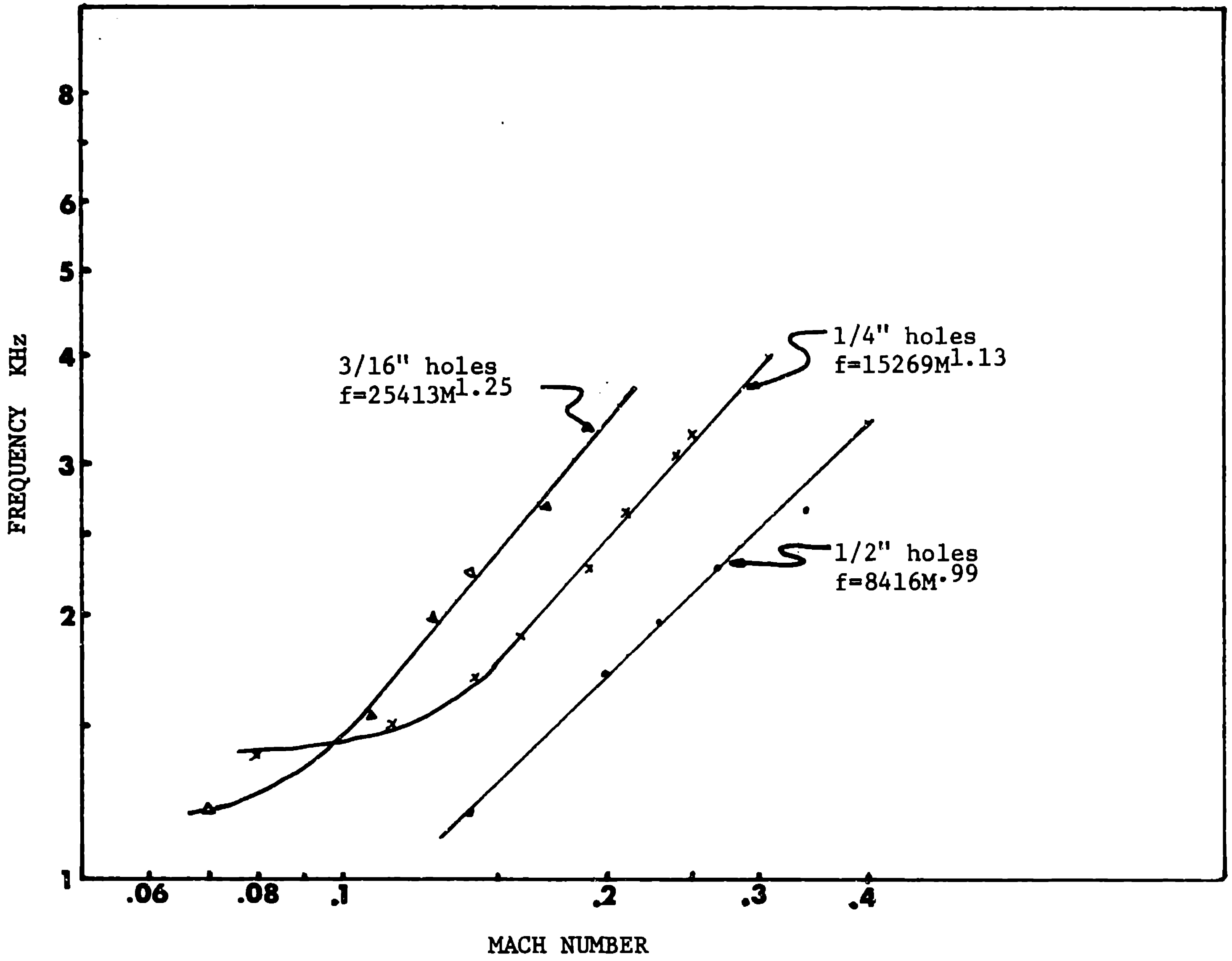


Figure 6: Frequency response of various liners with one inch hole spacing.

ship that these functions are almost linear $(n \simeq 1)$. The peak amplitude increases with increasing hole size and the amplitude increases to a maximum, then decreases back to the white noise level in the duct. A typical plot for 1/4 and 3/16 inch holes is shown in Figures 7 and 8.

3.4 Change of Hole Spacing

The next investigation was concerned with change of the hole spacing. The hole spacing was simply changed by filling the necessary holes with plasticene, giving the surface a smooth finish and backing the hole with tape on the cavity side of the liner. The tape was to insure that a pressure differential would not force the plasticene out of the hole. First, the 3/16 inch hole liner was changed to 2-inch spacing, and it was immediately seen that this configuration did not exhibit any self-excitation. This also shows that there must be a critical hole size-hole spacing relationship for these instabilities to exist. For the 1/4 inch liner a screech was observed for 2-inch, 3-inch, and even 4-inch hole spacings as plotted in Figure 9. In this detailed investigation of the 1/4 inch hole size it is readily seen that there are two separate regions of self-excitation. The first region consists of the diagonal lines in Figure 9 that follow at $f = CM^n$ relationships. We see that the 4-inch spacing exhibited such a weak screech that it was not recorded. But the trend seems to be consistent with the n of $f = CM^n$, being approximately

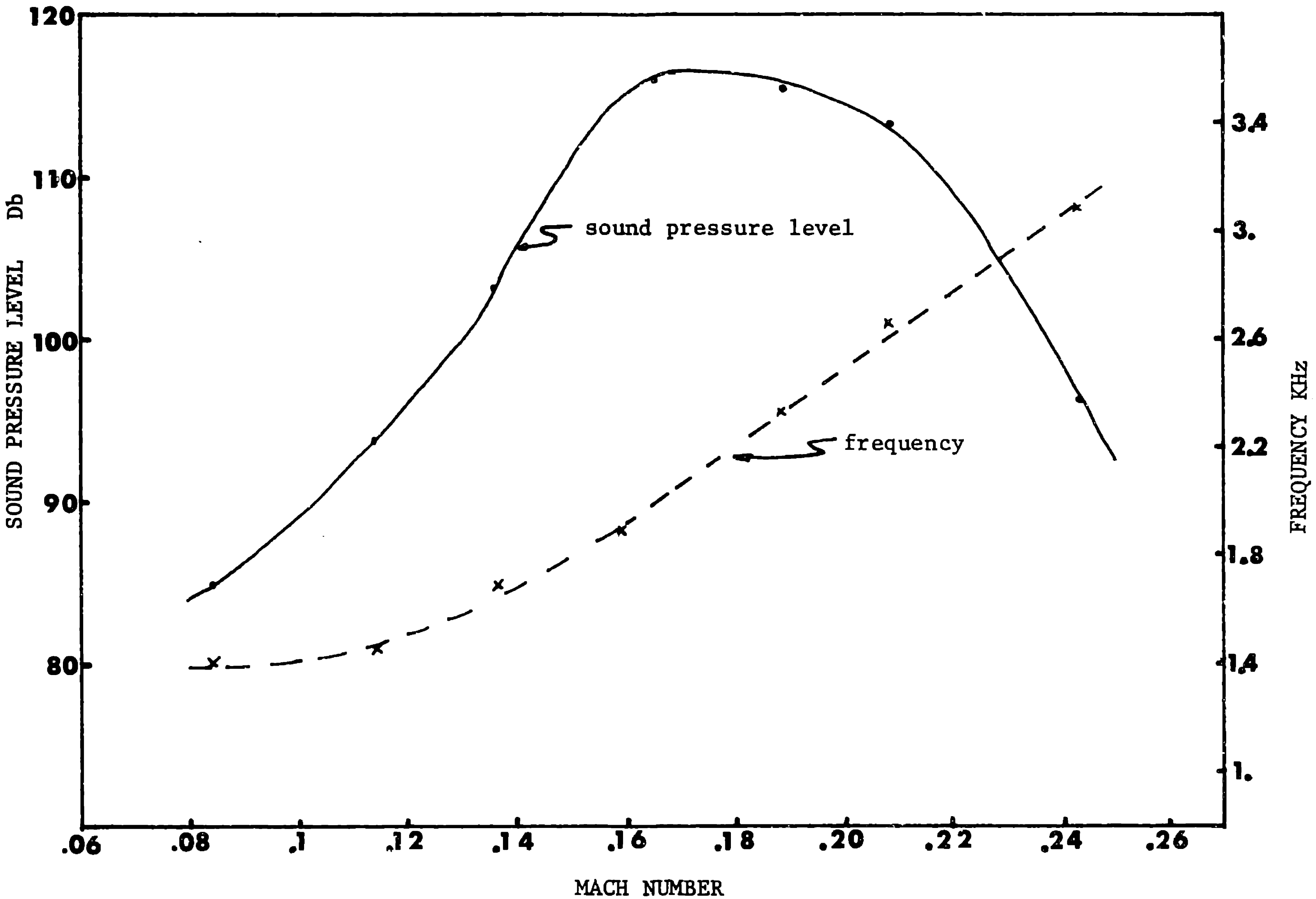


Figure 7: Sound pressure level and frequency of 68 inch liner with 1/4" holes at one inch spacing.

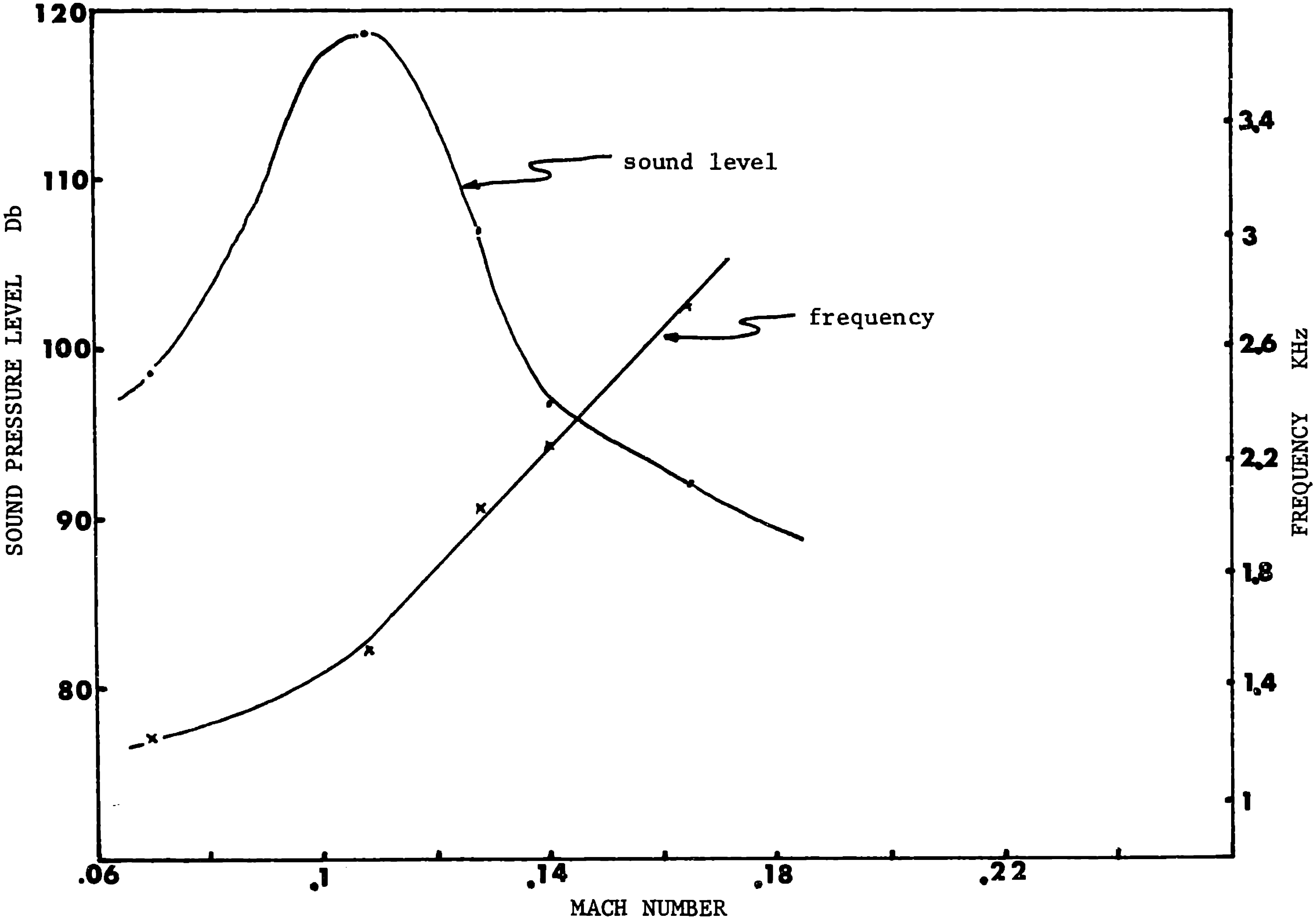


Figure 8: Sound pressure level and frequency of 68 inch liner with 3/16 inch holes at one inch spacing.

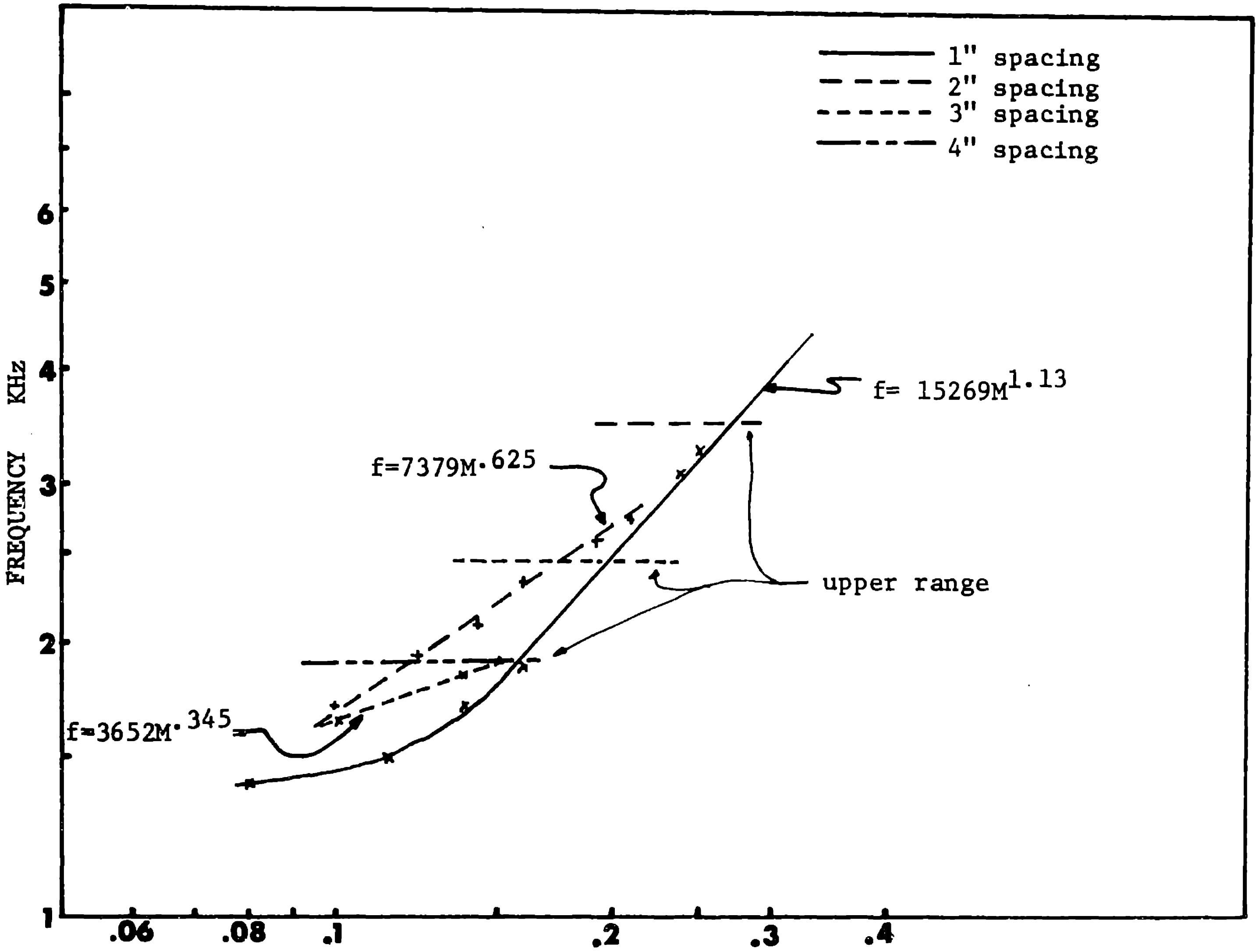


Figure 9: Response of duct with 68 inch long liner with 1/4 inch holes at various hole spacings.

halved for each increase in hole spacing. If this is true, then for the 4-inch spacing we would expect approximately $f = CM^{.17}$. The corresponding amplitudes are shown in Figure 10 with the 3-inch spacing being very weak, which explains the absence of the screech at a hole spacing of 4 inches. It is observed as shown in the typical graphs at the end of the report (of 1-inch and 2-inch spacing 1/4 inch holes) that at the ranges with high amplitude excitation that many other modes or harmonies are excited. This is particularly noticeable in Appendix Figures A-III-4 and A-III-5.

The second range of excitation consists of a single constant frequency throughout the entire range. This excitation phenomenon occurs right about at the cutoff point of the first excitation (lower range) as mentioned above, and this frequency is higher. In Figure 9 these constant frequency plateaus are evident. The plateau for the 1 inch spacing is not on this graph because the apparatus was not constructed to measure such high flow speeds, but this higher excitation does exist at about 7850 Hz, as shown in Appendix Figures A-III-7 through A-III-9. The flow speed could not be recorded, but the duct finally choked at the outlet during the highest flow rate. The sound pressure level curves vs. Mach number are shown in Figure 11. It is seen that the amplitude of the 4-inch spacing is quite strong in the upper range as compared to

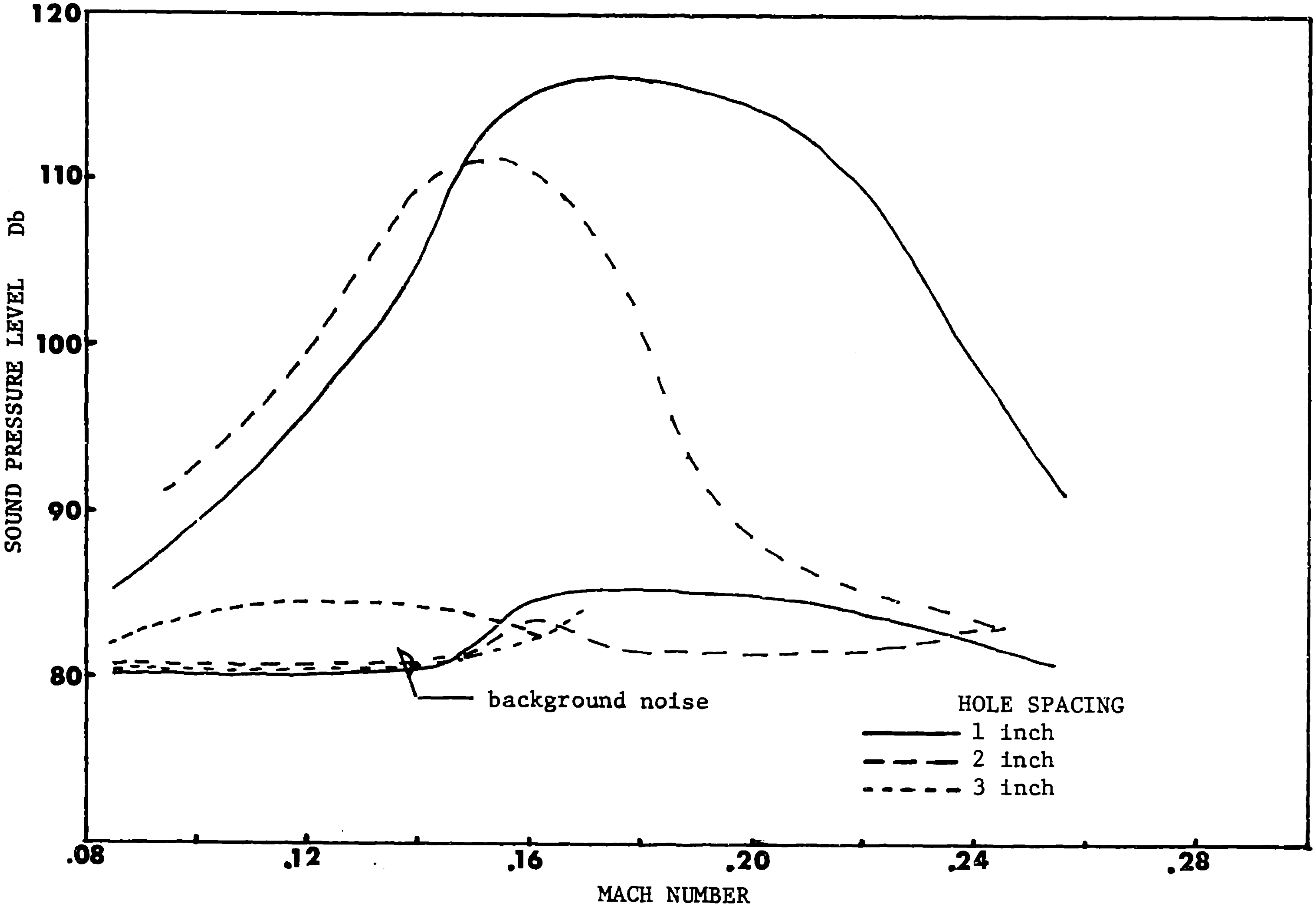


Figure 10: Sound level vs. Mach number for lower range of excitation for various hole spacings (1/4 inch holes).

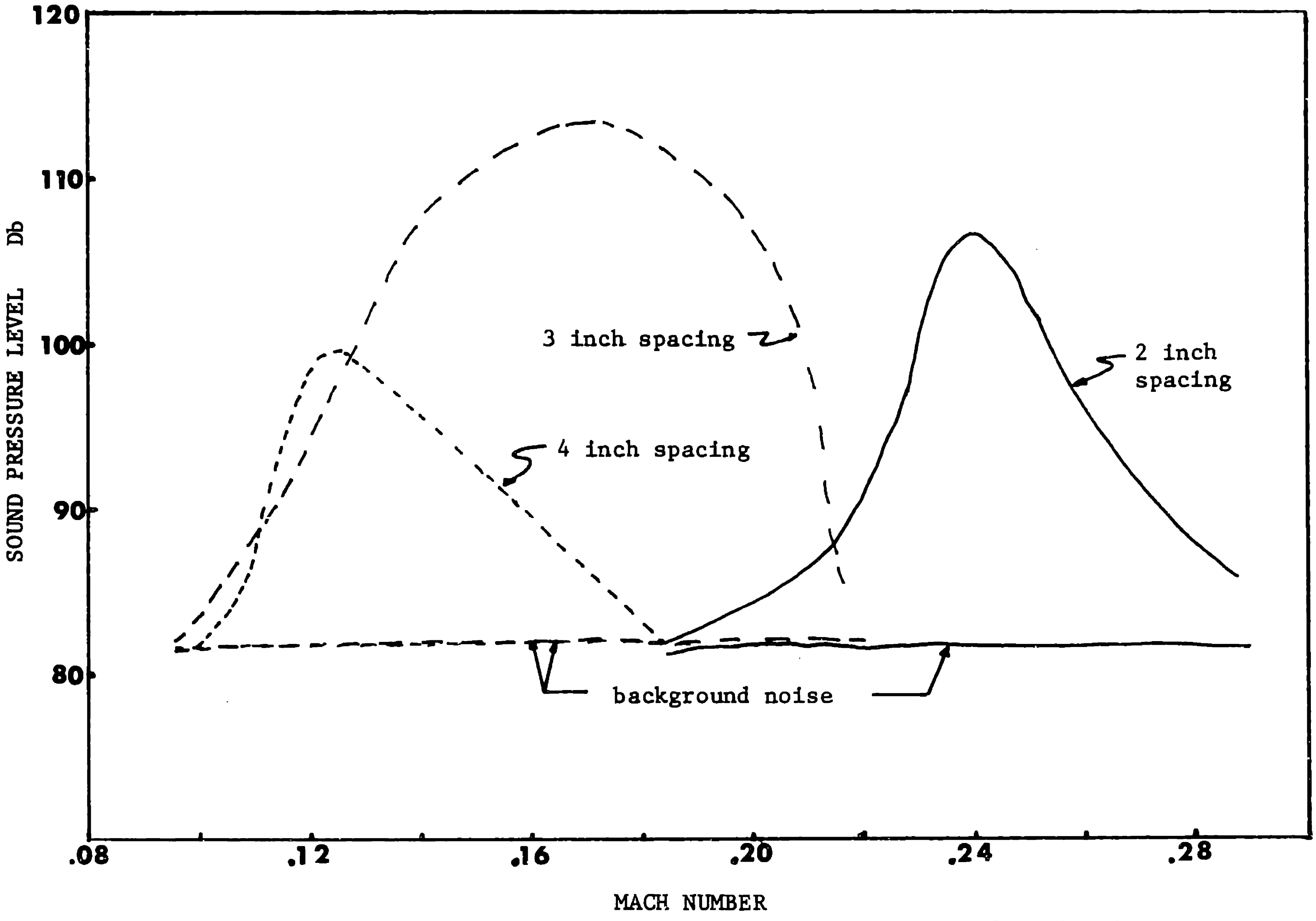


Figure 11: Sound level vs. Mach number for upper range of excitation for various hole spacings (1/4 inch holes).

the amplitude in the lower range. This strengthens the idea that there are two independent mechanisms producing the upper and lower ranges of excitation.

3.5 Damping of Cavities

Next we damped the cavities to see whether the two ranges could be further separated. The effect of damping is shown on Figure 12. It was readily seen that the cavity, when filled up to the hole, did not screech in any range, showing that the material at the bottom surface of the hole prohibited instabilities from occurring, similar to the wide meshed tissue backing used by Mechel[14]. With damping configuration #1, the characteristics of self-excitation were basically unaffected, which showed that damping was not sufficient. For the damping configuration #2, a frequency shift was observed for the lower excitation range, but the upper range was completely unaffected. This leads us to the conclusion that the lower range of excitation is cavity dependent, while the upper range is somehow independent of the cavity and possibly coupled with the duct, for example. We see that the characteristic slope of $f = CM^n$ was unaffected, but only the constant changed. The amplitudes of excitation are graphed as a function of Mach number in Figure 13. The amplitude of the lower range was much more affected than the upper range, as shown by the decreased amplitude of damped #2.

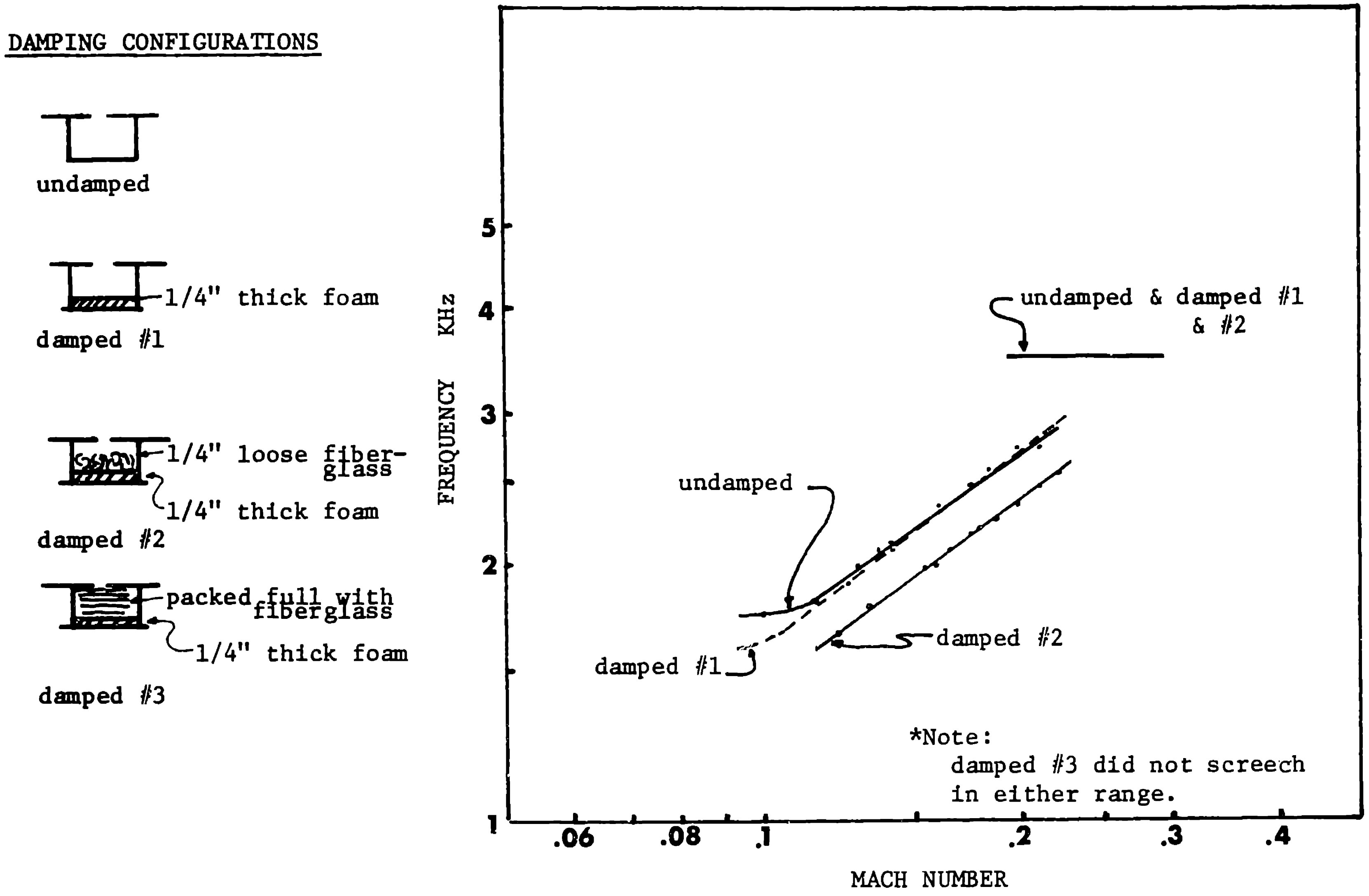


Figure 12: Frequency vs. Mach number for various damping configurations.

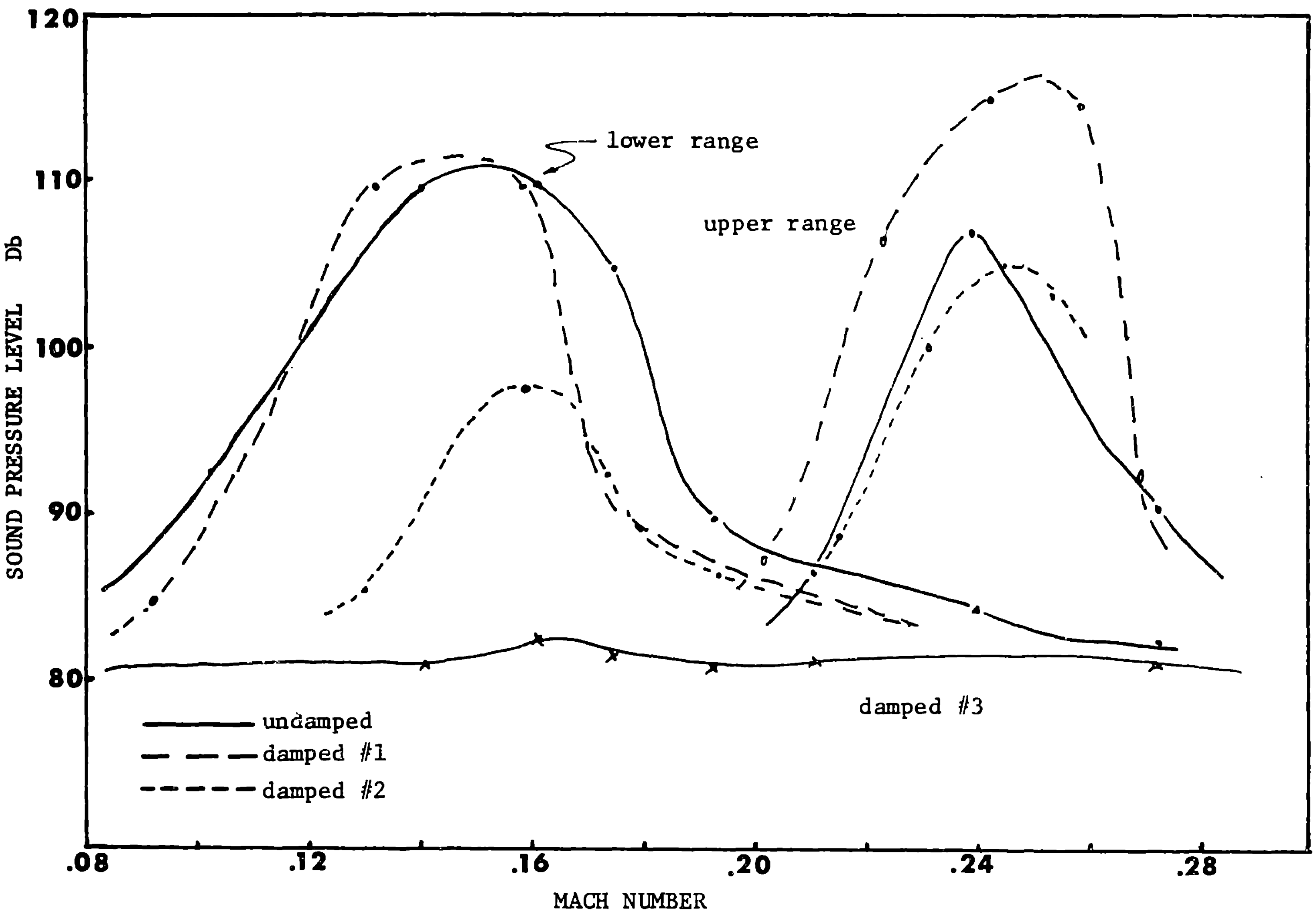


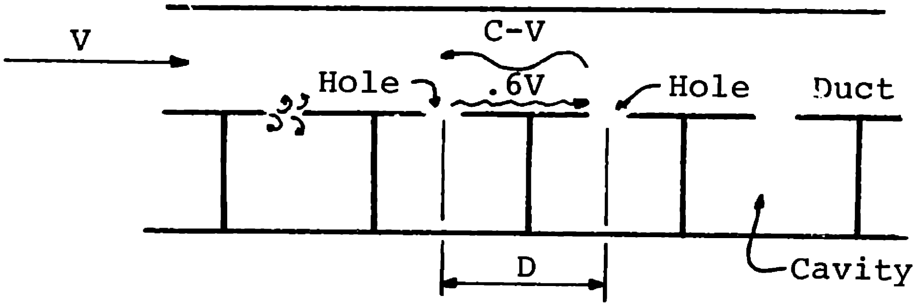
Figure 13: Sound level vs. Mach number for various damping configurations (1/4 inch holes with 2 inch spacing).

One final observation was that for the 1/4 inch hole the number of holes present was decreased by 5 at a time to note the change in amplitude. As expected, the amplitude simply decreased with decreasing number of exposed holes, until an insignificant level was reached at about 10-15 holes.

3.6 Analysis

The first most obvious note to be made in that the excitation frequency was not that of the cavity resonance. But it was discovered that for the 1/4 inch and 1/16 inch holes the frequency of maximum amplitude corresponds to twice that of the cavity resonant frequency. This is shown in Figures 7 and 8. The results for the 1/4, 2 and 3 inch spacing for the lower range are not quite as conclusive to confirm this idea. It is seen that at 2-inch spacing, the Mach number corresponding to twice the resonant frequency in Figure 9 does not correspond exactly to the maximum amplitude in Figure 10.

Also examined was the idea of a simple feedback mechanism between holes. If we assume that the disturbance produced by the first hole is convected downstream at approximately 0.6 of



the free stream velocity and, upon striking the downstream hole, is fed back at acoustic velocity minus free stream, then:

Velocity of Disturbance: Downstream = 0.6 V
Upstream = C-V

$$\text{Time downstream} = T_d = \frac{D}{0.6V}$$

$$\text{Time upstream} = T_u = \frac{D}{C-V}$$

$$\text{Total time} = \frac{D}{0.6V} + \frac{D}{C-V} = D\left(\frac{1}{0.6V} + \frac{1}{C-V} \right)$$

$$= \frac{D}{C}\left(\frac{1}{0.6M} + \frac{1}{1-M} \right)$$

$\therefore$ the characteristic frequency:

$$\nu = \frac{1}{T} = \frac{12C}{D} \left[\frac{0.6M(1-M)}{1-0.4M} \right]$$

for C = 1120 ft/sec D = 1 inch M = 0.2

we have for D = 3/4 (hole edge to edge)

ν = 1402.4 Hz ν = 1879 Hz

The frequency does not correspond to the data collected here. If we change the convected velocity to 0.8 V and use 0.75 for

D (hole edge to hole edge) we get a reasonable 2400 Hz which corresponds to Figure 9. For 2-inch hole spacing, D = 2 - 0.25 = 1.75 inch and at $M = 0.15$ we get an unreasonable answer. There is, though, still strong reason to believe that acoustic reflections are taking place to provide a feedback mechanism.

Next, the work of Mechel[9] is investigated, especiallly his partial wave analysis of signal amplification. The concept of partial waves may be the basis for this self-excitation, at least in the upper range. Mechel[9] describes that since the phase velocity of the fundamental wave is too high to interfere with the much lower flow velocity only partial wave amplification is possible here. These partial waves, which are components of spatial Fourier synthesis, are described by Mechel[7] . Appendices 2 and 3 of Mechel[7] describe partial waves in detail. Mechel's result for the condition of wave amplification is:

$$V = \frac{U_0}{1 + \frac{nU_0}{f\ L}}$$

where V is the flow velocity and if equal to U_n which is the phase velocity of the n^{th} wave.

U_0 is the phase velocity of the fundamental wave.

L is the distance between the holes.

A problem encountered is getting the phase velocity of the fundamental wave in the presence of absorptive boundaries. In the work of Galaitsis[15] the phase velocity vs. frequency was obtained by experiment for a cavity of about 1100 Hz resonance frequency. The same form was used and a plot patterned after Galaitsis is shown on Figure 14.

In comparing the result of partial waves with the experimental results we see that good results were obtained with the upper range of excitation (constant frequency). For the 1/4 inch holes, 2-inch, 3-inch and 4-inch spacing the results are as follows:

1/4 inch hole 2-inch spacing let $n = 2$ using f from Figure 7.

$L = \frac{2}{12} = 0.167$ ft $\quad f = 3500$ from Figure 12

$$U_0 = C_1 = 1234$$

$$V = \frac{1234}{1 + \frac{1234(2)}{3500(0.167)}} = 236 \text{ ft/sec} \rightarrow \text{actual } 263 \text{ ft/sec}$$

1/4 inch hole 3-inch spacing $n = 3$

$$V = 179.0 \text{ ft/sec} \rightarrow \text{actual } 187.0$$

1/4 inch hole 4-inch spacing $n = 4$

$$V = \frac{1344}{1 + \frac{1344(4)}{1495(0.33)}} = 146.6 \text{ ft/sec} \rightarrow \text{actual } 135.3$$

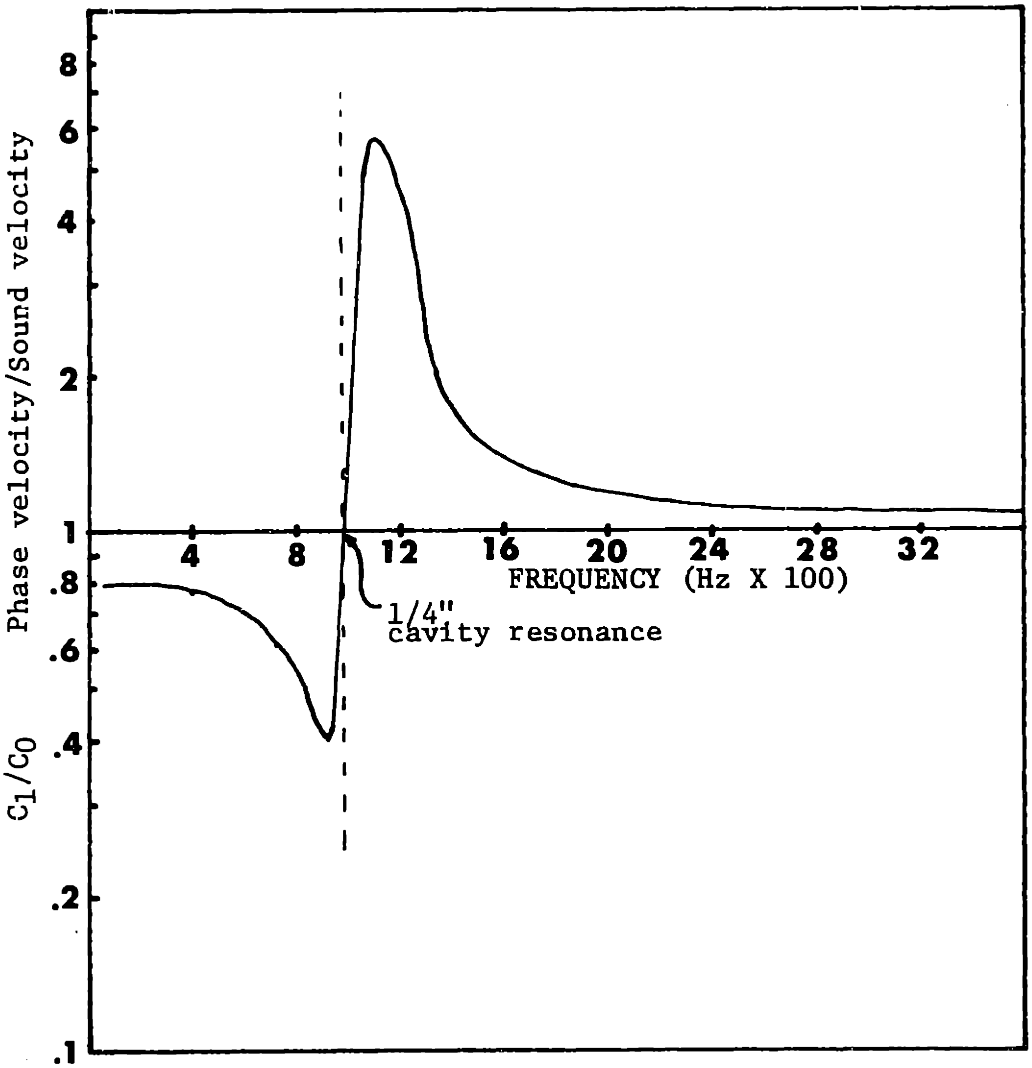


Figure 14: Phase velocity *vs.* frequency patterned after Galaitsis[15].

It is seen from these results that the partial wave relation is within the experimental results when the n is increased by one for each increase in spacing. Also it is observed that the velocity is not a strong function of phase velocity. This analysis is only to serve as an indicator as to whether this type of theory can be applied as an amplification method of the liner perturbations.

3.7 A Closer Examination of Screech Data

The purpose of this section is to present the results of a closer look at the lower range of excitation, as described earlier in this chapter. From this investigation, we see that the increase in screech frequency with Mach number is not continuous, but there are a number of small discontinuous jumps. This phenomenon was only noticed here, because the increase in Mach number was made in many small increments rather than only 10-15 data points as before. There is, though, still reason to believe that there are two separate ranges (and mechanisms) of screech as proposed in the first section.

The apparatus consisted of the same equipment used in the initial investigation, shown again in Figure 1. The major difference here is that the data were taken in extremely small increments of Mach number, both increasing from minimum to maximum and back again. This was done to note the hysteresis effects which clearly exist.

From Figure 15 we see that frequency does increase with Mach number, but it increases along specific excitation frequencies. The arrows show the path followed by increasing the Mach number. Decreasing the Mach number lets the frequency versus Mach number follow to the lower extent of each constant frequency line as shown. The tendency is for the excitation to stay at the existing frequency as long as possible, thus producing the hysteresis effect.

It was noticed that right before the transition point where the frequency was about to change that the next frequency jump could be induced by simply putting a slight perturbation at the inlet, such as a pencil point. The wake produced by the object induces a frequency jump to the next level. When the object was removed the frequency often jumped back to the original frequency. Also two and sometimes three simultaneous frequency levels were present if one was careful in adjusting the flow. Appendix figures A-III-20 through A-III-27 show the presence of two frequencies simultaneously. As the flow rate increases the lower frequency diminishes while the higher frequency grows until only the upper frequency exists.

Figure 16 is the graph for the 1/4 inch hole liner, but with two inch spacing instead of one. This graph shows the upper range as in the first report. As demonstrated before the upper range is present also in the one-inch spaced liner, but is not shown in Figure 15 because we did not investigate

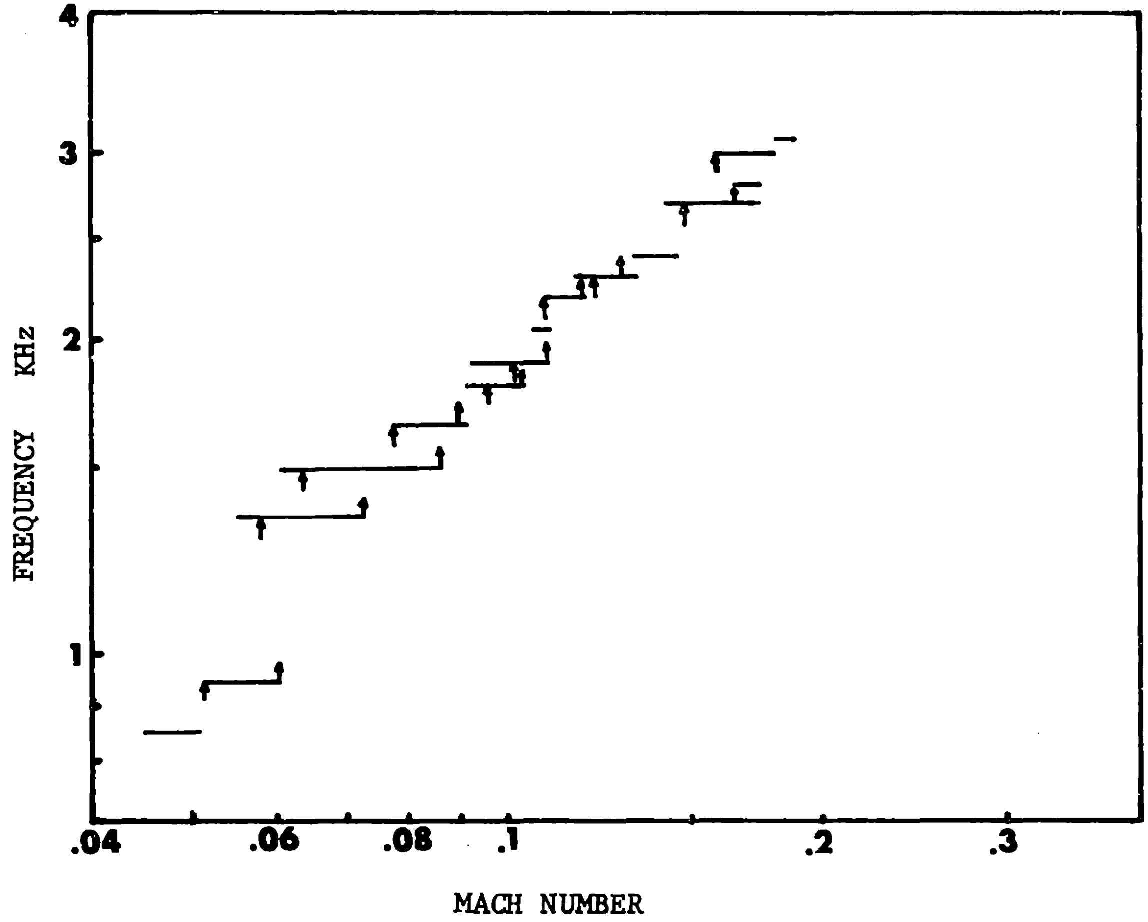


Figure 15: Steplike response of screeching liner,noting the hysteresis effects(1/4"holes,1" spacing).

high enough flow rates here. This upper range in Figure 16 has different properties than the lower range, such as no hysteresis, a much more stable tone and as in the previous report this screech is unaffected by resonator damping as the case for the lower range.

The closer examination of the screeching of these liners has shown that the screech frequency is not always completely predictable, but is rather dependent on small fluctuations in flow rate, inlet perturbations, and minor changes in hole geometry. In Figure 17 the frequency versus Mach number graph is quite different than that of Figure 15. Although these liners both have 1/4 inch holes at one-inch spacing, the hole geometries are different. Figure 15 had holes that were sharp edged, while Figure 17 holes are countersunk on both sides of the liner giving a different hole edge geometry, thus noticeably changing the screeching effects. This countersinking seems to lower the maximum frequency of screech. An additional note to be made is the fact that at close examination most of these frequency plateaus are not perfectly constant, but increase slightly with Mach number. An answer for this effect may be that the convective velocity increases thus shortening the period and raising the frequency.

The excited frequencies may correspond to certain eigenfrequencies of the cavity-liner combination similar to that in the edgetone as examined by Power[1]. The edgetone in Powell's

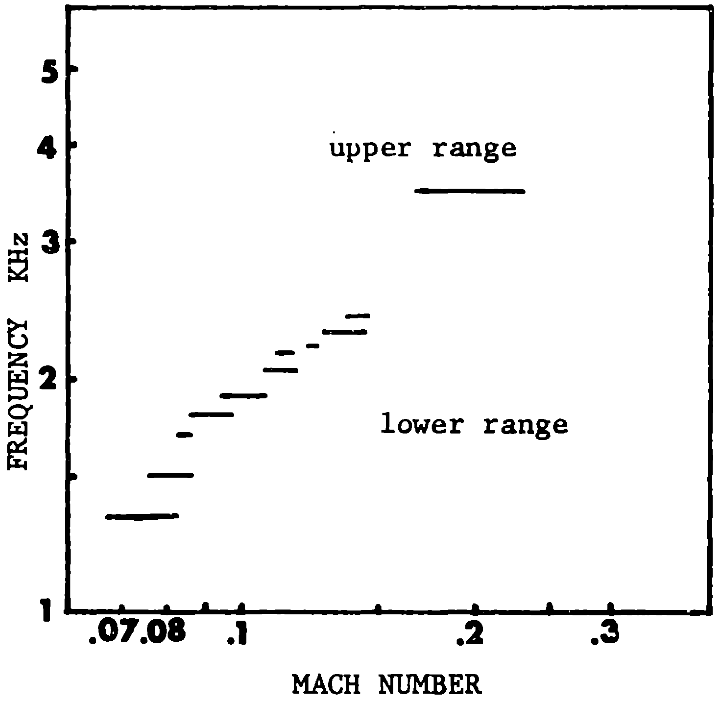


Figure 16: Steplike response of screeching liner (1/4" hole, 2" spacing).

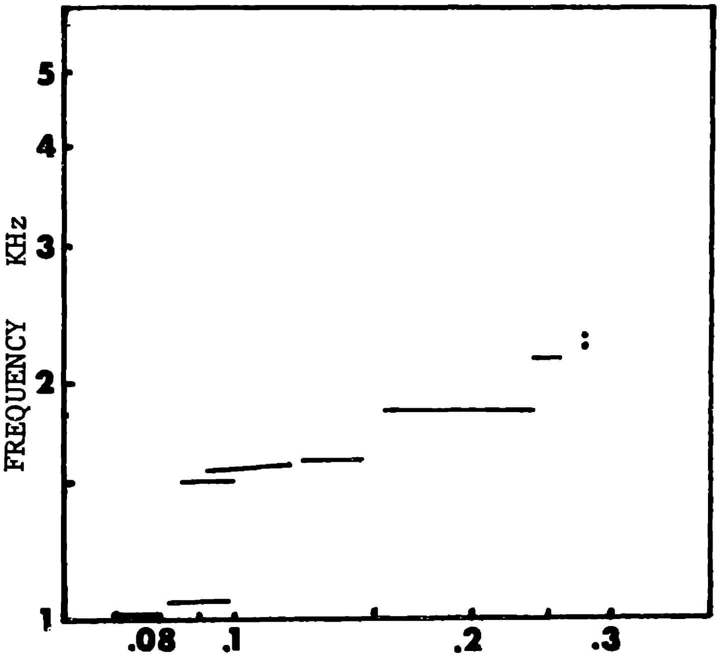


Figure 17: Steplike response of screeching liner (1/4"hole, 1"spacing). Countersunk hole configuration

experiment had the same hysteresis effects and frequency jumps as shown here. Also in a paper by Nyborg et al [3] the marked effects of having a resonator adjacent to an edgetone generator were shown. The tones produced in this particular paper seem to be governed by the eigenvalues of the resonator. The experimentation of Chapter IV is formed to investigate the effect of the resonator backing.

3.8 The Response of the Highly Perforated Liner

In addition to the investigations earlier in the chapter a short experiment was performed with a highly perforated liner backed with the standard one-inch cavities. The liner exhibited a spectrum as shown in Appendix A-III-28 through A-III-30. As one can see, many frequencies are excited in contrast to the previous liners. An obvious reason for this would be the fact that there is a more irregular surface and therefore more characteristic feedback distances. The perturbations produced at a hole could be reflected back from many other neighboring holes. Reflections could be from its nearest neighbor and also 2, 3 or more holes away. The idea of reflections from more than the nearest hole can figure here since the holes are very close in contrast to the previous liners where the minimum distance was one inch. This multiple feedback could not work well for larger distances because as we have shown earlier with 3 and 4-inch spacing that the excitation becomes extremely weak.

The spectra here have many peaks that don't seem to correspond to any expected duct modes, showing that a more random hole arrangement gives a more random exhibition of screech. A note to be made is that the peaks did increase in frequency as the flow velocity increased which gives the same type of response as the liners earlier in the chapter.

This may be the basis for the thought of making liner perforations completely random to effectively spread the acoustical energy over the spectrum instead of directing it into a discrete tone as seems to happen in previous uniform liners.

3.9 Conclusions

A general thought of most investigators of this and similar phenomena is that the instability producing the screech begins with the production of a series of vortices produced and shed at each hole. This perturbation must somehow be transmitted or convected with the flow and either amplified or fed back by reflections to reinforce the next vortex or an integer number of vortices after the first one.

From the data collected in this chapter one can see that change in hole size and spacing does in fact change the response of the liner-duct configuration, but pinpointing the exact source of this instability is the major problem.

CHAPTER IV

EFFECT OF CAVITY GEOMETRY CHANGE

4.1 Experimentation

In this chapter the effect of changing the geometry of the cavities backing the perforated liner is investigated. Examining this data can help us determine the role that the cavity plays in sound production.

The first half of the chapter has mainly to do with cavity volume change due to lengthening the cavity. All other parameters such as duct length, cross section and liner plate geometry (1/4 inch holes spaced 2 inches apart) stay constant here. The cavity cross section is at all times 3/4 inch by 7/8 inch but the cavity length is changed from one inch to 70 inches (entire liner length) at the specified intervals (Figure 18).

The second half of the chapter investigates the effect of a change in cavity depth. If a feedback instability is occurring by reflection of sound from the cavity bottom, then this experiment will reveal this. Since it was found that the screech occurs at full cavity length (70 inches), this length was held constant and only the depth was changed by raising a back plate in the cavity (Figure 20).

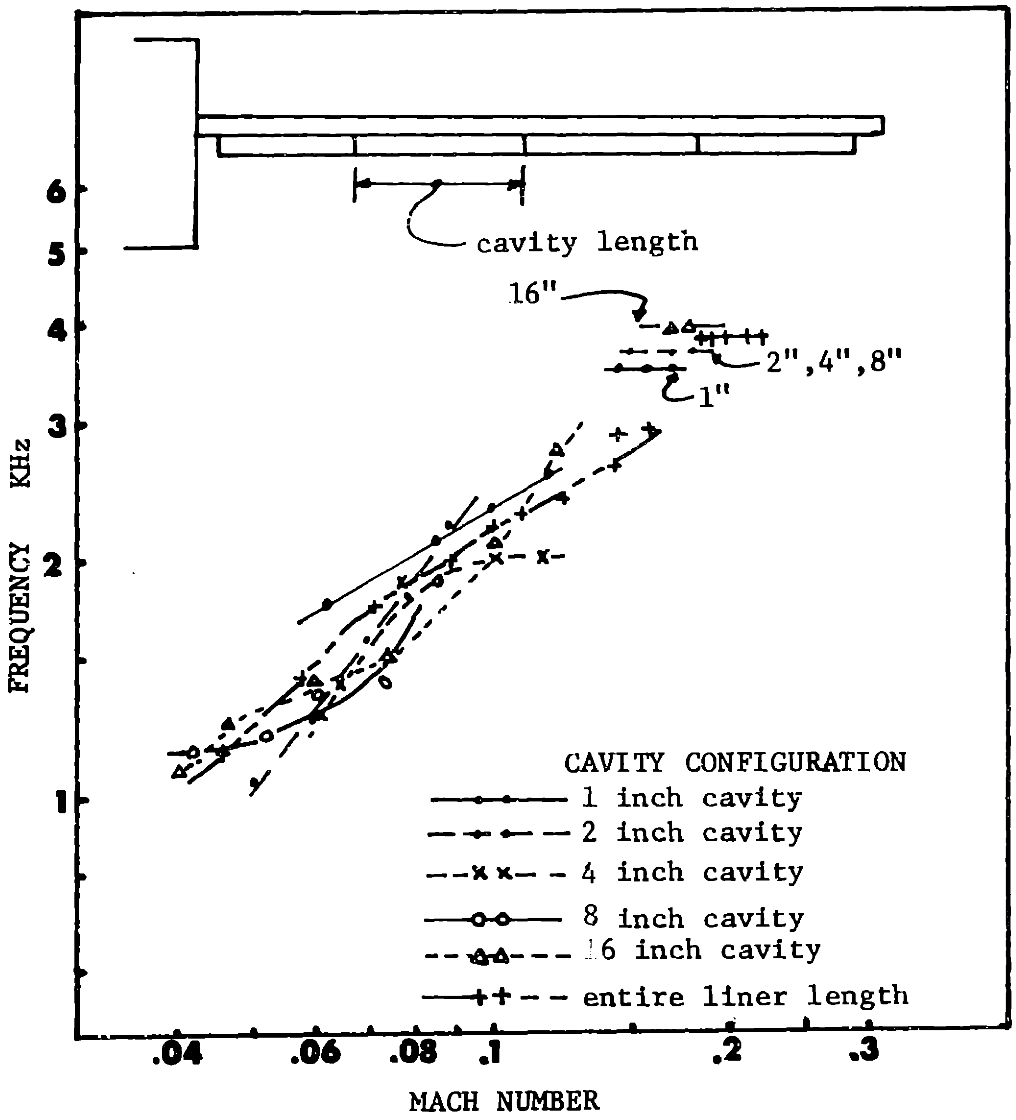


Figure 18: The effect of lengthening cavity backing on perforated liner.

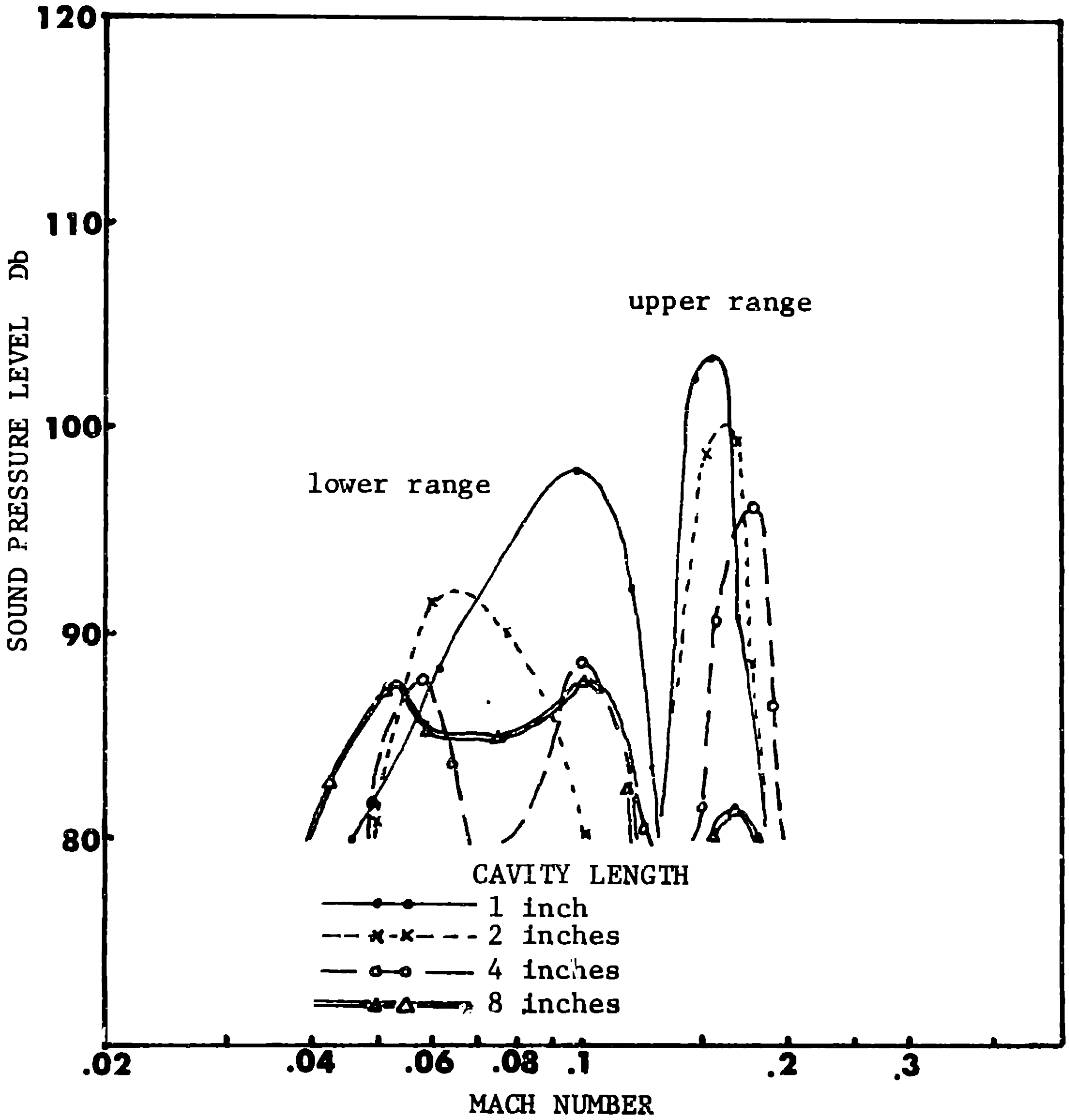


Figure 19: Sound level vs. Mach number for various cavity lengths with 7/8" cavity depth constant (1/4" hole, 2" spacing).

4.2 Cavity Length Change

Appendices A-IV-1 through A-IV-7 show some typical spectra at several cavity lengths. From the graph (Figure 18) we see that the screech frequency does not seem to change in any obvious pattern and all looks to be close enough together to be the same taking into account varying of frequency along constant frequency plateaus as in Section 3.7. The upper range (constant range) seem to change somewhat with cavity length increase, but in no immediately obvious pattern.

Looking at the magnitude plot (Figure 19) it is seen that the magnitude of screech does decrease somewhat with cavity length increase as well as shift. From this magnitude plot we see various shifting and splitting of magnitude peaks as length is increased, which at this time has not been analyzed in detail.

A conclusion can be made that the cavity resonance does not play a direct role in frequency determination of the instability, otherwise a drastic change in excitation frequency would have been exhibited. From this data, the upper range is seen to be slightly dependent on the cavity geometry.

4.3 Cavity Depth Change

Next the cavity depth was changed as previously described and the same conclusions seem to apply here. As seen from

Figure 20 the screech frequency seems to be within a screech envelope as before, but in this case the magnitude seems to decrease more significantly than with cavity length change.

As before this effect cannot be called a direct influence on screech frequency. If a feedback instability relied upon the depth of the cavity bottom for reflection we would expect a much more marked change in frequency with depth change.

The frequency of screech may not change significantly, but the magnitude does decrease with decreasing depth as in Figure 21. Finally when the back plate is face-to-face with the back of the perforated liner, the excitation is nearly gone. Since the frequency does not make any marked changes one could propose that the characteristic distance determining the screech frequency is not the cavity depth. Decreasing the depth, though, probably does weaken the vortex production at the hole by confining the area where the vortex forms thus weakening the entire screech mechanism. Sample spectra are shown in Figures A-IV-8 through A-IV-12. It is also interesting to note that the same type of magnitude split occurred as with length increase (Figure 21).

4.4 Conclusions

From both of these cavity geometry change experiments it can be concluded that the cavity itself does not seem to be

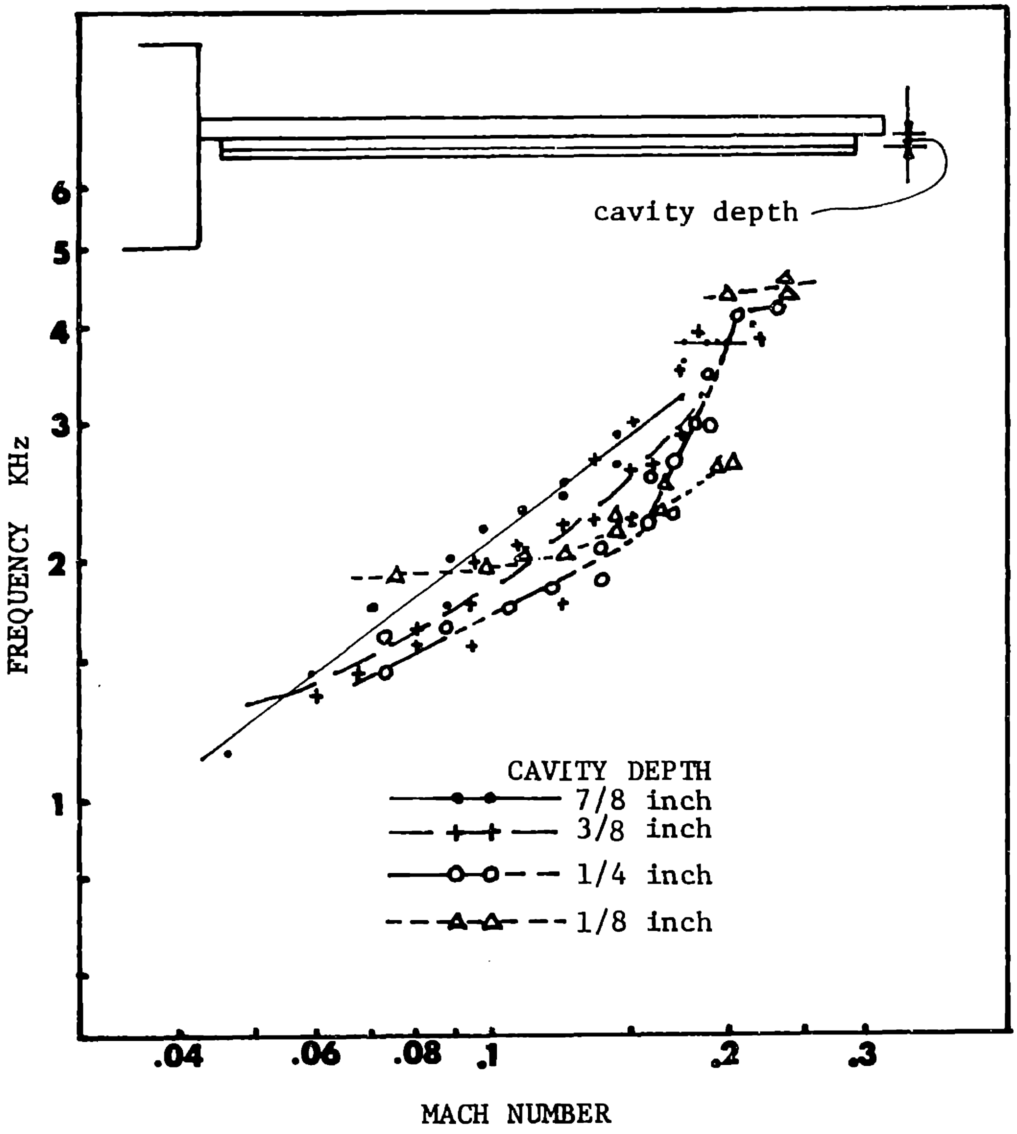


Figure 20: The effect of changing depth of perforated liner backing on screech.

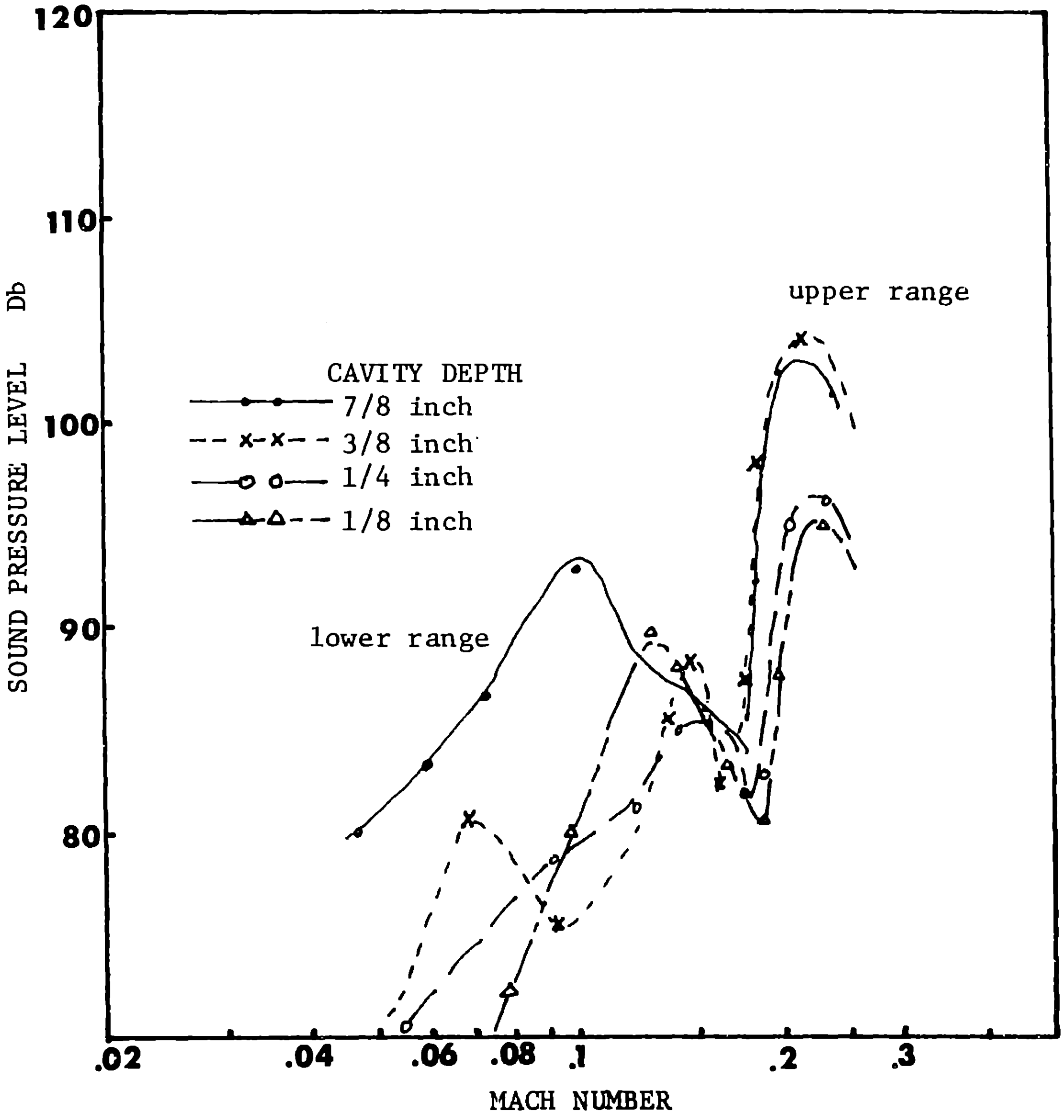


Figure 21: Sound pressure level vs. Mach number for various cavity depths. Cavity extends lengthwise over entire liner. (1/4inch hole, 2 inch spacing).

a prime cause of controlling the instability or a direct cause of an acoustic reflection or feedback. It does, however, seem to govern the magnitude and quality of the screech instability, possibly by indirectly controlling the vortex formations at the holes.

By decreasing the depth of the cavity we primarily confine the vortex production and by lengthening the cavity we effectively change the impedance of the cavity thus possibly causing a change in vortex behavior. The depth change did have a more drastic effect on the response than cavity length change.

We see that both magnitude plots (Figures 19,21) exhibited two peaks in the lower range itself which is at this time an unanswered phenomenon.

CHAPTER V

ISOLATED CASES OF LINERS WITH ONE, TWO AND THREE HOLES IN A ONE FOOT DUCT

5.1 Object and Experimental Configuration

This chapter is concerned with the investigation of liners consisting of only one, two and three holes with resonant cavity backing. The purpose of this experiment is to try to separate single hole and multiple hole excitation and compare these results to the long liners investigated in the earlier chapters.

The setup shown on each graph (Figures 22, 23 and 24) consisted of a one foot duct (7/8 inch by 3/4 inch cross section) with three removeable liners which allowed three different size holes (3/16 inch, 1/4 inch, 5/16 inch) at single and multiple hole configurations. Each hole was backed with a 1 inch by 3/4 inch by 7/8 inch undamped cavity. Air was drawn through the duct as before with a microphone placed at the inlet typical to previous investigations.

5.2 Results

It is immediately seen from Appendices A-V-1 through A-V-10 that there is a set of discrete excitations in each array. These tones behaved somewhat differently than that of the long arrays of previous chapters in that there was not a set of excitation frequencies that changed with Mach number. The

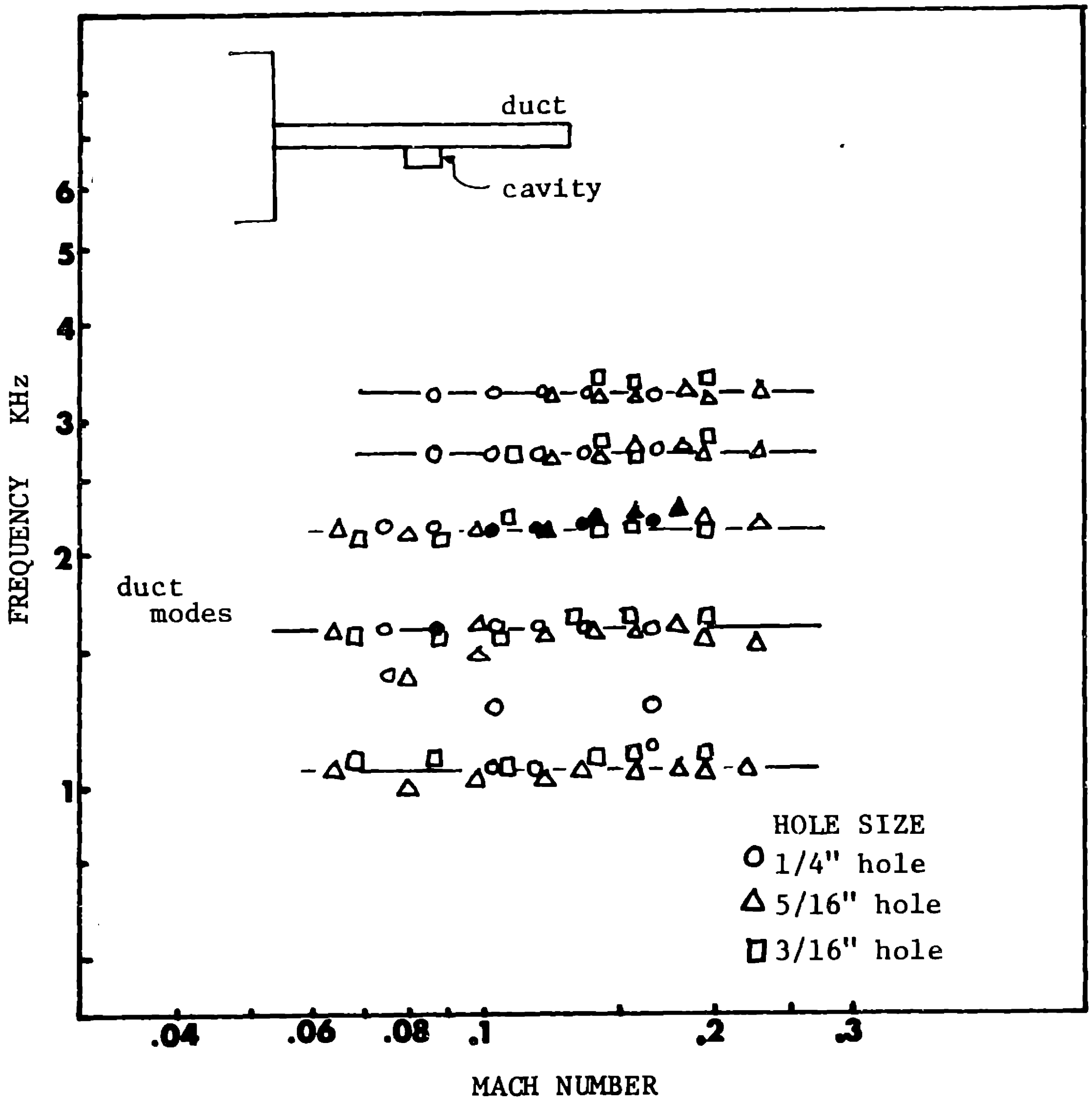
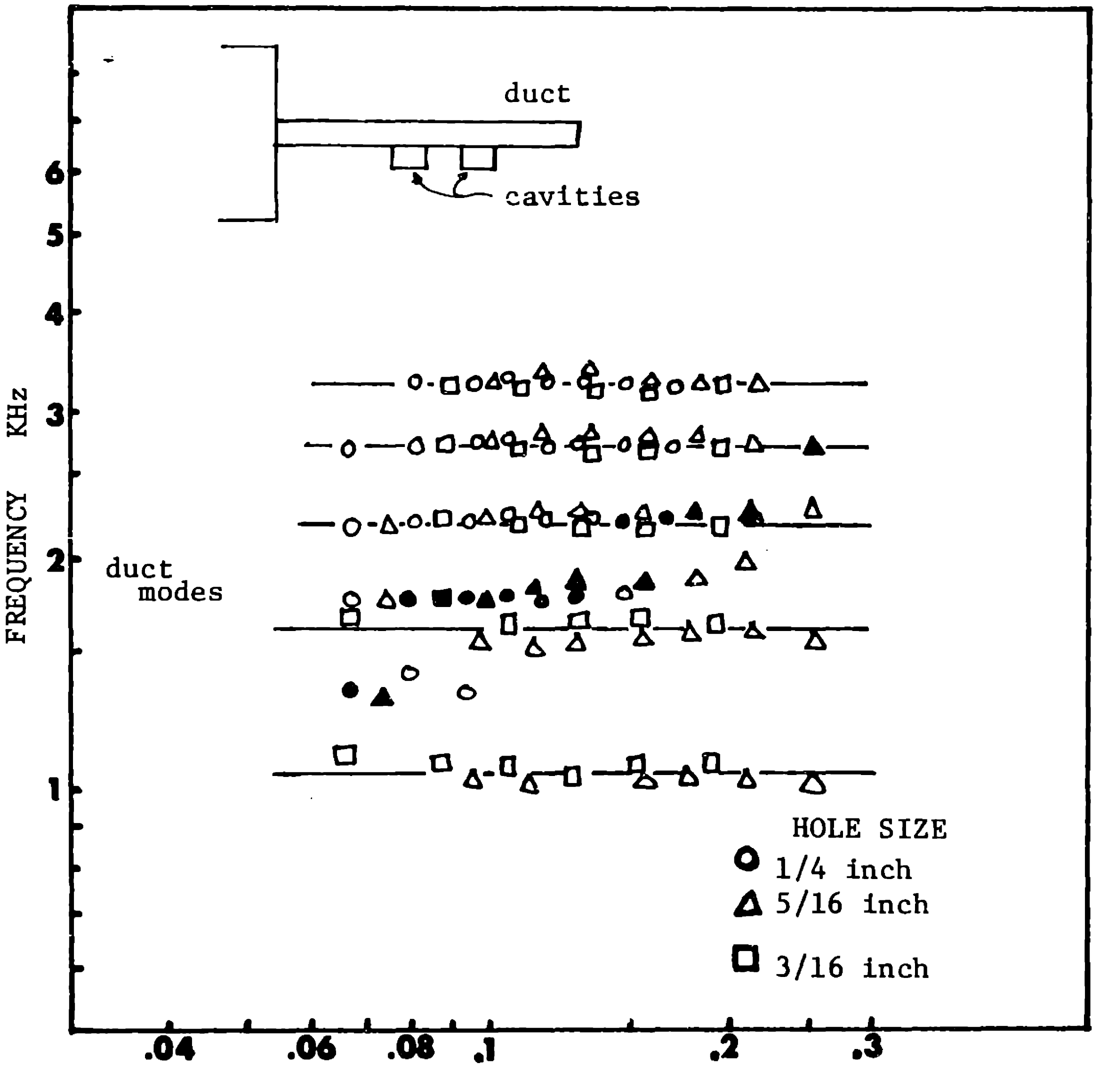


Figure 22: Response of a single hole-resonator in a one foot long duct. Solid lines are axial duct modes excited by turbulent flow in the duct with solid liner (no holes). Filled in points on graph are points of significantly high amplitude.



MACH NUMBER

Figure 23: Response of 2 resonators at 2 inch spacing in a one foot long duct. Solid lines are axial duct modes excited by turbulent flow in the solid(no holes) duct. Filled in points on graph are points of significantly higher amplitude.

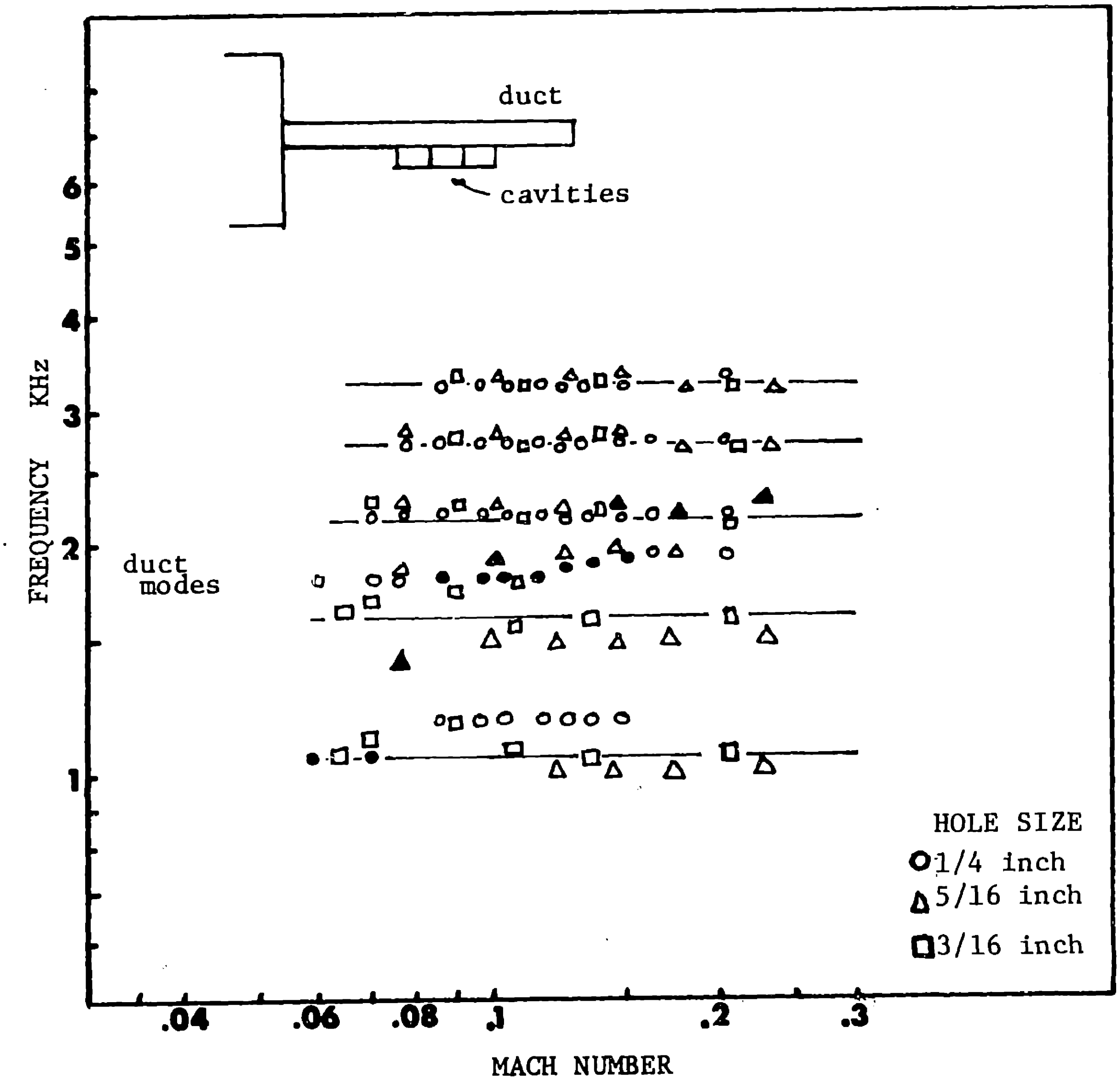


Figure 24: Response of 3 resonators at one inch spacing in a one foot long duct. Solid lines are axial duct modes excited by turbulent flow in the solid (no holes) duct. Filled in points on graph are points of significantly higher amplitude.

excitation frequencies seemed to stay quite constant with Mach number except for the excitation present between the duct modes in the 2 and 3 hole liners as will be shown.

As seen from Figures 22, 23 and 24, there were excitations at the axial duct modes of the one foot duct with the excitation magnitude increasing accordingly with the increase in the number of holes. But we see, though, that there is an excitation present in the 2 and 3 hole liners (Figures 23, 24) that is virtually missing in the single hole liner (Figure 22). This particular excitation does increase in frequency with Mach number and is of significantly higher magnitude as shown by the darkened points on the graph.

The fundamental axial duct modes seem to be excited and all of the peaks in the appendix graphs are at the modal intervals except the tones produced with the 2 and 3 hole liners which is between the duct modes. Also it is a general conclusion that the change in impedance by adding these liners did not seem to appreciably change the modal response. For example, by looking at the 1/4 inch holes (Appendices A-V-1 to A-V-4), we see that the peaks follow the modal peaks of the control duct except for the peak at about 1650 Hz at low Mach numbers that increases to about 1800 Hz shown in Figures 23 and 24. For the single hole configuration we see that all the peaks correspond to the modal peaks although the magnitude is greater than the control duct.

It is interesting to note that with the 3/16 holes, the same type of independent response between the modes was not as pronounced showing, as in Chapter 3, that the 3/16 hole with this 1/8 inch liner thickness was approximately on the threshold of excitation where with hole sizes smaller than this did not exhibit these excitations.

Going back to the idea of convection and feedback as presented in Section 3.6 using .8V as the convective velocity we see that reasonable results are obtained using this formula with an integer multiple of frequency of 2 for the 2 inch spaced liner and 1 for the one inch spacing. We have as tabulated:

Characteristic frequency:

$$\nu = \frac{12C}{D} \left[\frac{.8M(1-M)}{1 - .2M} \right]$$

Mach Number	ν(Hz)	nν(n=2)
.08	460	919
.10	564	1128
.15	807	1615
.20	1068	2137

By taking these results and comparing them to Figure 23, we see there is a close correlation between these results and the darkened points on the graph except at low Mach numbers.

For the one-inch spacing we get:

Mach Number	ν(Hz)	$n\nu$(n=1)
.08	1072	1072
.1	1316	1316
.15	1884	1884
.2	2389	2389

Again, if we compare these points with the filled in points on the graph we get a good correlation. This gives us a reasonable explanation of how these instabilities are being amplified, although this theory does leave out the dependence of hole size if there exists any at all in this configuration.

5.3 Conclusions

From these observations, we may conclude that it is the interaction between holes and not only an instability produced by a single hole.

The fact that the 2 inch and one inch spacing exhibited approximately the same response is left unexplained for the time being. The only immediate answer that can be given is that possible with the 3 hole liner the hole interaction was taking place between the first and third hole thus making this also a 2 inch hole interaction distance as in the 2 hole liner.

Comparison to the long liners of Chapter 3 is quite difficult at this point. The characteristics of the response of these ducts is quite different, but a fair comparison cannot be made unless these isolated cases of one, two and three holes are tested in a long duct as in Chapter 3 to get away from this strong modal excitation.

It is also worth noting that the frequency of excitation can be obtained analytically using the feedback analysis in Chapter 3 with .8V as the convective velocity. This gives us an important base that may be used to form future experiments that may verify this theory.

CHAPTER VI

INLET AND OUTLET NOISE AND ITS RELATION TO BROADBAND LINER NOISE

6.1 Apparatus

In this Chapter, the effect of inlet and exit noise and the relation of these to the overall duct noise level is investigated. The object is to determine whether the effect of inlet and exit noise from a duct masks any noise produced by the liner itself.

The experimental apparatus simply consisted of three ducts (7/8 inch by 3/4 inch cross section) of one foot, three foot and six foot lengths. A pitot tube was mounted about 6 inches from the exit and the ducts were mounted to a surge tank which was hooked to a steam ejector to provide a sufficiently quiet source of suction. A microphone was mounted in the surge tank and also in front of the duct inlet as shown in Figure 1. The inlet microphone was placed such that it did not obstruct any flow up to the maximum Mach number investigated. The signals were then fed through a spectrum analyzer, spectrum averager (averaging 16 spectra) and then plotted on an X-Y plotter. Various flow rates were recorded with and without a foam lining. The foam lining consisted of a 3/16 inch foam placed along one side of the entire length of each duct. This liner gave only a slightly smaller cross section to the duct which allowed slightly higher flow rates. The maximum flow rate is limited by the steam ejector.

A note to be made is that the pitot tube placement is not too critical for these low Mach numbers (.02 - .25). For a Mach number of about .2, the flow deviated from the front of the 6 foot duct to the end only about 10 feet/sec., which is allowable. At higher Mach numbers, careful consideration would have to be made as to the flow rate measuring technique.

6.2 Data Examination

Appendices A-VI-1 through A-VI-7 are sample spectra for the unlined ducts. It is seen that the exit noise is quite dominant in the low frequency range of less than 1000 Hz, whereas the inlet noise dominates the mid-frequency range (about 5000 Hz at maximum). The inlet noise seems to excite the exit noise significantly as seen from the increase in the exit noise level in the range of 5000 Hz. It is clearly evident from simple calculations of:

$f = c/2l$ (where f is the frequency;
c is sound speed and
l is the duct length)

that the peaks in the inlet noise correspond to the excitation of the first axial mode in the duct. The divisions are not quite as evident in the 6 foot duct because they are small and easily masked by the broadband noise. The peaks in the

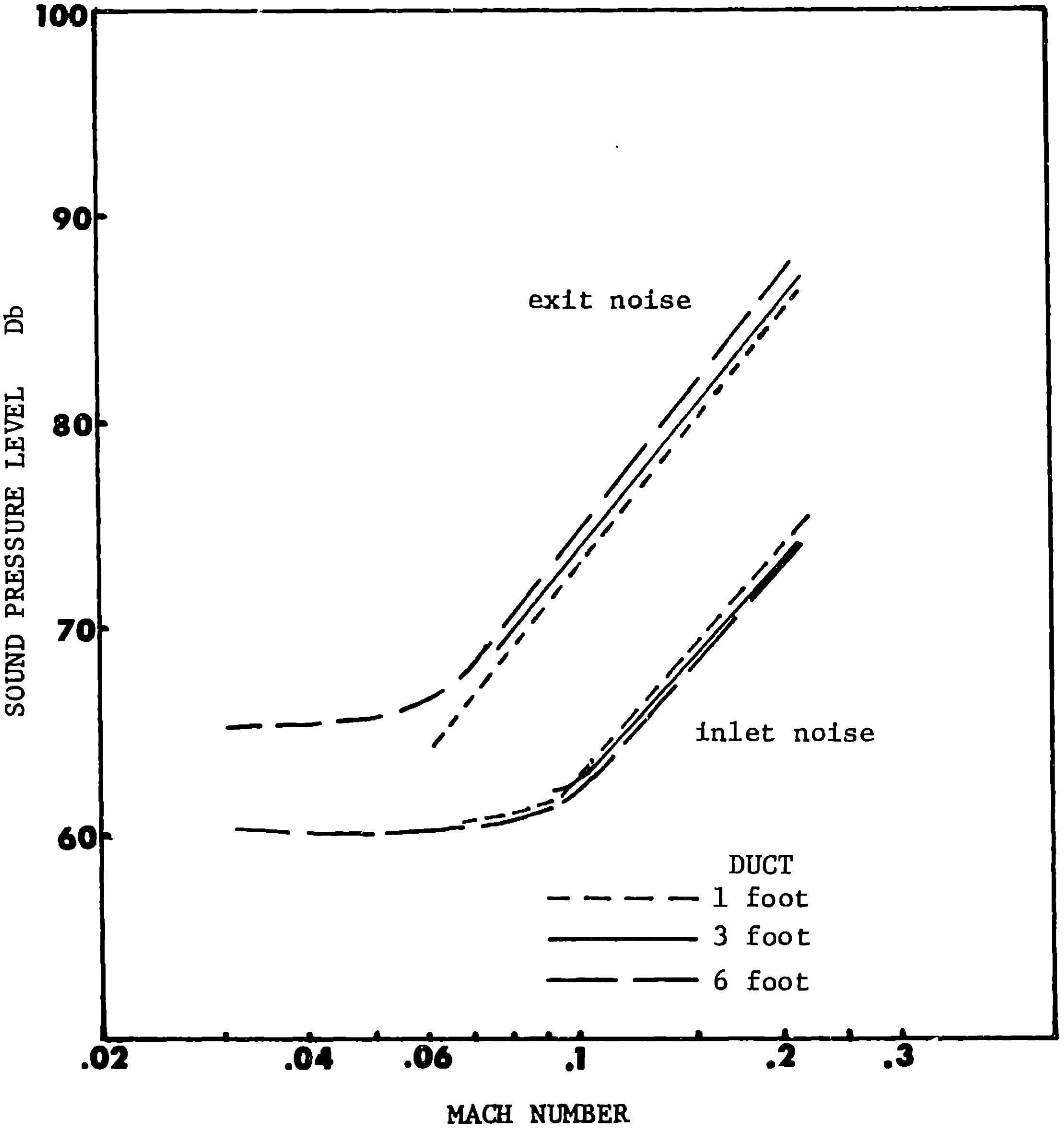


Figure 25: Comparison of noise levels of 1, 3, and 6 foot unlined ducts.

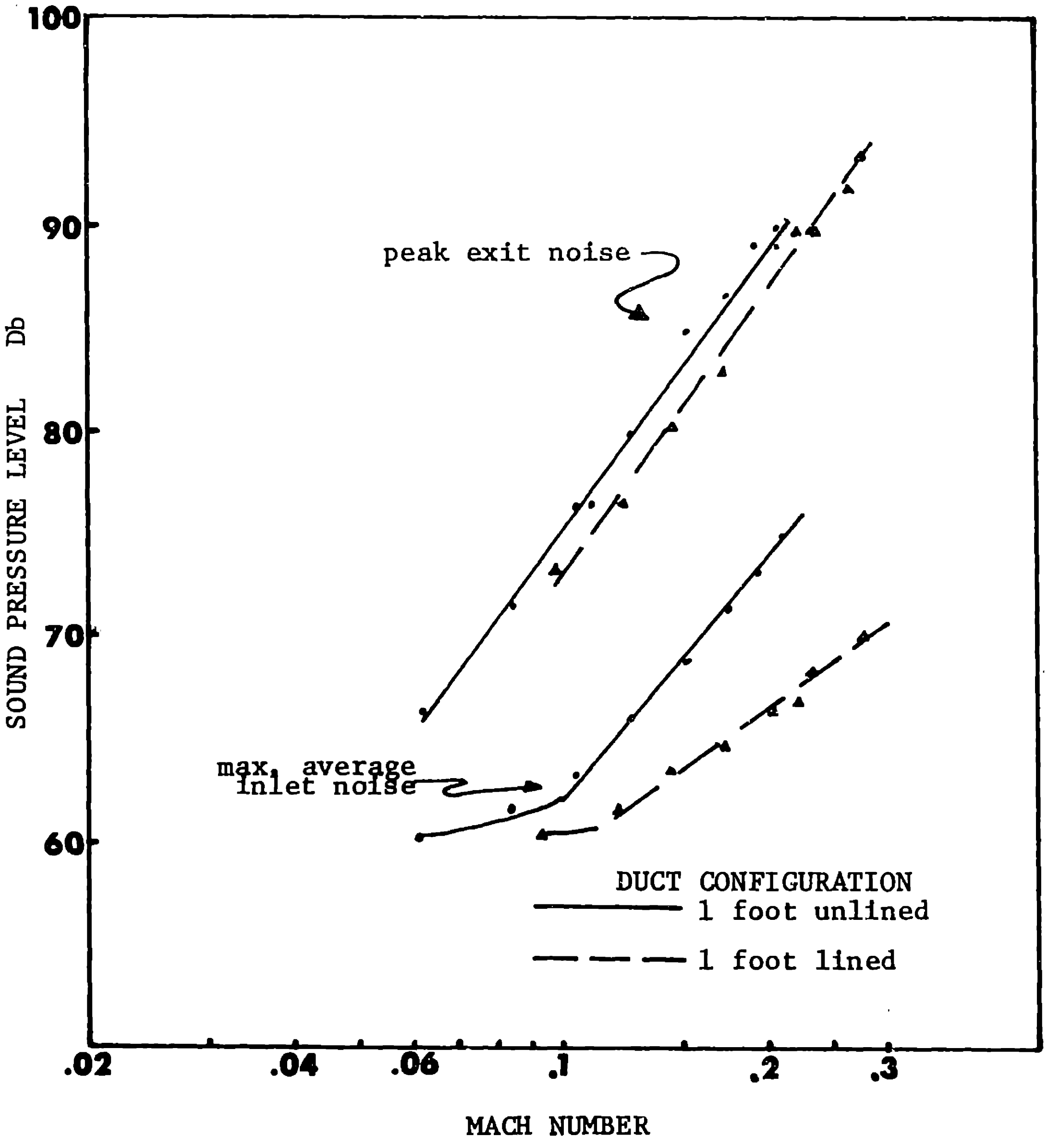


Figure 26: The effect of duct lining on inlet and exit noise of a one foot duct.

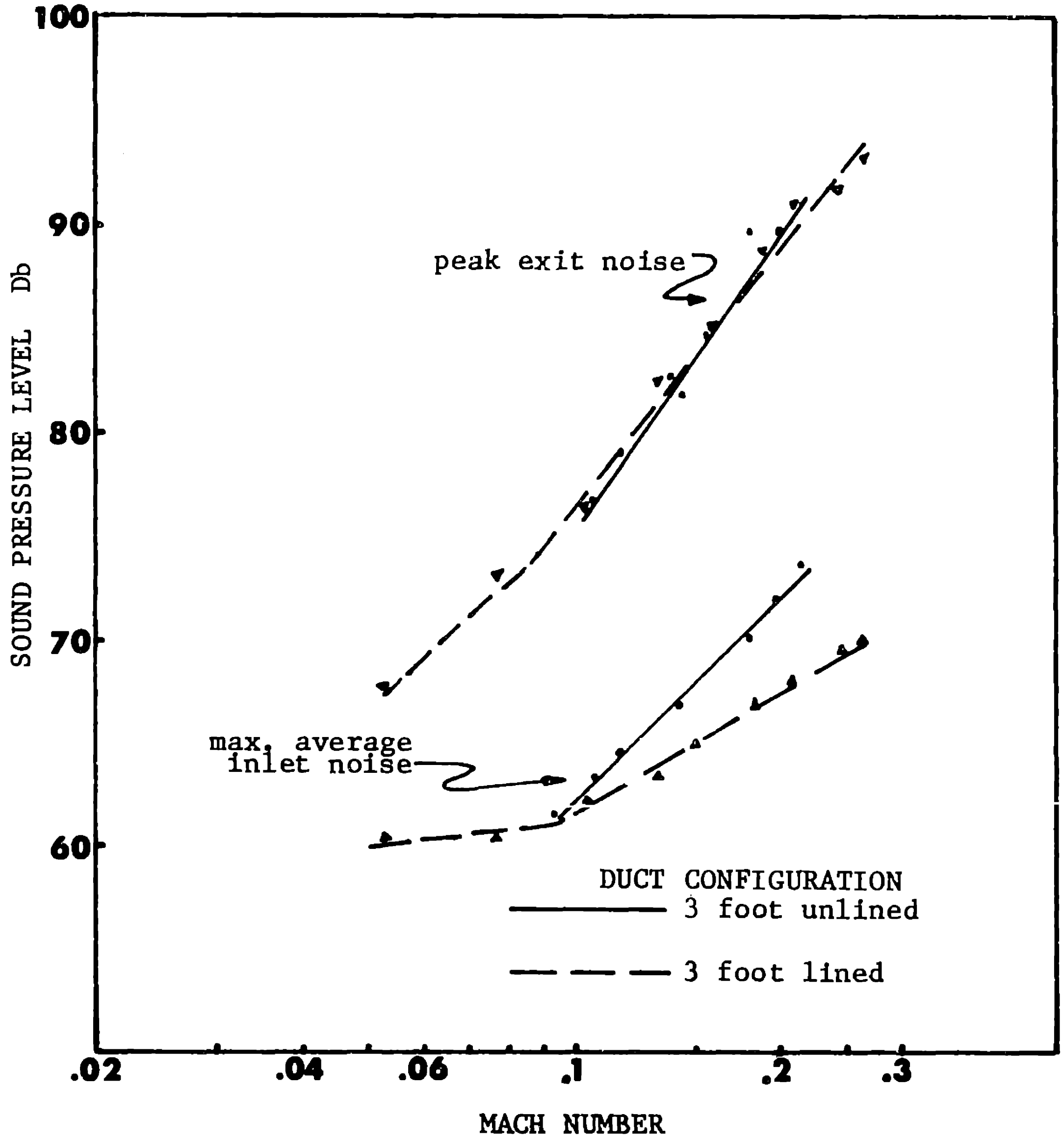


Figure 27: The effect of duct lining on inlet and exit noise of a 3 foot duct.

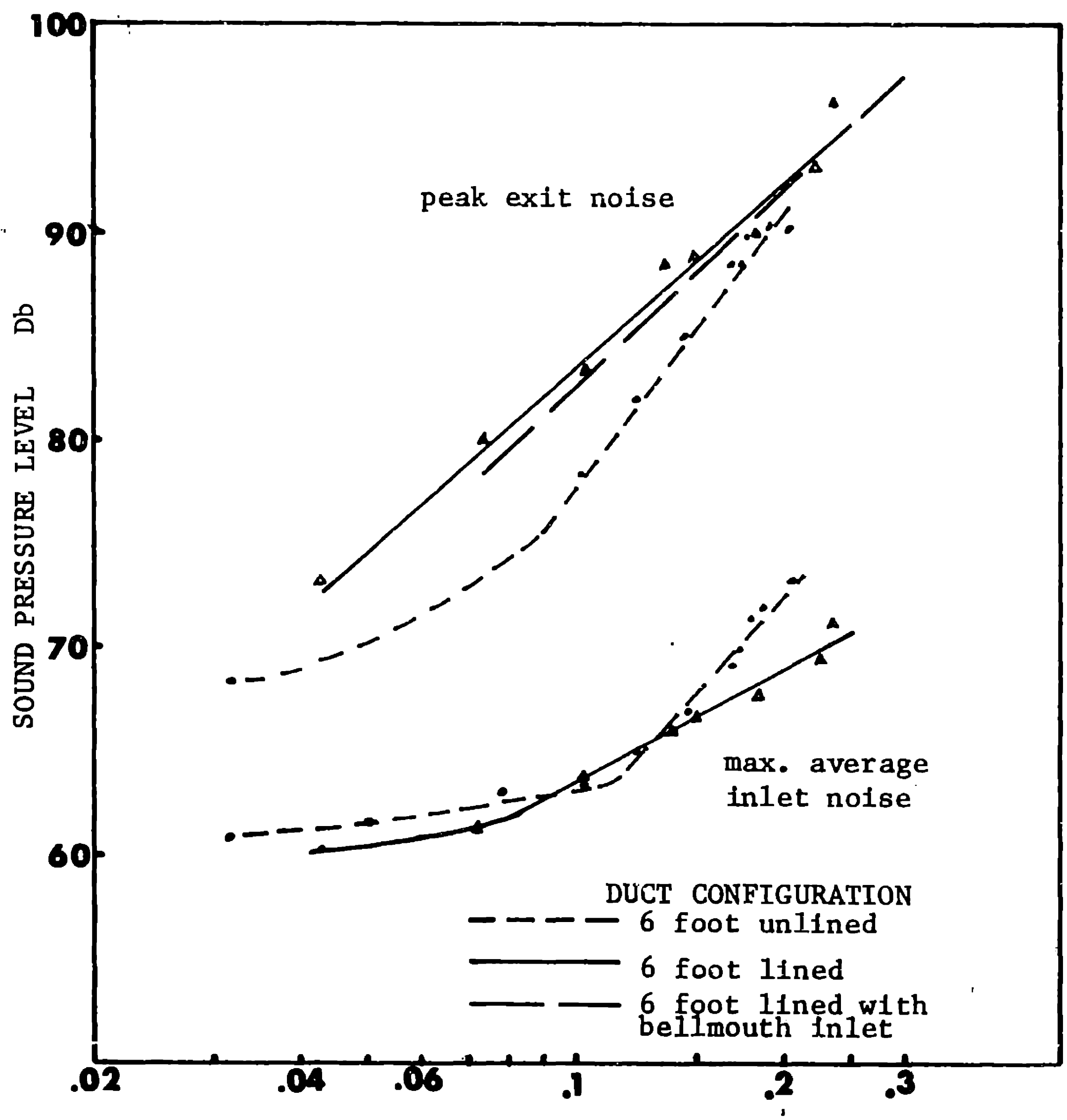


Figure 28: The effect of duct lining and bellmouth inlet on inlet and exit noise of a 6 foot duct.

exit noise seem to correspond to the fundamental cross mode (m=0, n=1) of the surge tank. It is seen from Figure 25 that the length of the duct does not appreciably effect the noise level of either the inlet or exit noise.

Next we look at the lined ducts. In Appendices A-VI-8 through A-VI-13, it is immediately seen that the axial modes exited by the inlet noise are damped out resulting in lower peaks and lower average inlet noise levels as shown in Figures 26, 27, and 28. The exit level, as shown by these figures, seems to increase with increasing duct length. As seen in Figures 26, 27, and 28, the cross modes in the exit are excited to a much greater extent resulting in a higher peak noise level.

Next, a bellmouth was added to see the change in exit noise. The inlet noise cannot be compared fairly to that without the bellmouth, because the placement of the microphone presents a problem. The characteristics of the inlet spectra, though, can be observed. From Appendices A-VI-14 and A-VI-15, is seen that with this particular bellmouth only the higher frequencies greater than 7 KHz are sufficiently subdued, therefore, the bellmouth does not allow us to subdue the 5 KHz peak to observe the effect on the similarly excited 5 KHz peak in the exit noise.

6.3 Summary

In summary, we see that the inlet and exit noise from a duct with flow may be much more significant than liner noise itself. The addition of the liner did not seem to increase the entire broadband base. The liner, though, is seen to have indirect effects on the inlet and exit noise by dampening fundamental duct mode excitation, therefore, decreasing inlet noise. Also, the exit noise level seemed to increase due to increased excitation of the tank cross mode excitation in the mid-range of the spectrum. The addition of the liner seems to have opposite effects on the inlet and exit noise. A further investigation may include an attempt to cut the inlet noise around 5 KHz to see if the 5 KHz increase in exit noise is also decreased, assuming the idea that the inlet noise is propagating down the duct.

CHAPTER VII

CONCLUSIONS AND DIRECTIONS OF FUTURE RESEARCH

The chapters of this thesis have presented specific sections of experimental investigations and results with comment and analytical discussion where applicable. Here we will quickly review the chapters and add a comment on future investigations.

7.1 Chapter III

Chapter III presents the results of the screeching of various liner geometries. A basic conclusion seems to be the fact that there exists two definite ranges of screech instability. The upper range seems to be at constant frequency over a substantial Mach number range. The lower range, conversely, is a screech that has a frequency that is dependent upon Mach number. This screeching, though, only increases along specific plateaus as shown in Section 3.7. These plateaus are possibly eigenvalues of a specific cavity resonance or feedback instability, although further experimentation will be needed to pinpoint the basic source of this effect.

We quickly attempted the use of two theories to possibly find the mechanism causing the screech. Both Mechel's[7] partial wave theory for the upper range of excitation and the multiple hole feedback theory for the lower range seem to make a certain amount of sense.

The high perforated liner was studied to a very limited extent and is actually a closer model to actual liners used in practice, but its complexity forces us to first try to understand simpler configurations, as in this thesis. We did see that the more random hole configuration gave a correspondingly more random response. This could possibly indicate that the more random the hole placement, the higher the number of excited frequencies. If we possibly can find ways to spread the acoustic energy widely over the spectrum we may be able to significantly cut the magnitude.

7.2 Chapter IV

Chapter IV basically revealed that this screech is not highly dependent upon the cavity behind the liner plate, as was expected, but is much more dependent upon the liner plate configuration itself. This fact does, though, allow us to concentrate on theories concerning hole-to-hole interaction rather than cavity resonances and the like.

7.3 Chapter V

Chapter V indicates that there does exist an interaction between the holes themselves. This was shown by the fact that the single hole liner in our configuration only excited the normal fundamental axial duct modes where the two and three hole liners excited the duct modes and also produced a discrete excitation between the normal duct modes that was dependent upon Mach number. This, still, was another experiment that seems to confirm the idea that the screech is produced by hole interaction.

7.4 Chapter VI

In Chapter VI we broke away from the perforated liners and attempted to throw some light upon the controversy of the broadband noise produced by rough foam type liners. Many investigators believe that the noise produced by the rough liner limits the length of the liner that can be used before the regeneration of noise be the liner is greater than that which is attenuated. As this may be and certainly is the case for certain configurations, here we are trying to show that the noise generated by inlet and exit noise is substantially more significant than the broadband liner noise. This seems to be the case for the configurations tested here. From the way that these ducts reacted in both the lined and unlined configuration, I think that this type of result warrants further investigation into the design of inlet, transition and exit configurations for ducts.

7.5 Further Research

I believe that this thesis begins to set the basis for some future experimentation which must go hand in hand with theoretical development in order to get an answer to these noise producing mechanisms. Because of the large amount of data collected here, high levels of detail were not possible, therefore, the reader should not only read the text, but he should closely examine the graphs and sample spectra for himself so that he may also formulate his own ideas for future research.

A wise method to approach this would be to concentrate upon one aspect of this liner noise such as hole-to-hole interaction and first develop some theory that might be later substantiated by experiment. For instance, just the investigation and comparison of one and two hole resonators in a duct along with theoretical backing could be very important and hopefully applicable to long arrays and even actual configurations used in practice.

After some theory is developed, then methods of damping these instabilities without changing the duct flow or the liner attenuation and effectiveness should be investigated. As we see, not only the theoretical answers to the noise producing mechanism but also an efficient method of reducing this liner noise is where we should concentrate future efforts.

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APPENDIX

The appendix is a collection of sample spectra taken from the large amount of data received. Much of these spectra are referred to in the text.

Chapter III Sample Spectra

68 1/4" holes at one inch spacing

Mach .084 - .243 ...... (A-III-1) - (A-III-7)

34 1/4" holes at two inch spacing

Mach .070 - .273 ...... (A-III-8) - (A-III-16)

68 1/4" holes at one inch spacing

High Mach number - approaching 1 A-III-17 - A-III-19

Slow increase in flow speed showing frequency steps

A-III-20 - A-III-27

Highly perforated liner

Mach .127 - .200 ...... (A-III-28) - (A-III-30)

Chapter IV

Control - No holes ...... (A-IV-1)

for 6 foot duct

34 1/4" holes at two inch spacing

cavity length change from 1" to entire liner length

......(A-IV-2)

Mach number approximately constant - A-IV-7

34 1/4" holes at two inch spacing

cavity depth change from 7/8" to face-to-face backing .... A-IV-8 - A-IV-7

Mach number approximately constant

Chapter V

Control no holes for 1 foot duct showing axial duct modes A-V-1

One foot duct with 1, 2 and 3 1/4" hole-resonators Mach number approx. constant A-V-2 - A-V-4

One foot duct with 1, 2, and 3 5/16" hole-resonators Mach number approx. const. A-V-5 - A-V-7

One foot duct with 1, 2, and 3 3/16 hole-resonators Mach number approx. const. A-V-8 - A-V-10

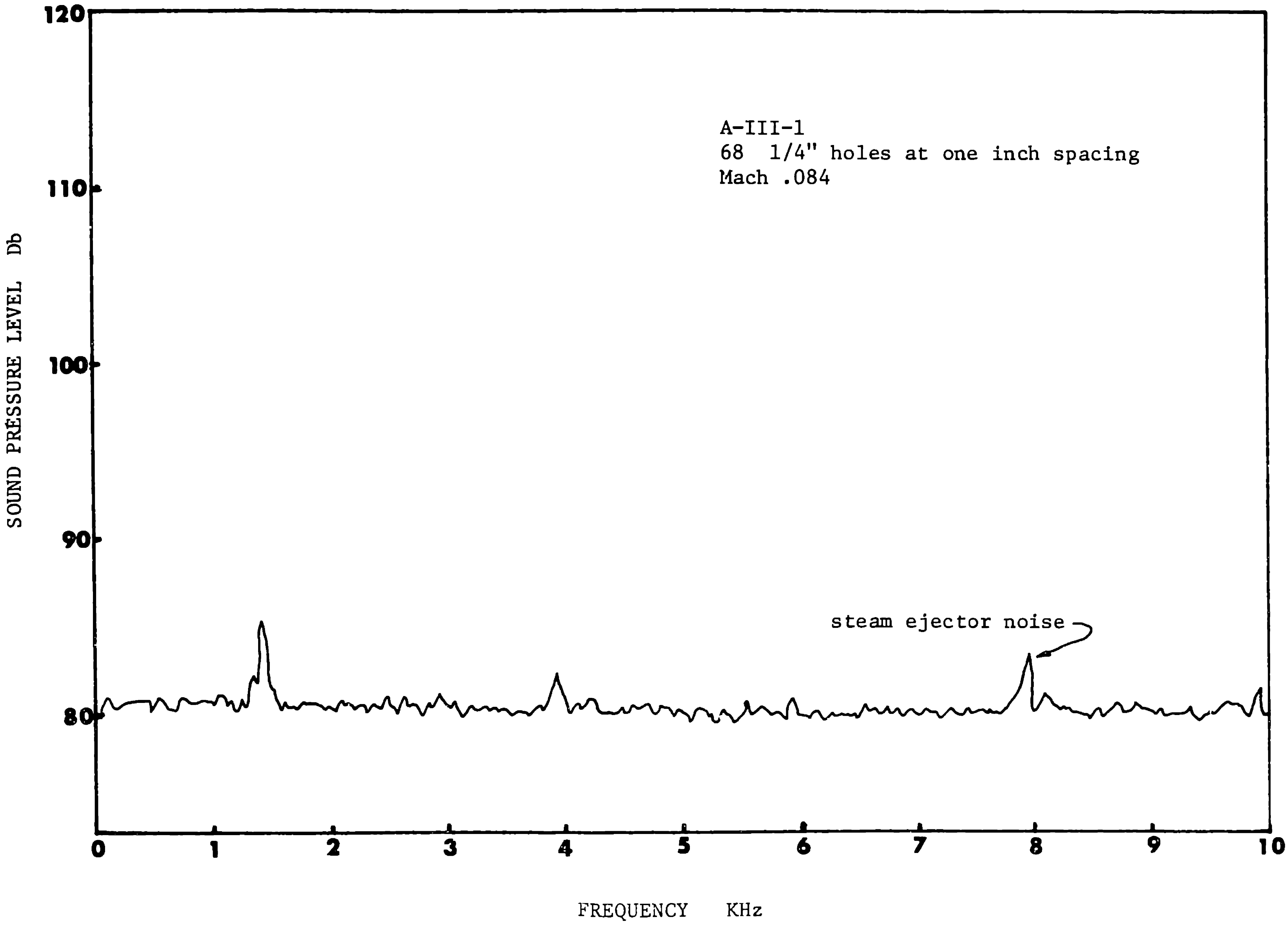
Chapter VI

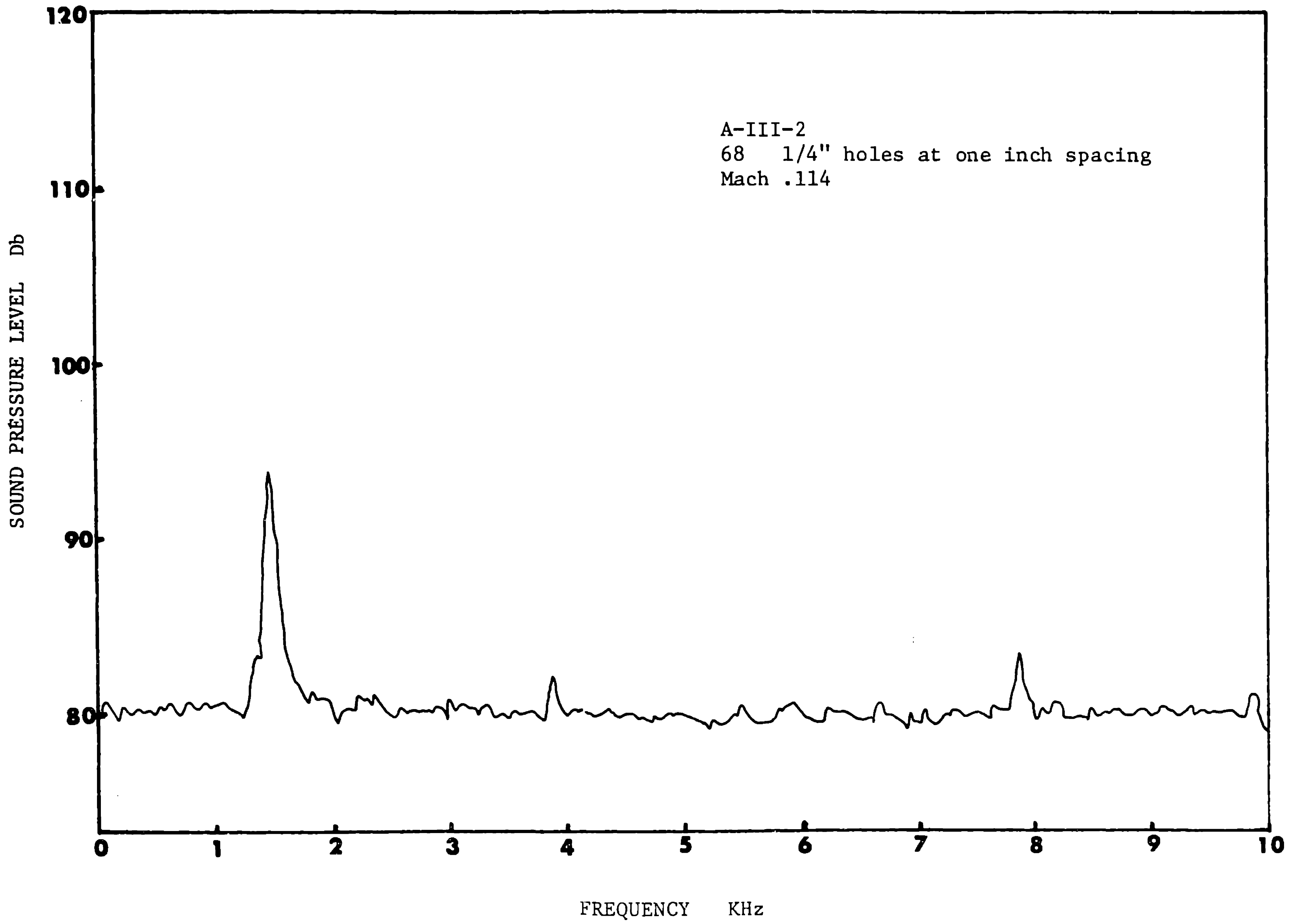
Control inlet and exit noise - no flow A-VI-1

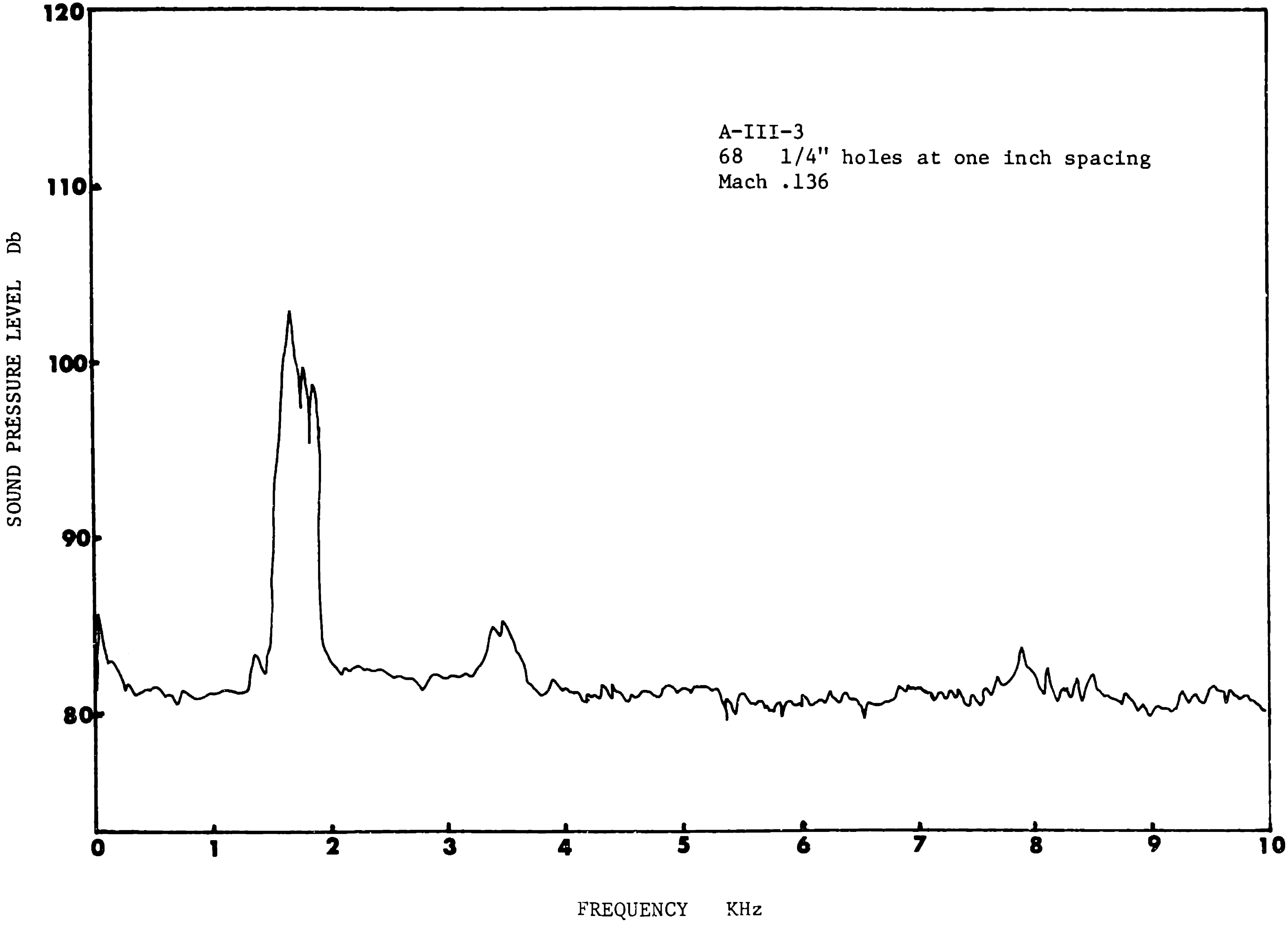
Inlet and exit noise - One foot, 3 foot and 6 foot unlined ducts at each at low and high Mach number A-VI-2 - A-VI-7

Inlet and exit noise - one foot, 3 foot and 6 foot lined ducts each at low and high Mach number A-VI-8 - A-VI-13

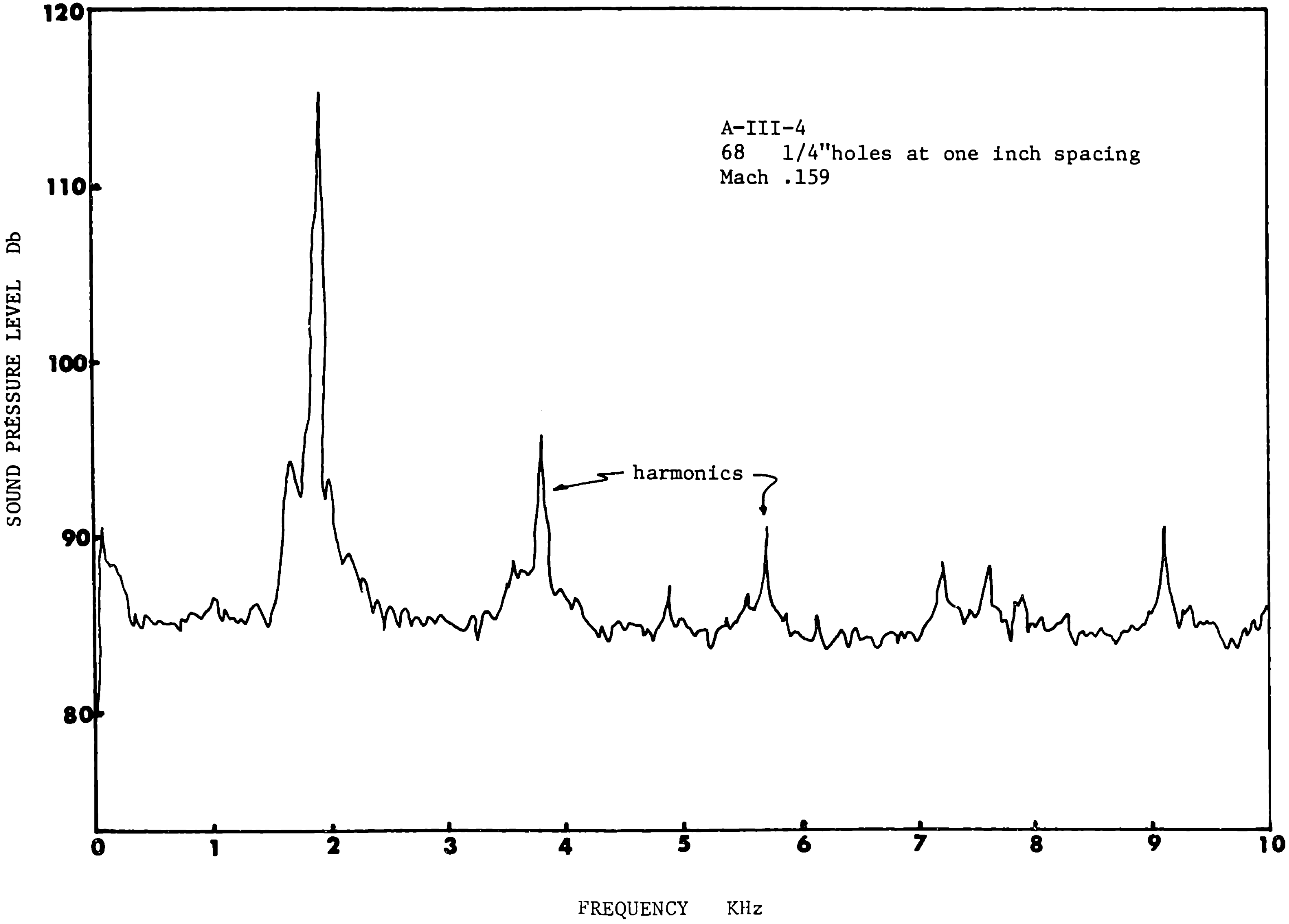
Inlet and exit noise - 6 foot lined duct with bellmouth inlet A-VI-14 - A-VI-15

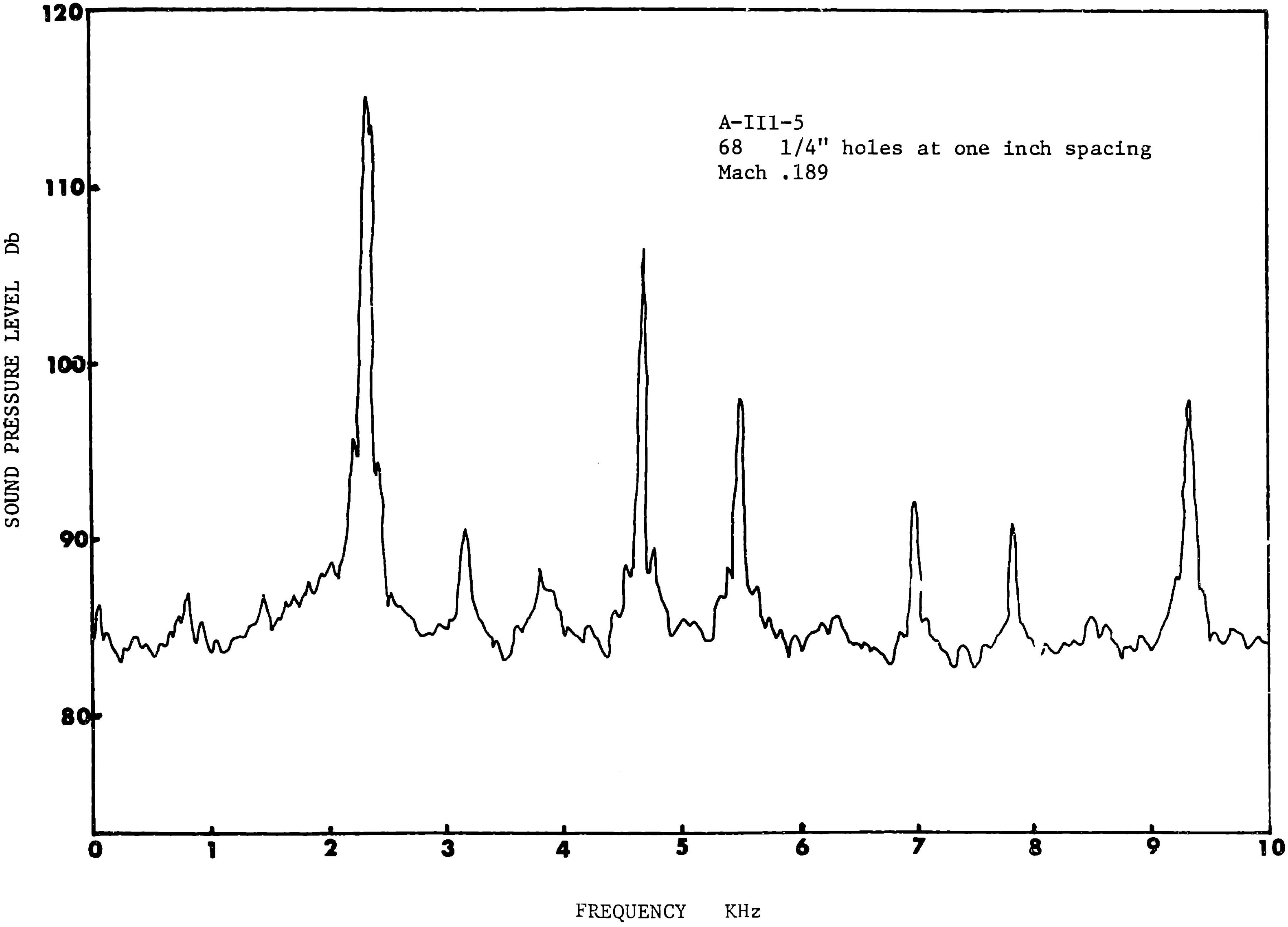

A-III-1
68 1/4" holes at one inch spacing
Mach .084
steam ejector noise
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

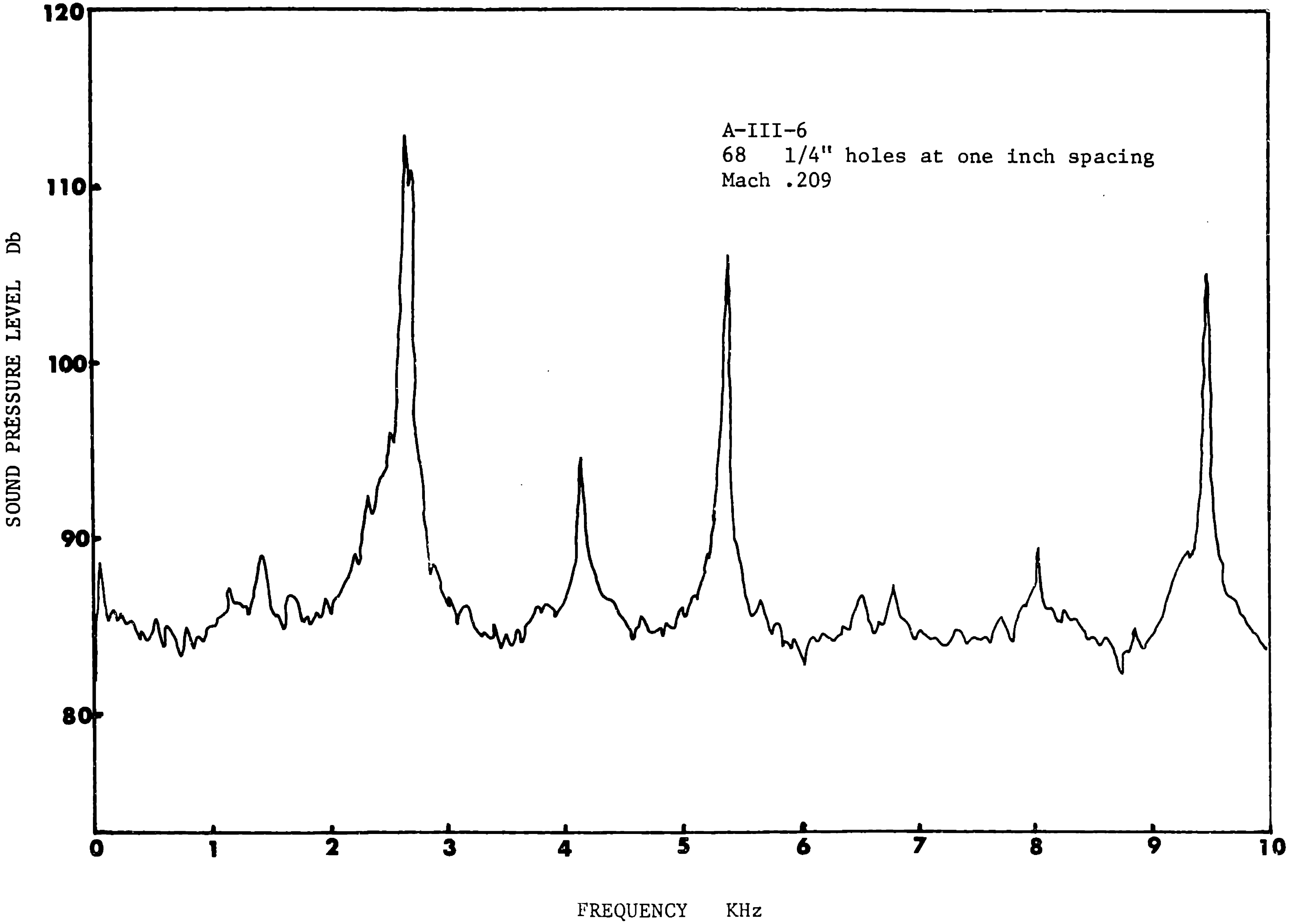

A-III-2
68 1/4" holes at one inch spacing
Mach .114
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

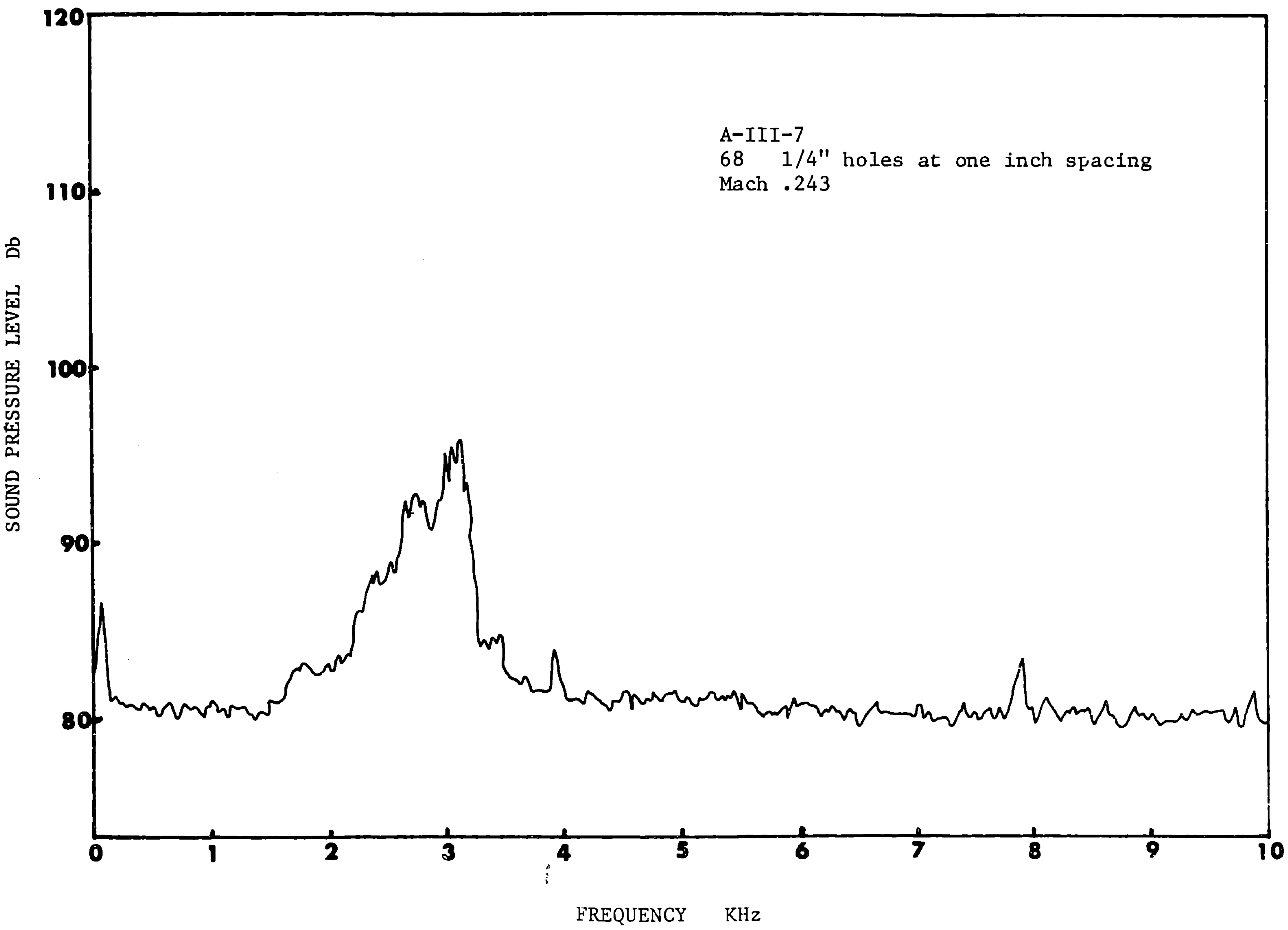


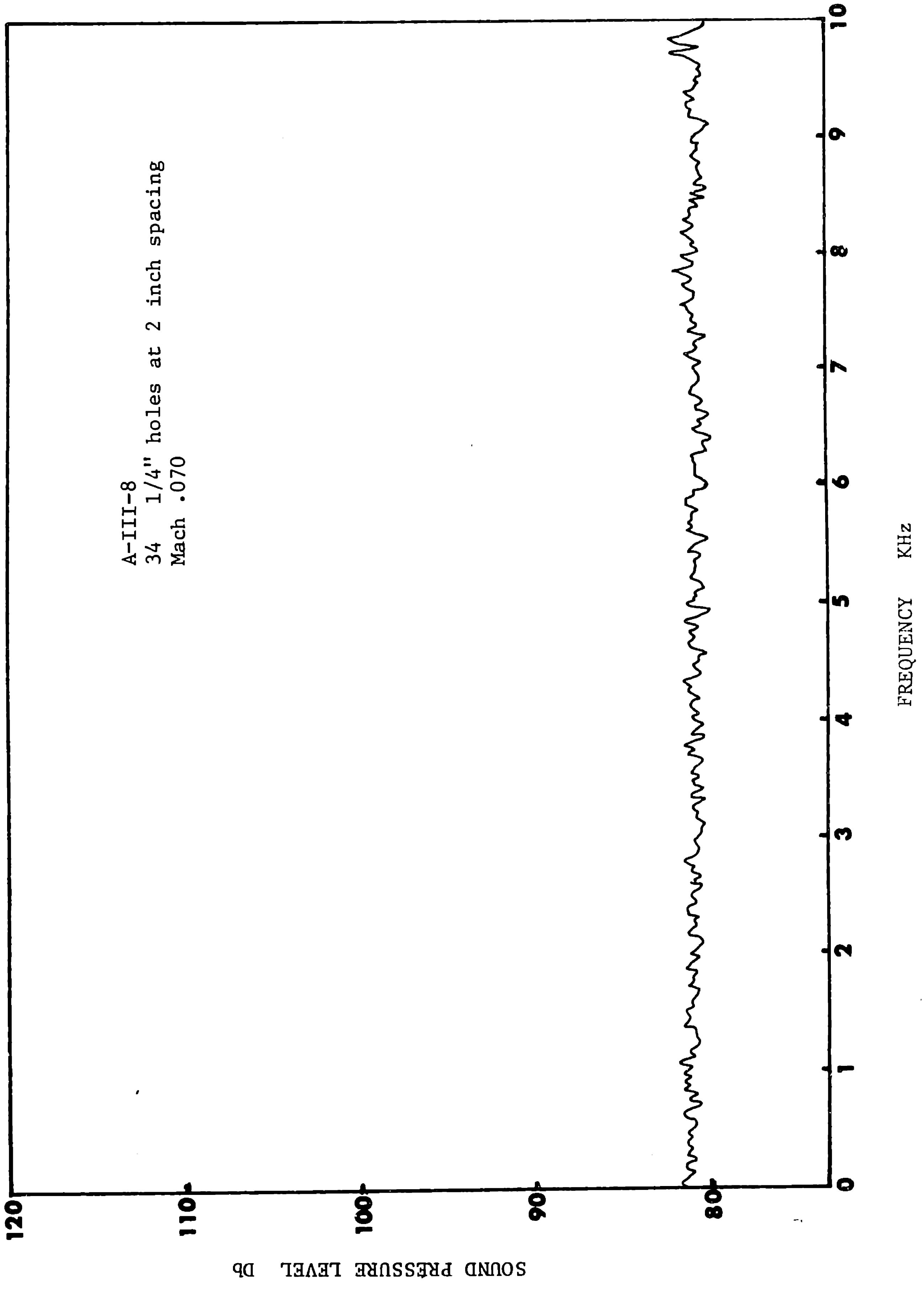
A-III-3
68 1/4" holes at one inch spacing
Mach .136

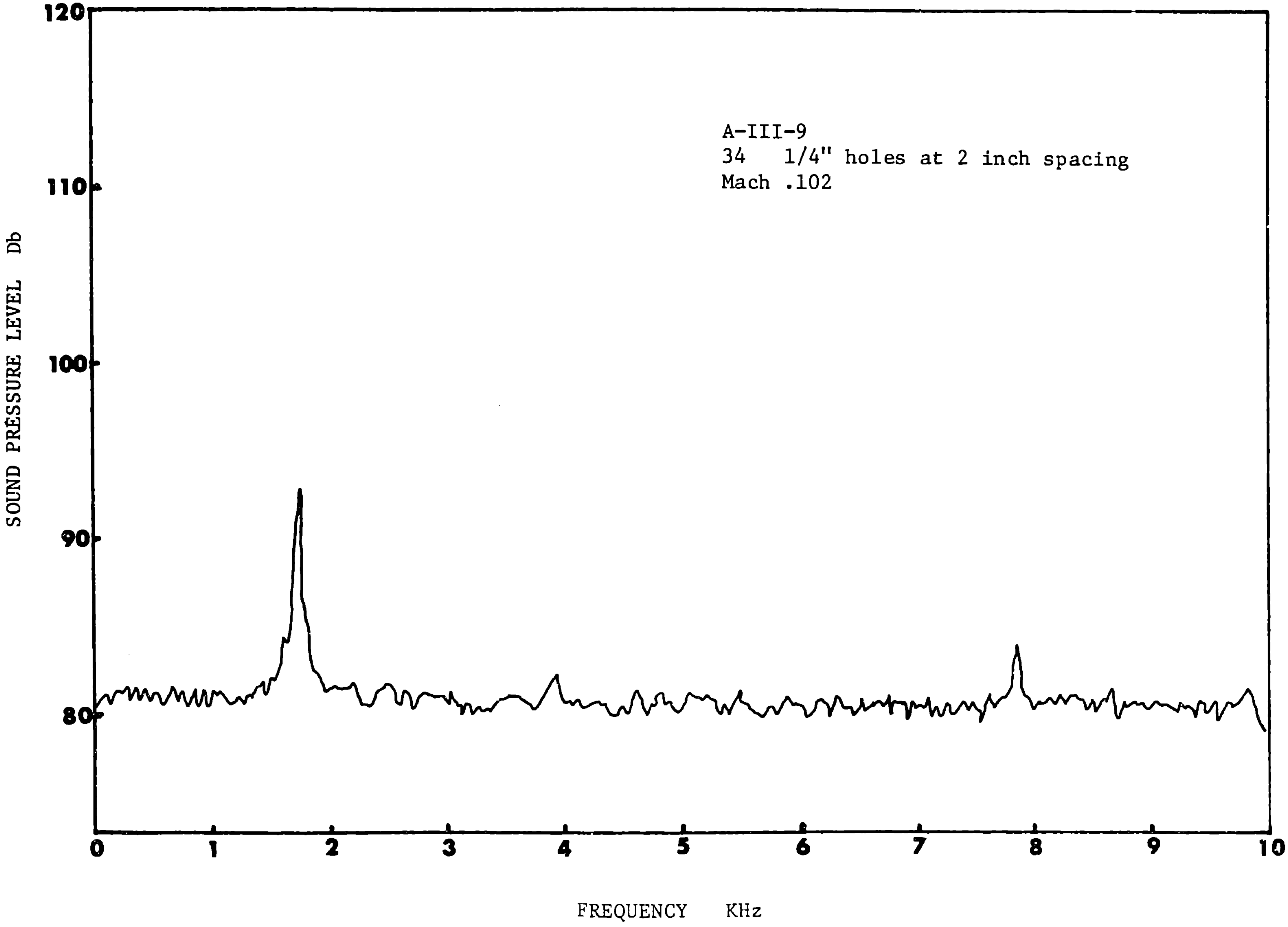

A-III-4
68 1/4"holes at one inch spacing
Mach .159
harmonics
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

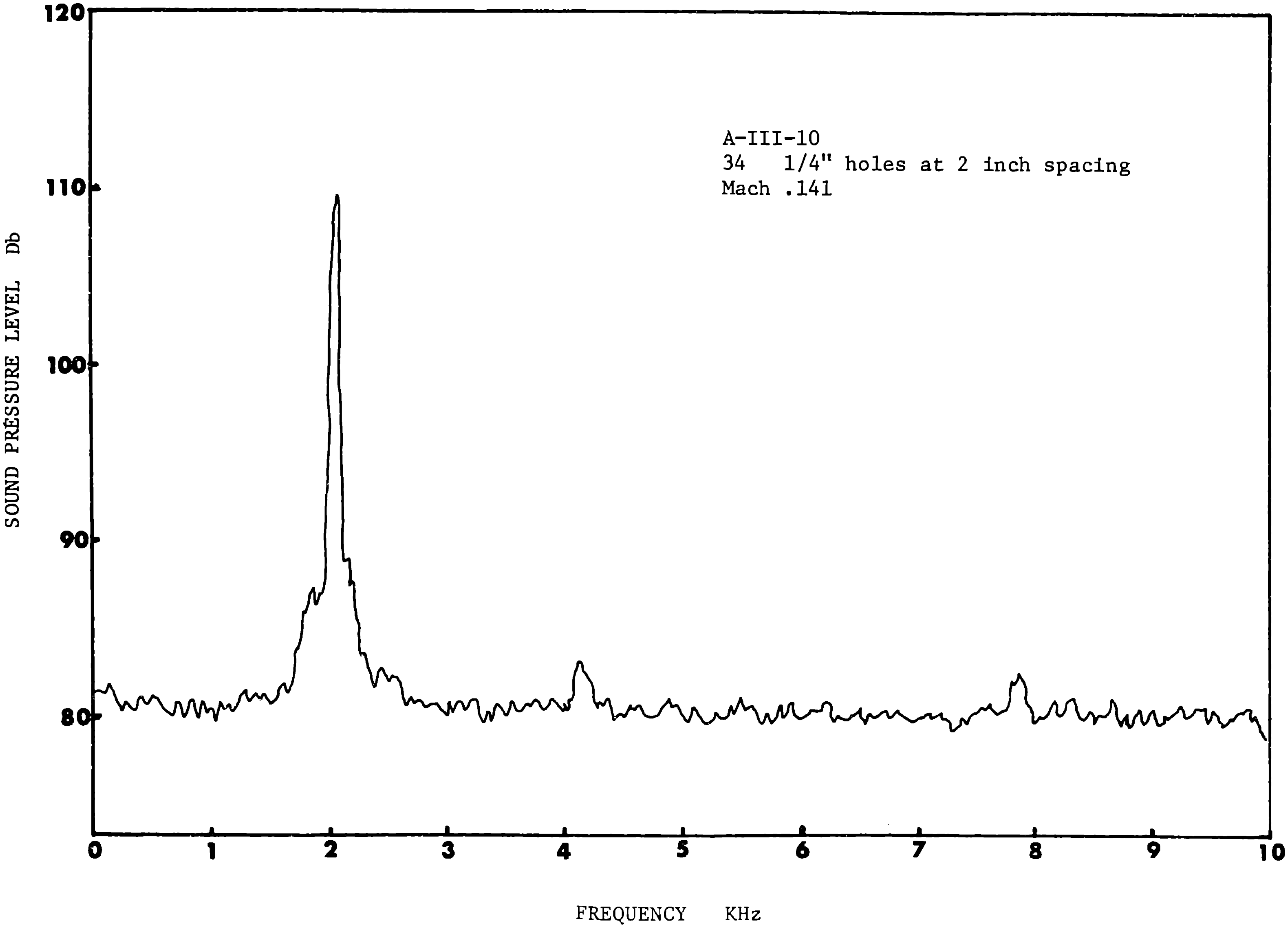

A-III-5
68 1/4" holes at one inch spacing
Mach .189
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

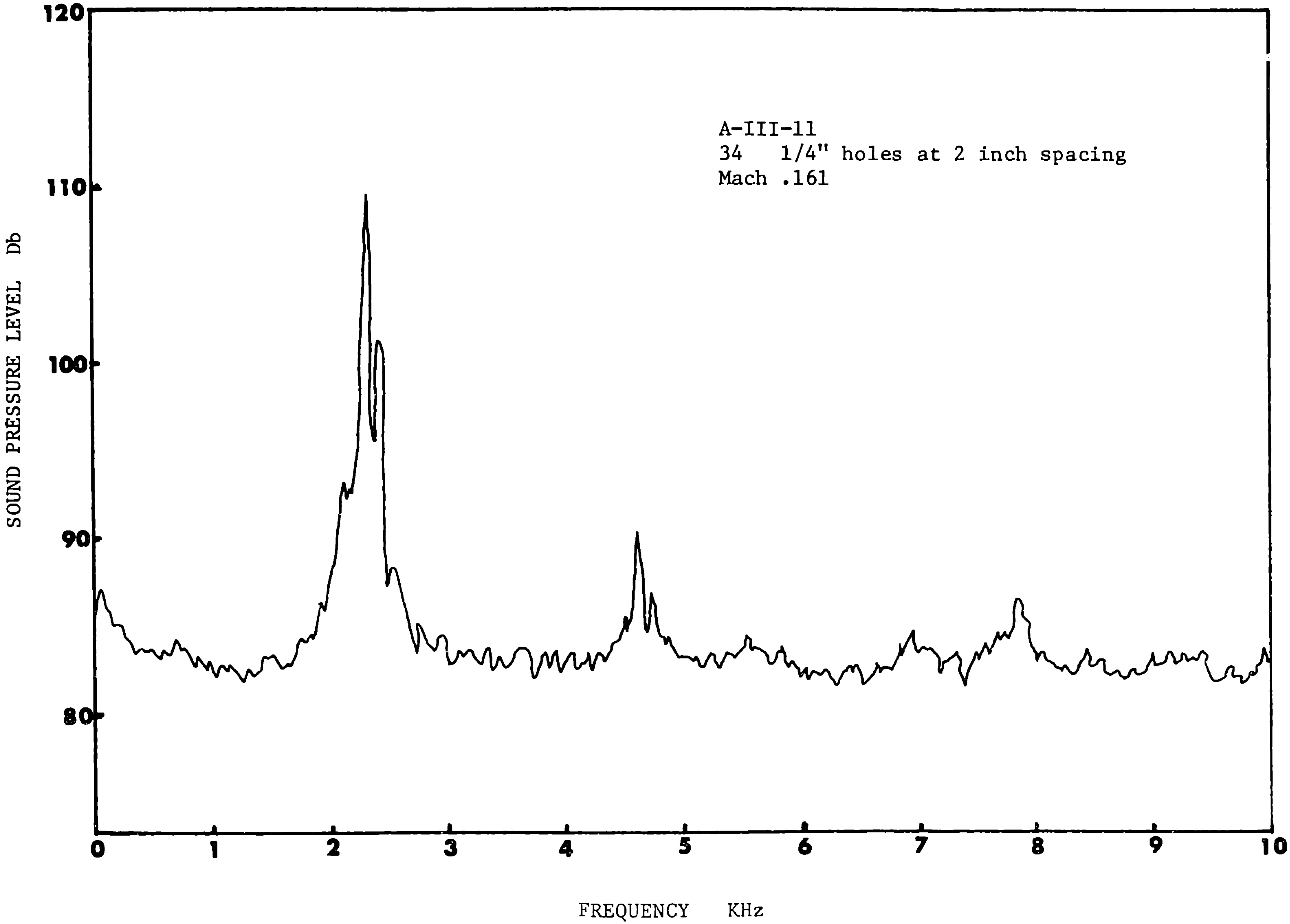

A-III-6
68 1/4" holes at one inch spacing
Mach .209
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

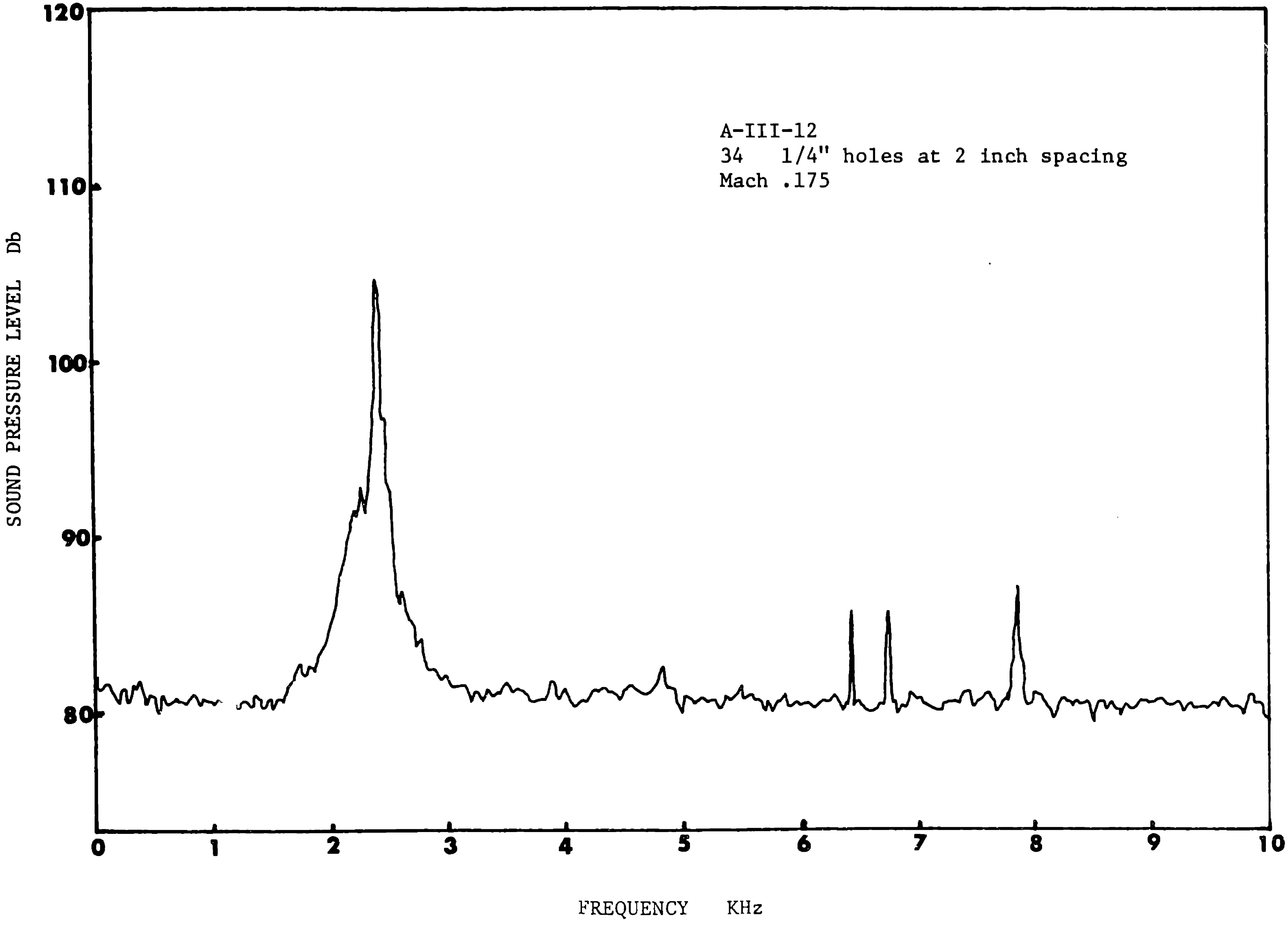

A-III-7
68 1/4" holes at one inch spacing
Mach .243
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz


A-III-8
34 1/4" holes at 2 inch spacing
Mach .070
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

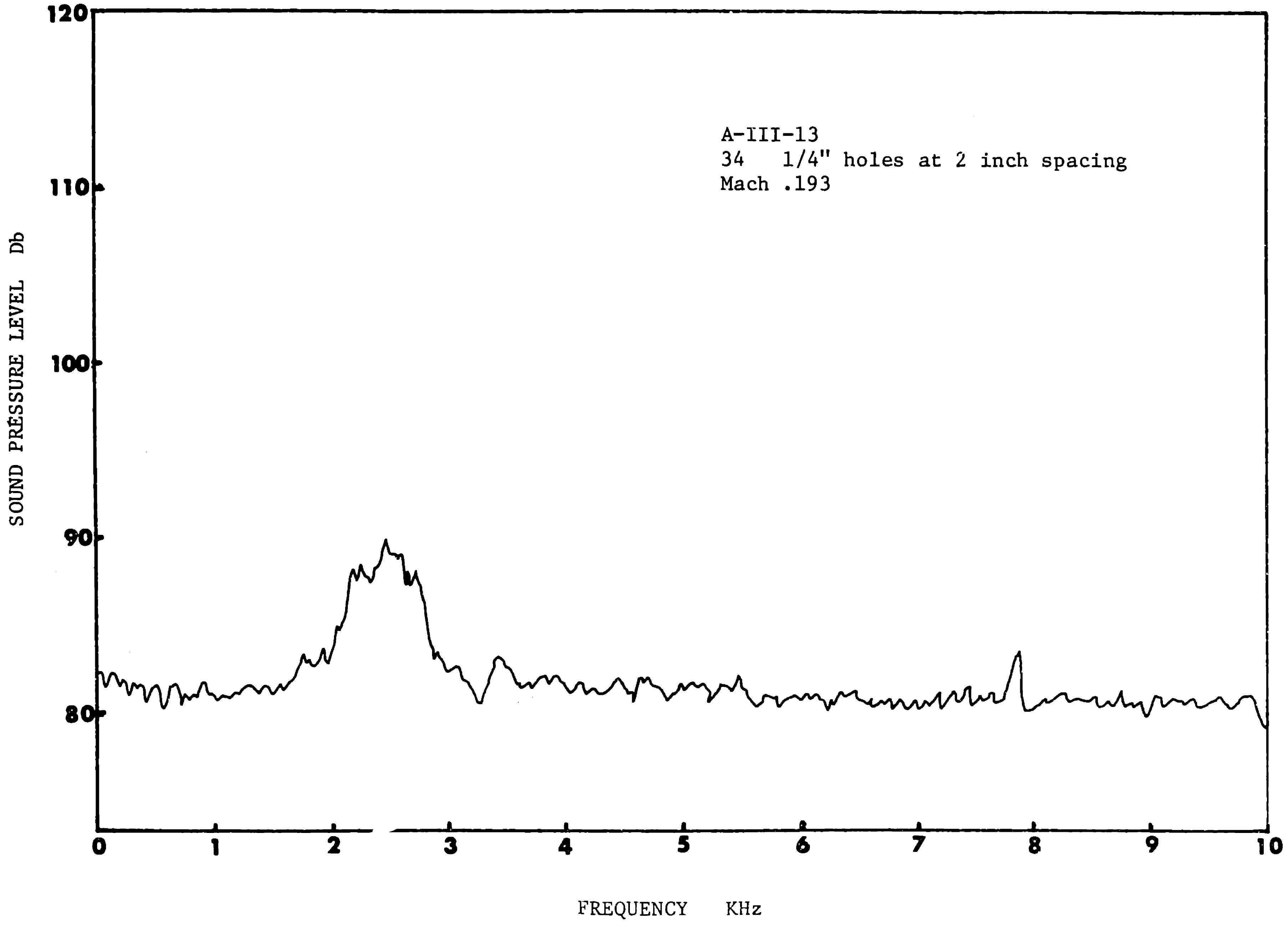

A-III-9
34 1/4" holes at 2 inch spacing
Mach .102
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

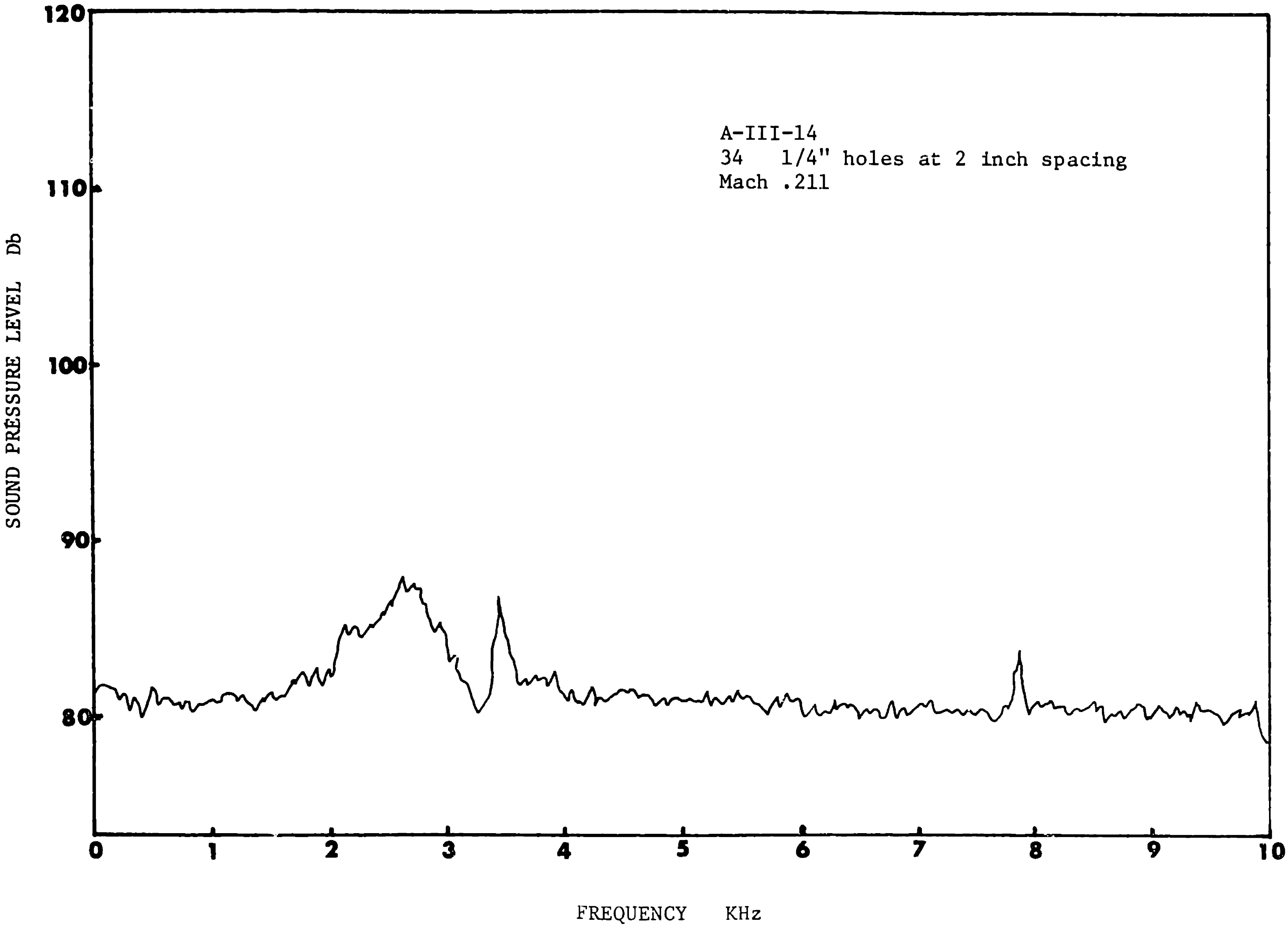

A-III-10
34 1/4" holes at 2 inch spacing
Mach .141
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

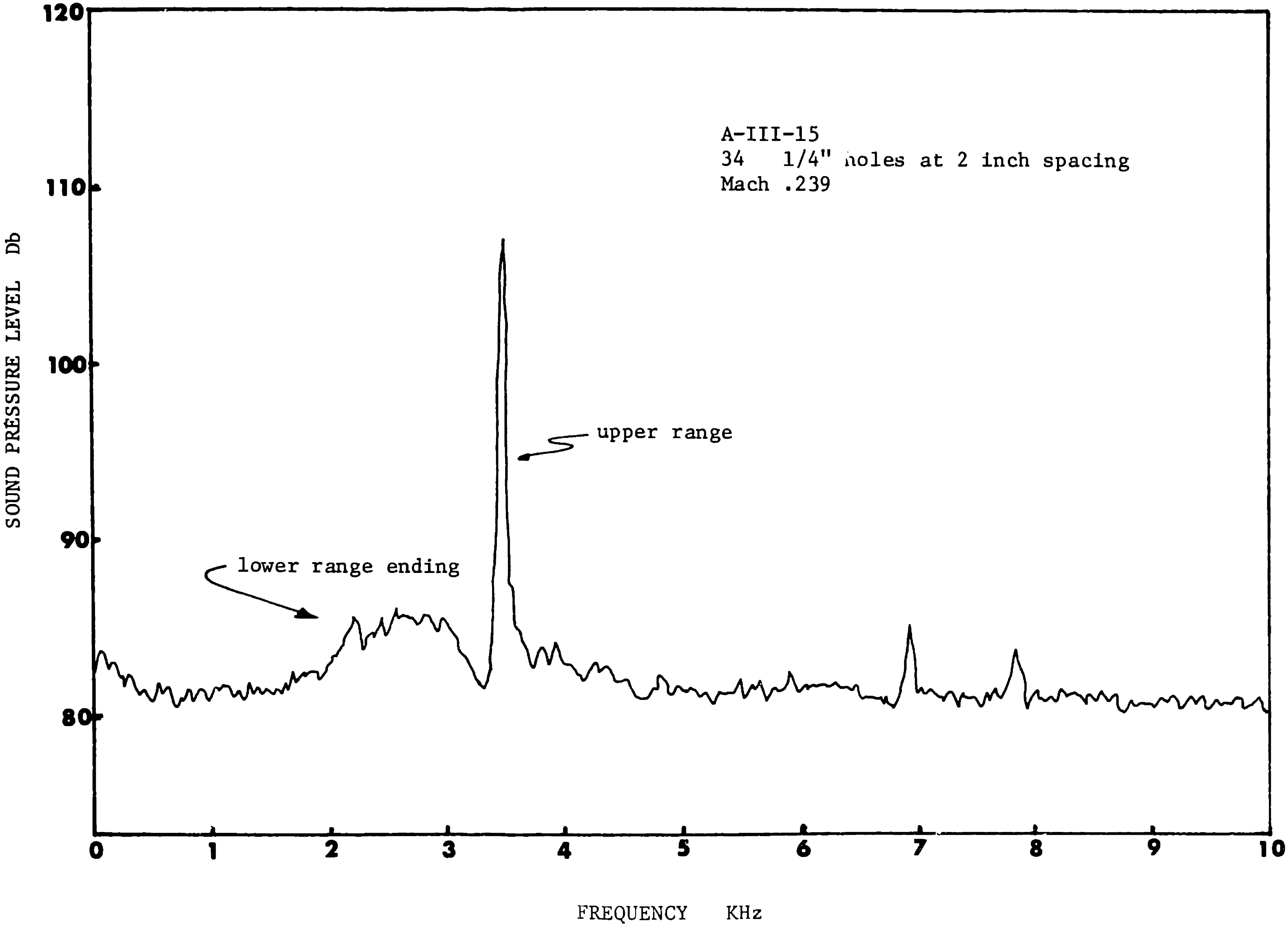

A-III-11
34 1/4" holes at 2 inch spacing
Mach .161
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

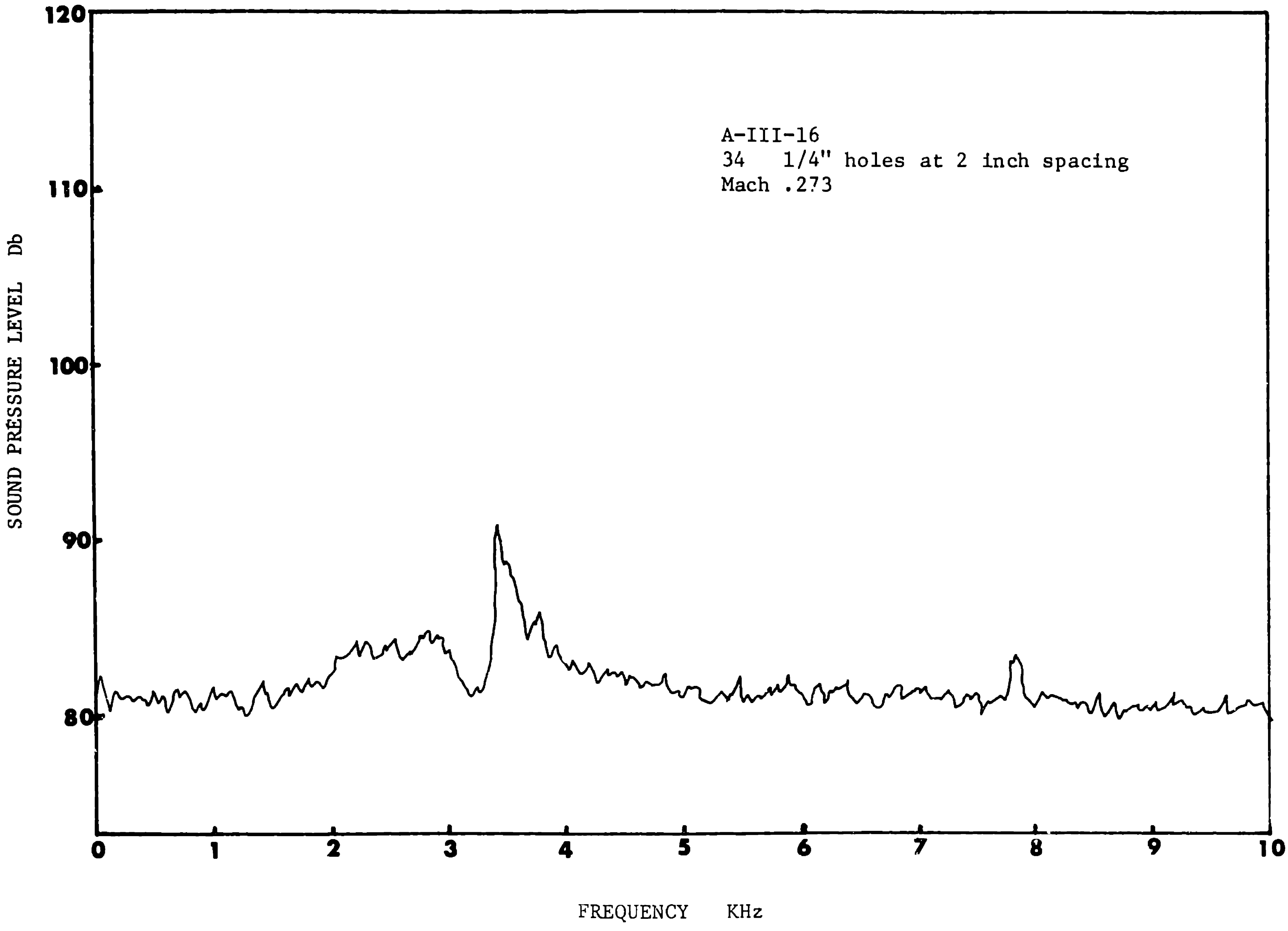


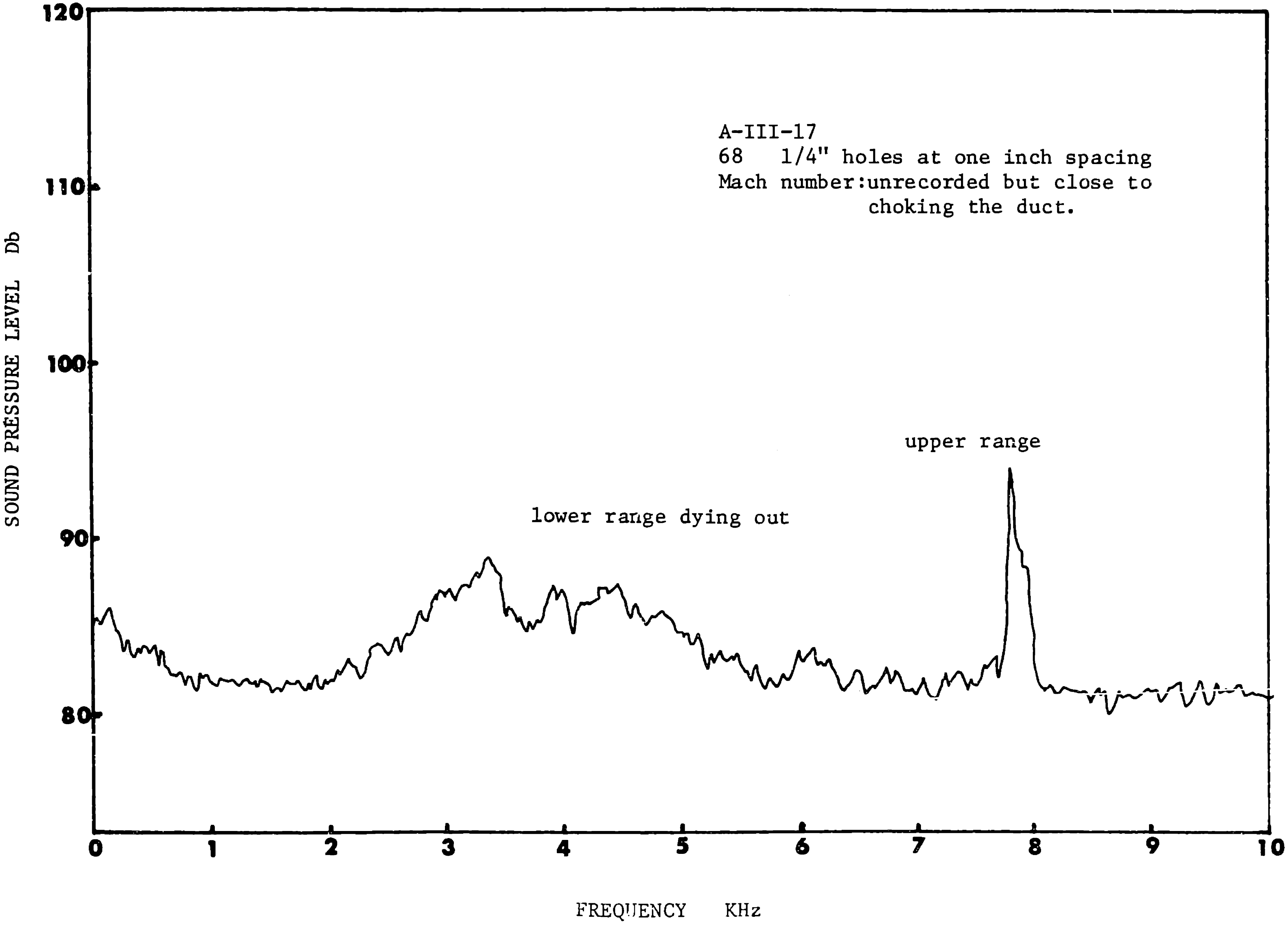
A-III-12
34 1/4" holes at 2 inch spacing
Mach .175

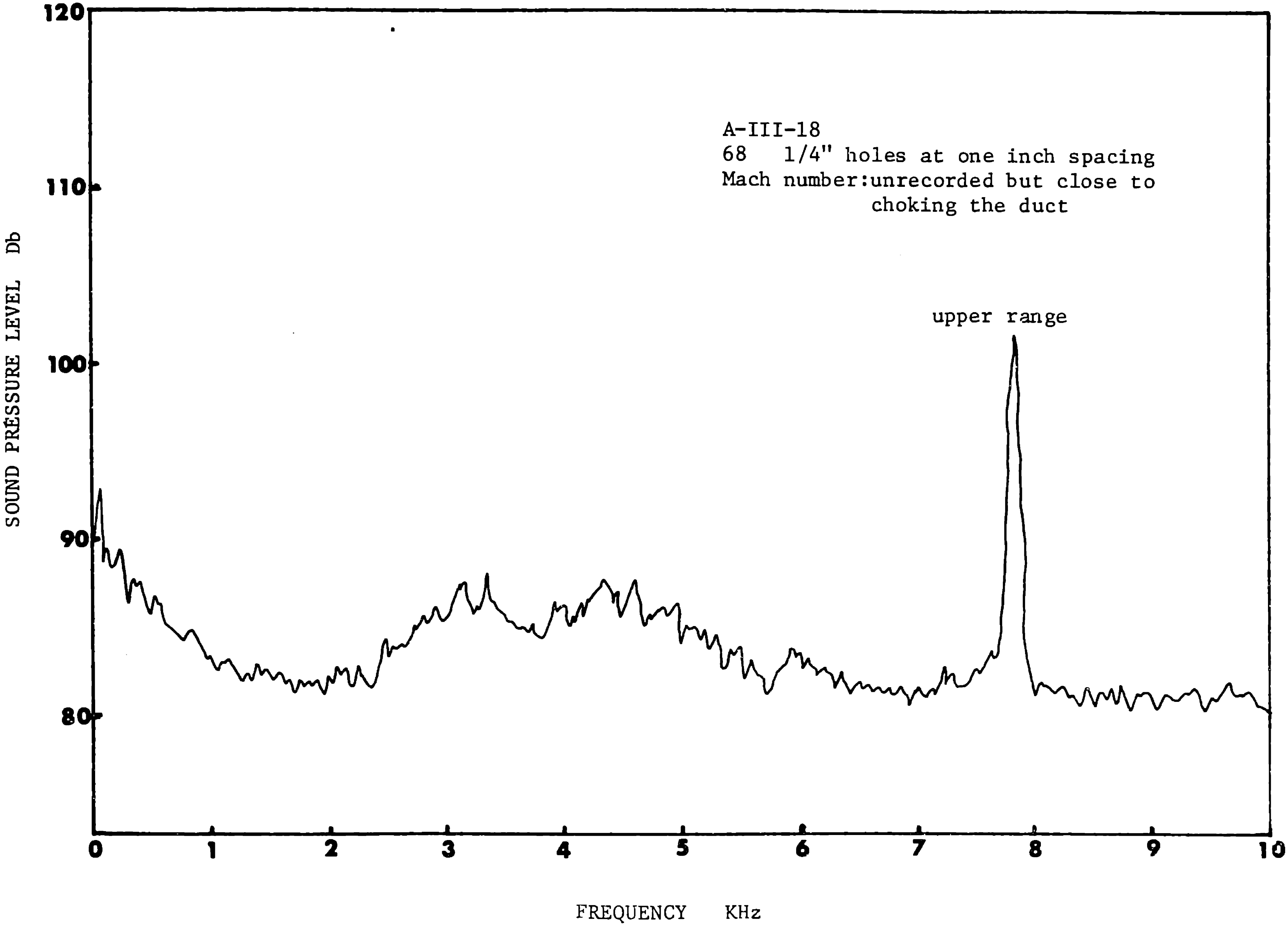

A-III-13
34 1/4" holes at 2 inch spacing
Mach .193
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

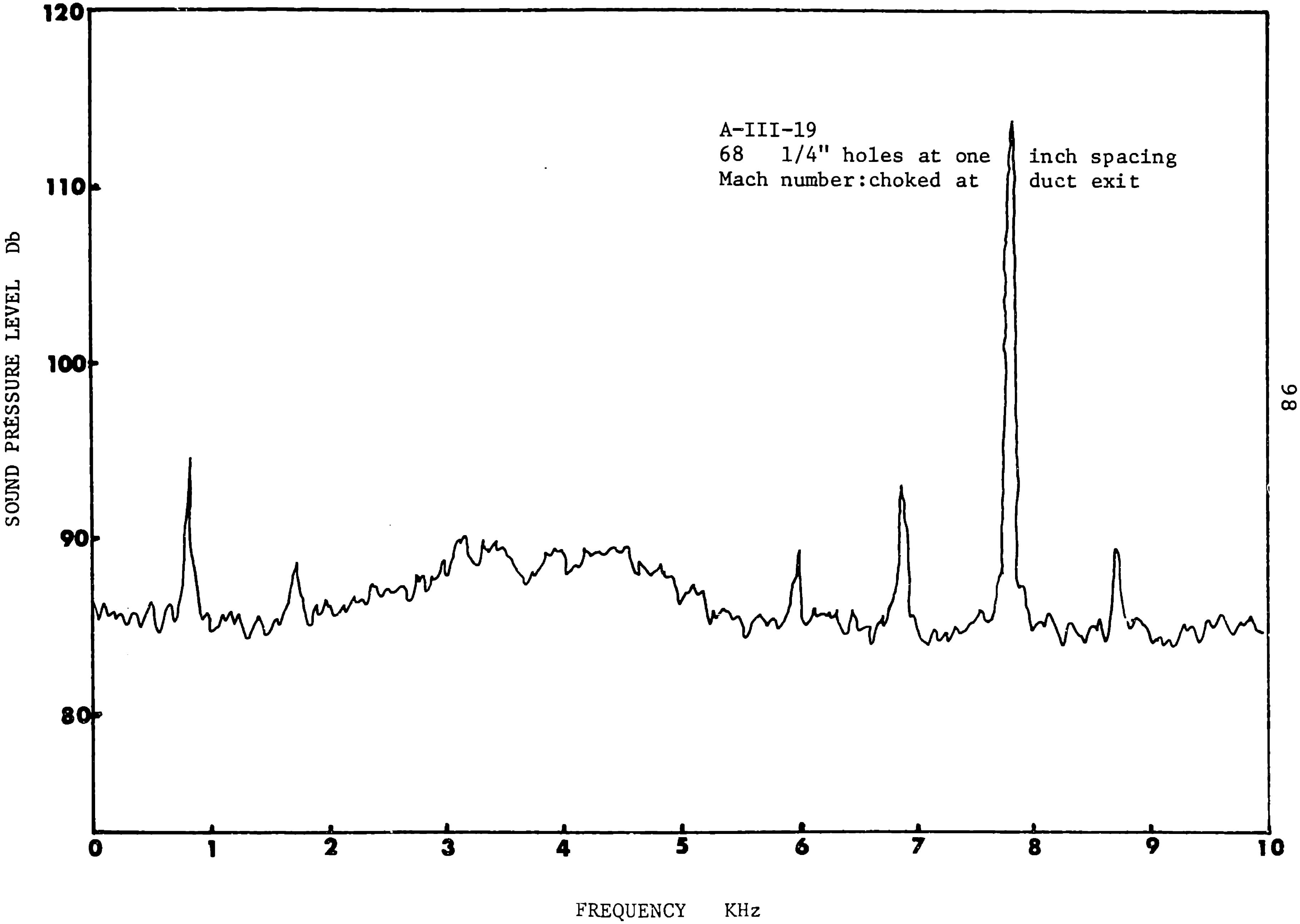

A-III-14
34 1/4" holes at 2 inch spacing
Mach .211
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

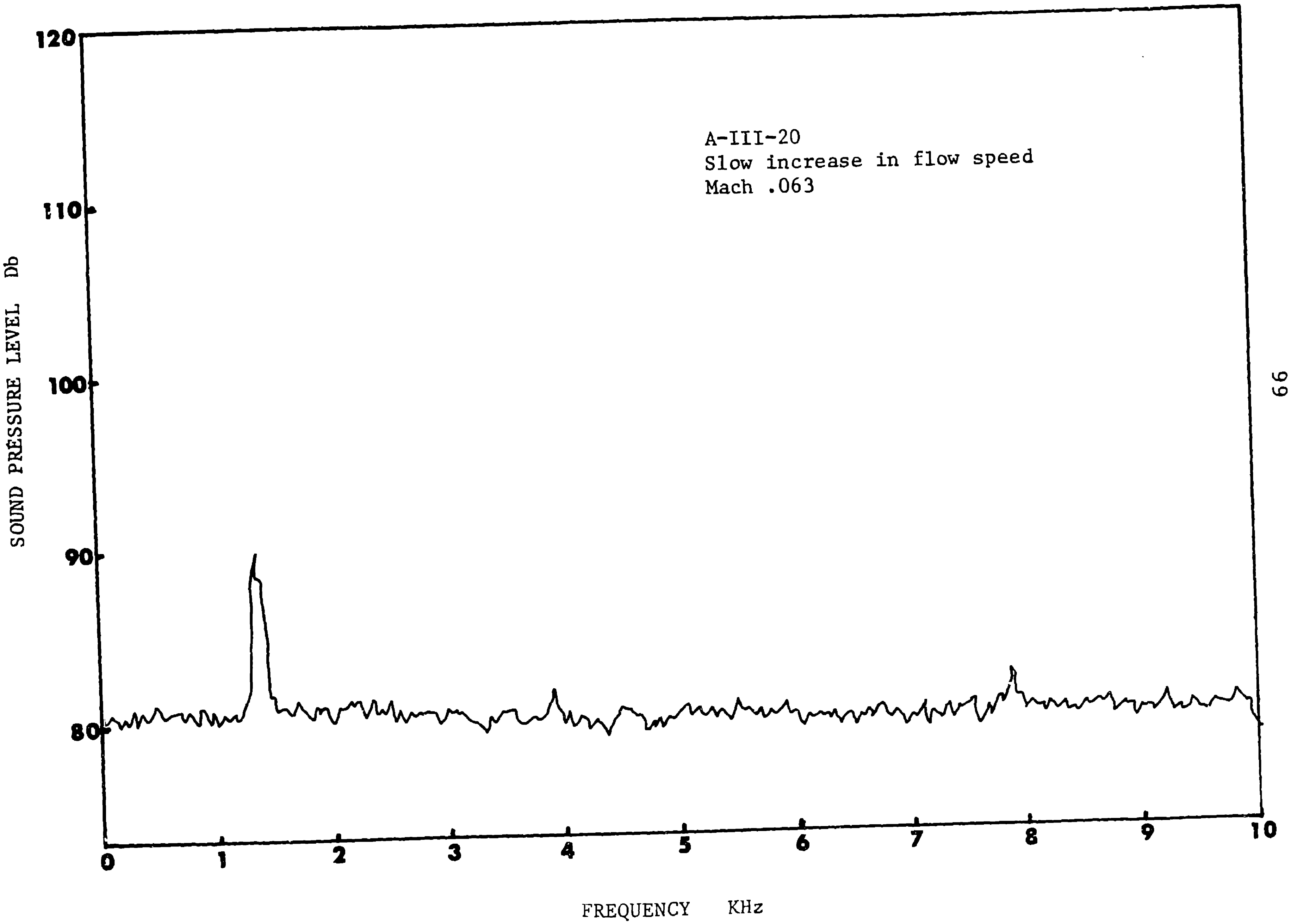

A-III-15
34 1/4" holes at 2 inch spacing
Mach .239
upper range
lower range ending
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

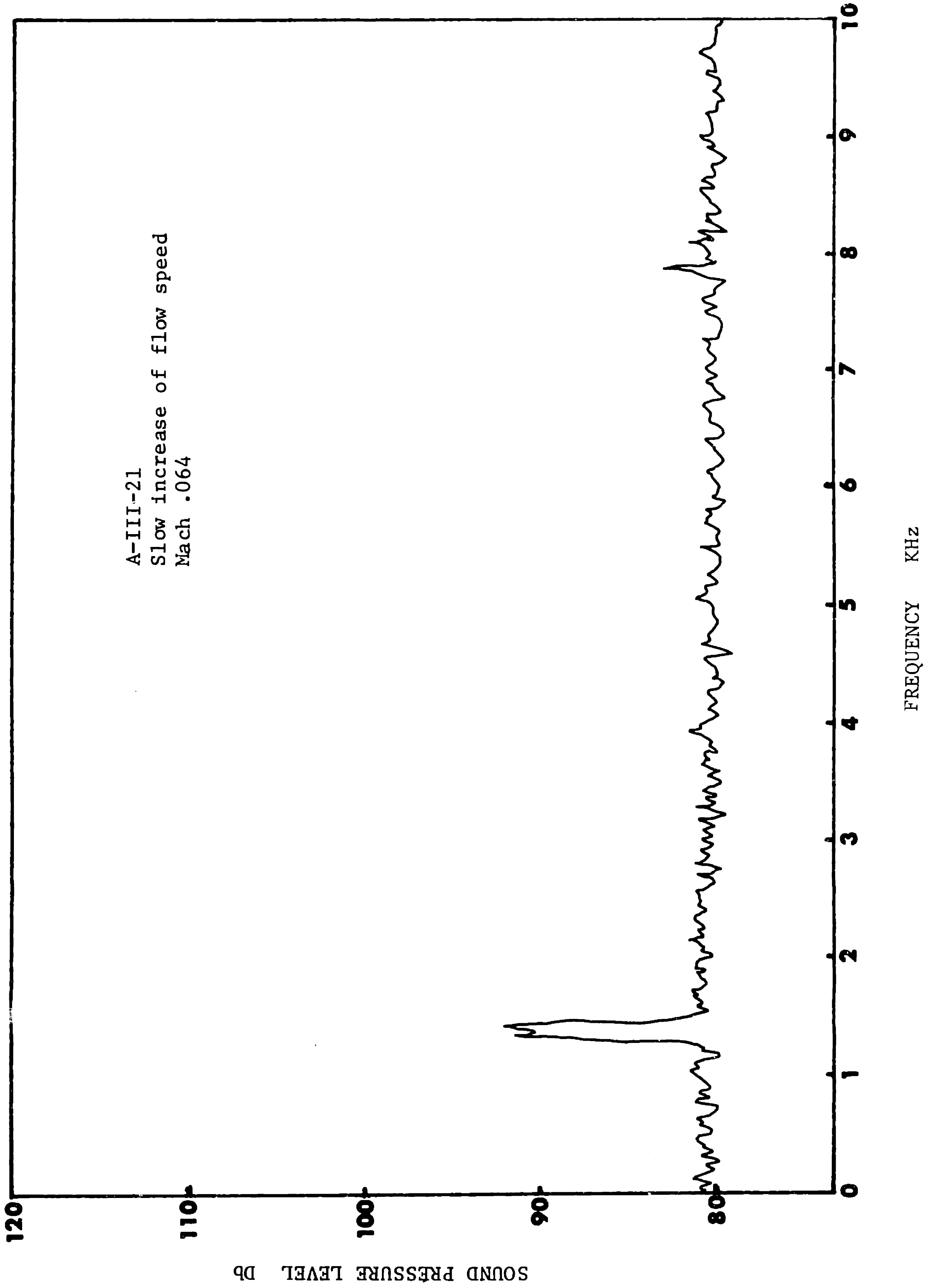

A-III-16
34 1/4" holes at 2 inch spacing
Mach .273
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

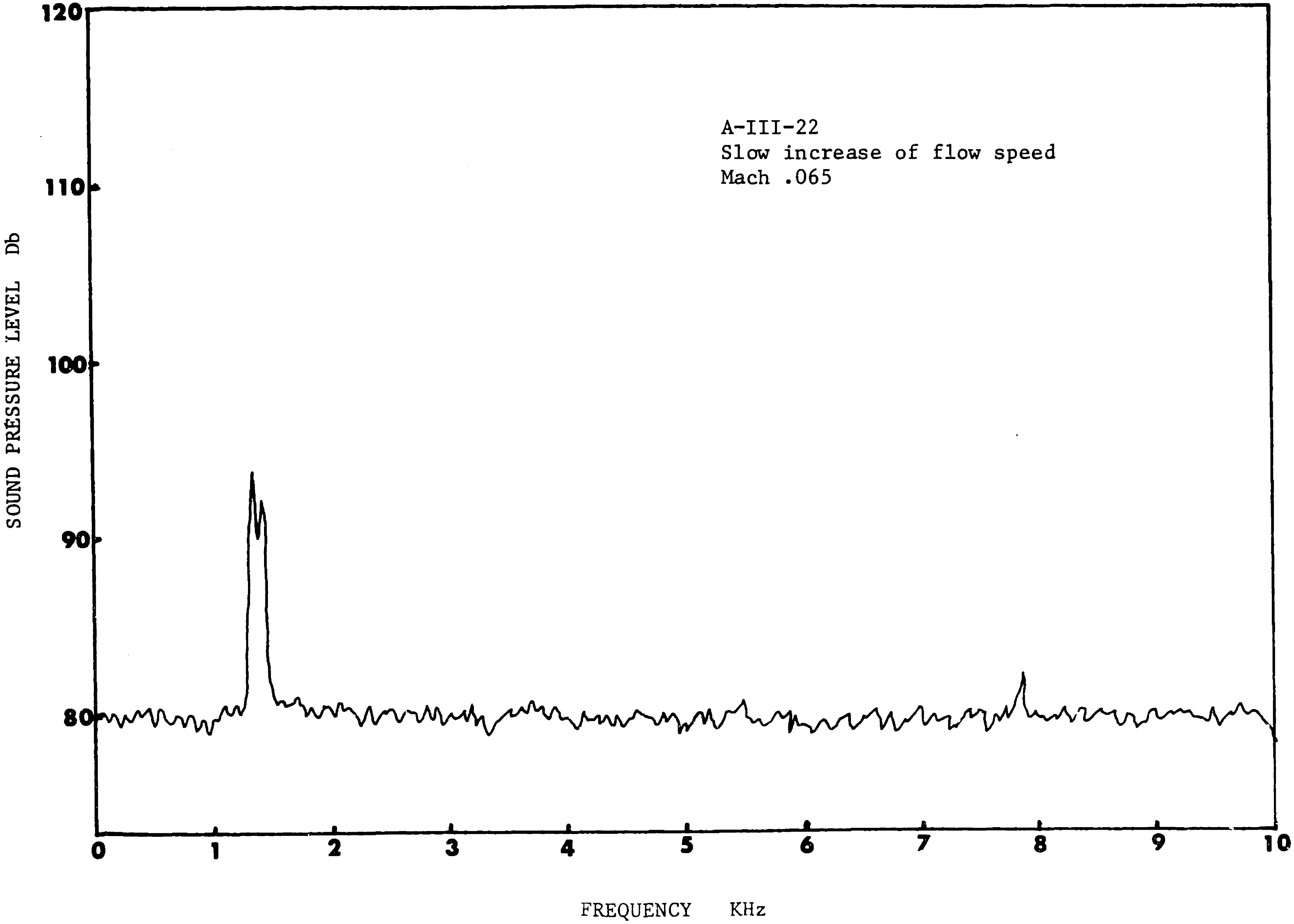

A-III-17
68 1/4" holes at one inch spacing
Mach number:unrecorded but close to choking the duct.
upper range
lower range dying out
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10


A-III-18
68 1/4" holes at one inch spacing
Mach number:unrecorded but close to
choking the duct
upper range
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

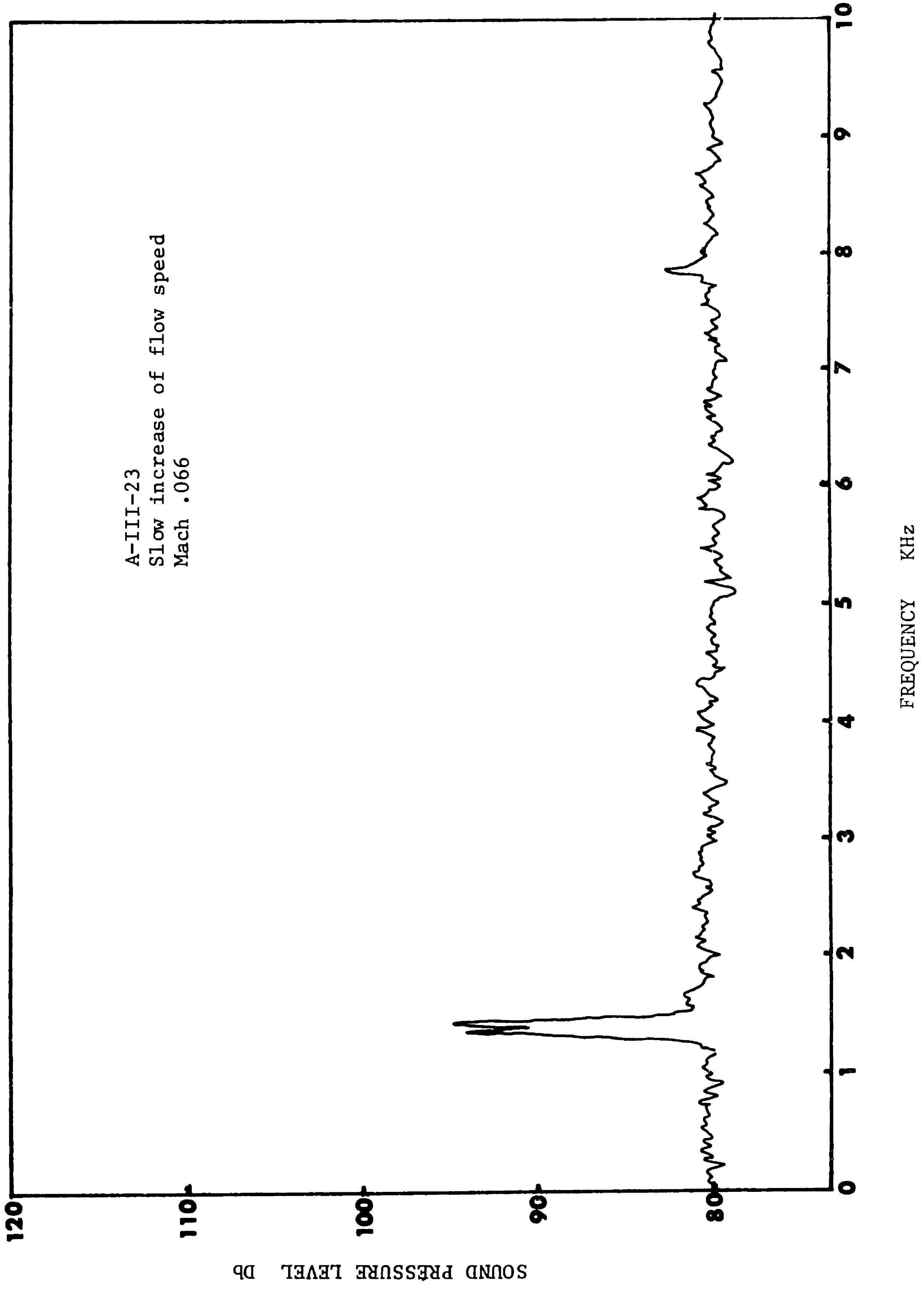

A-III-19
68 1/4" holes at one inch spacing
Mach number:choked at duct exit
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

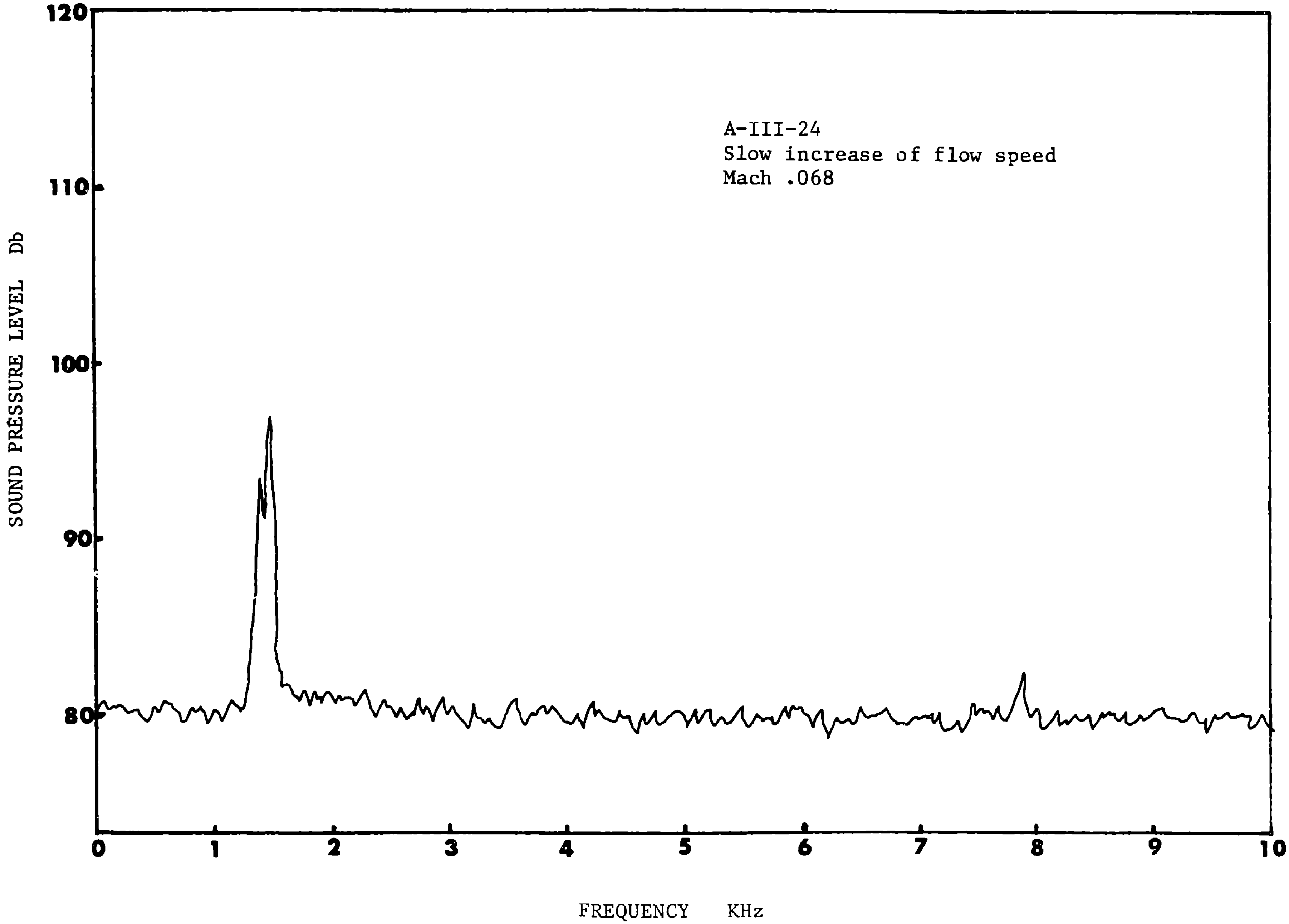

A-III-20
Slow increase in flow speed
Mach .063
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

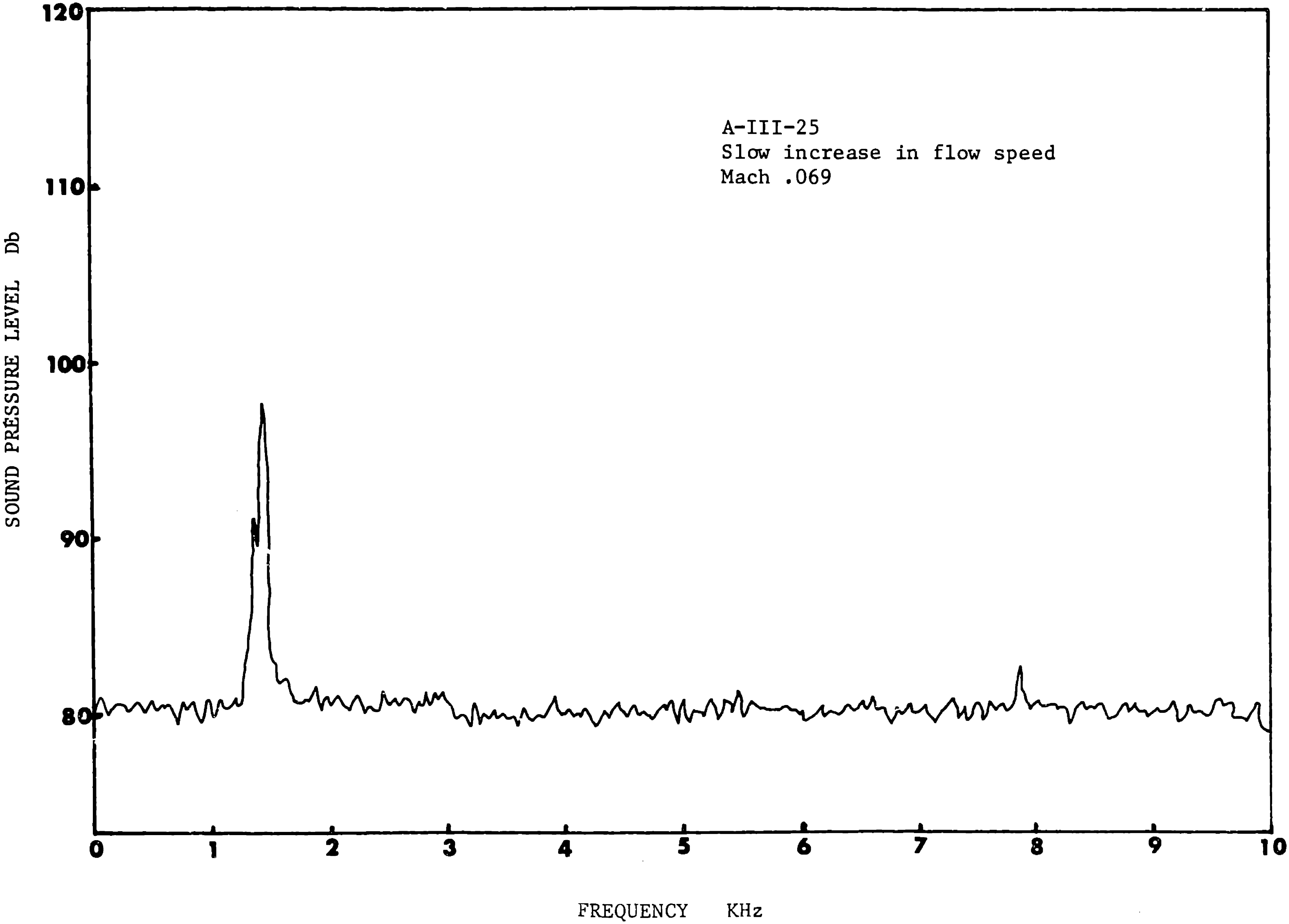

A-III-21
Slow increase of flow speed
Mach .064
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

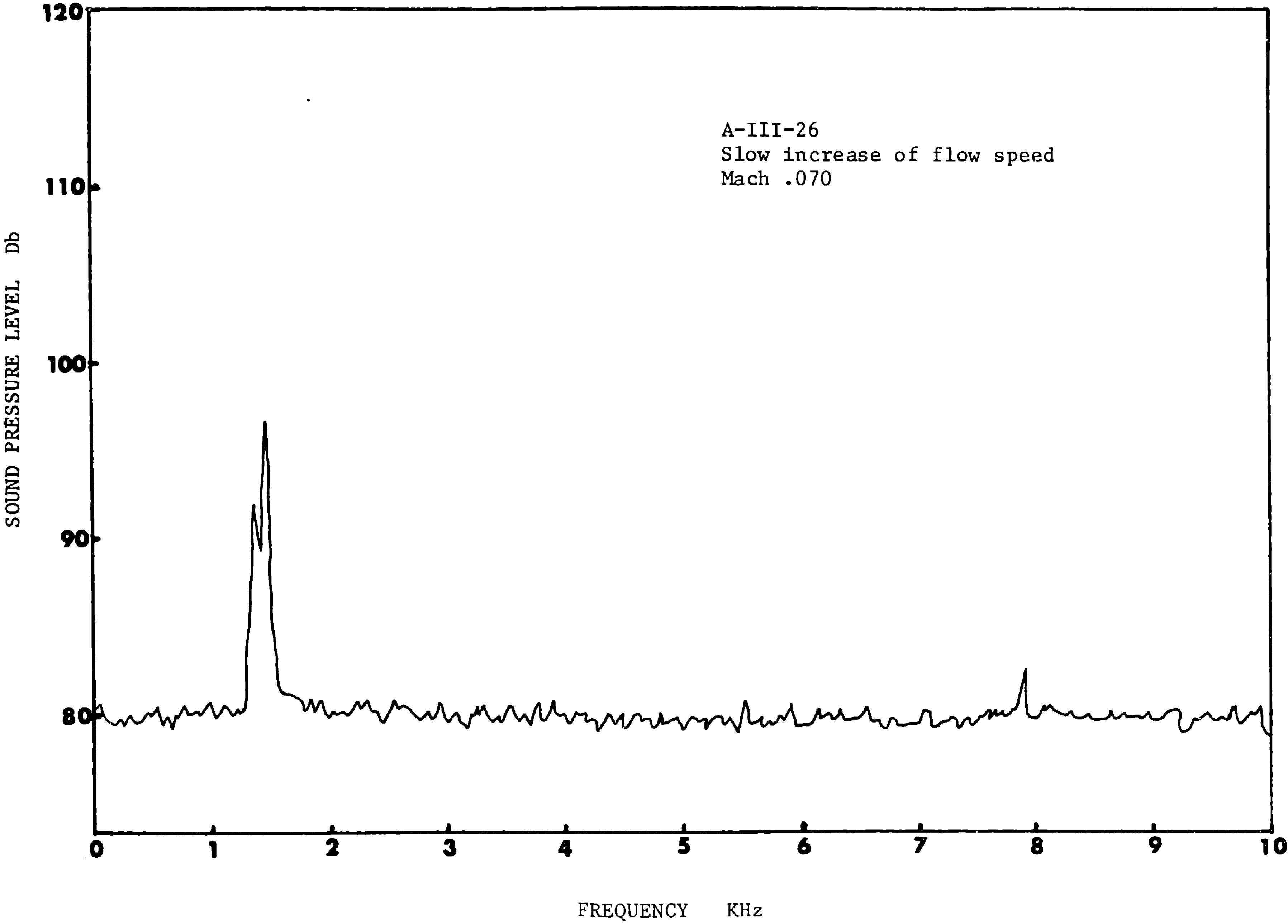


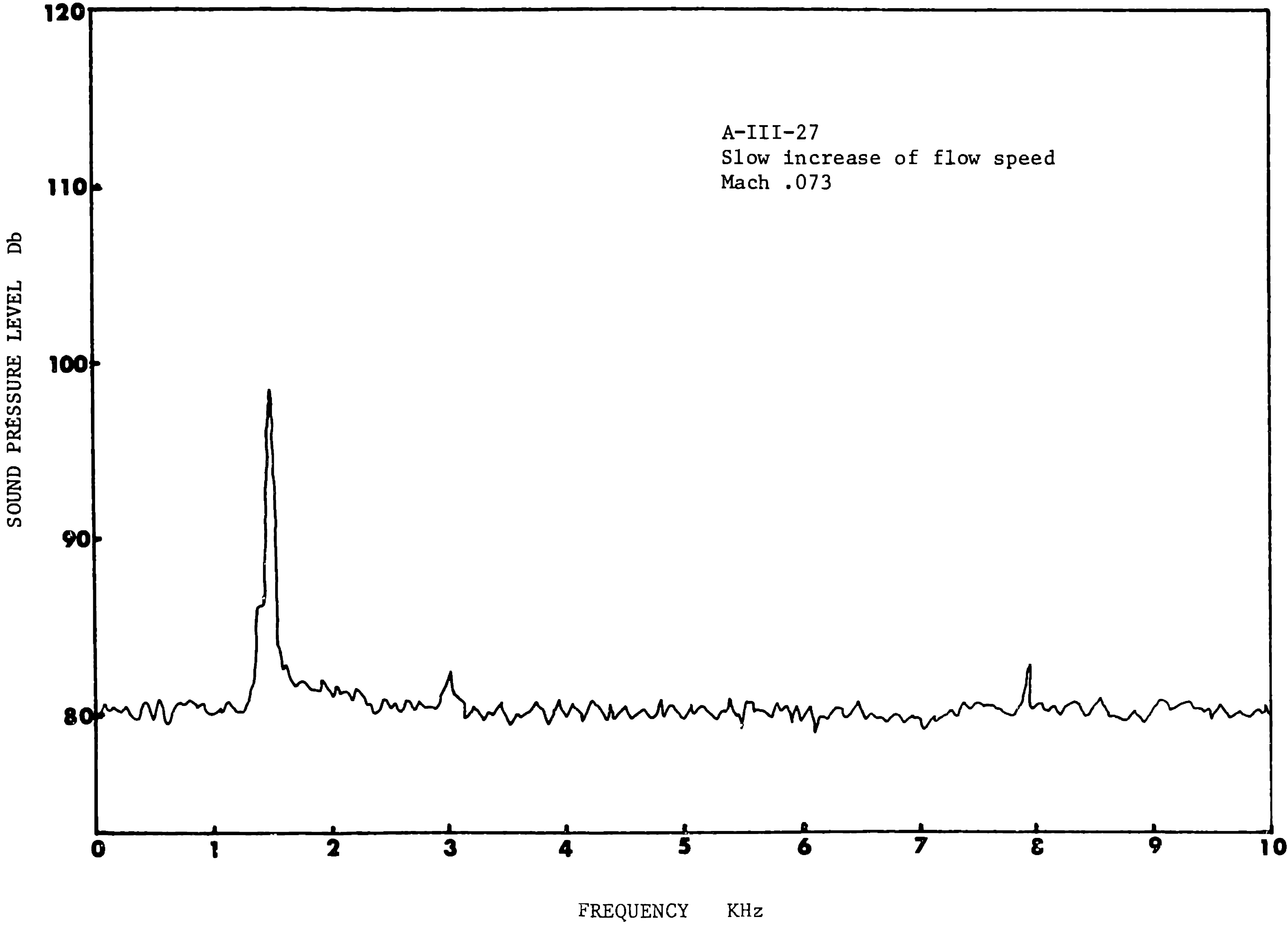
A-III-22
Slow increase of flow speed
Mach .065

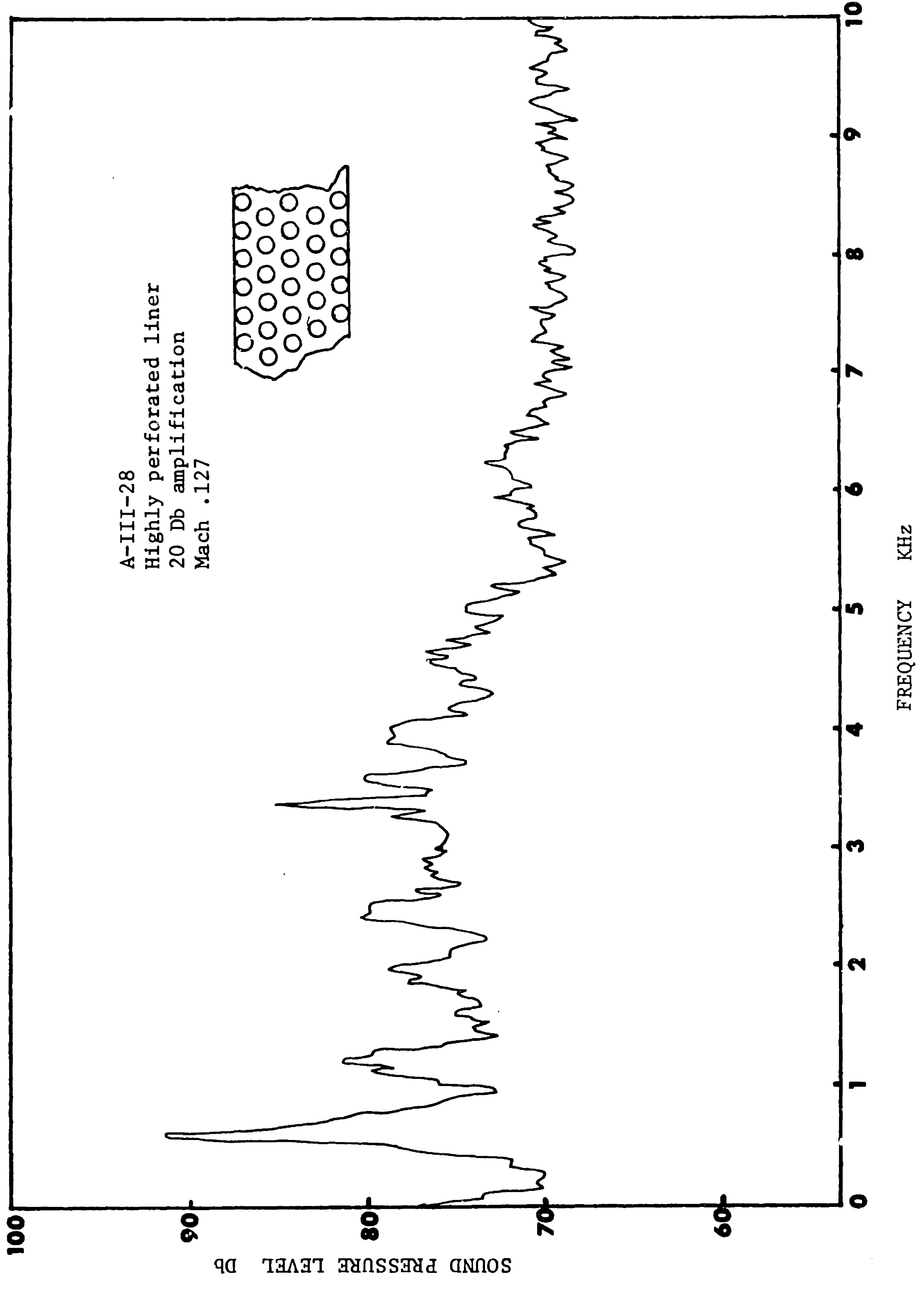

A-III-23
Slow increase of flow speed
Mach .066
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

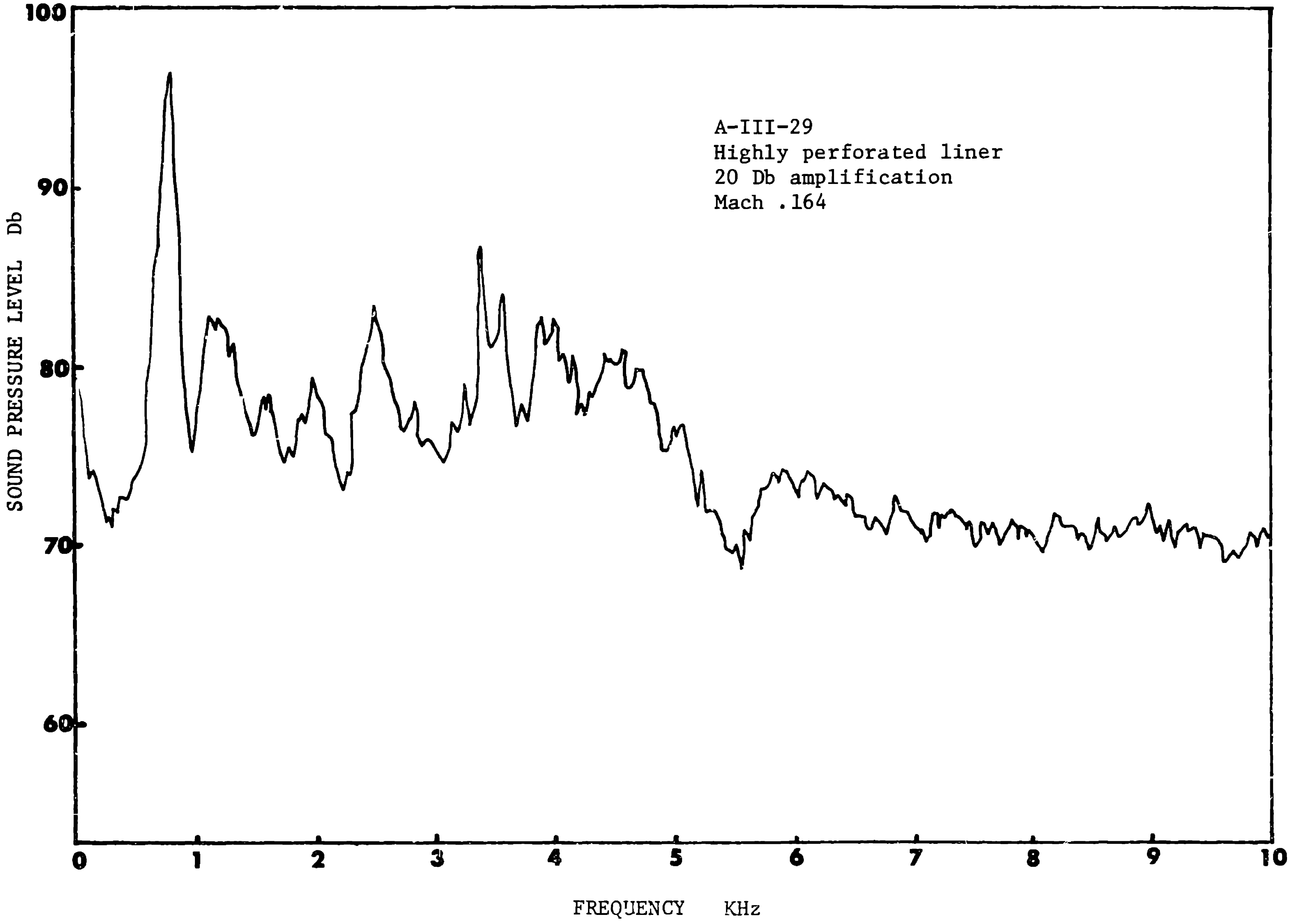

A-III-24
Slow increase of flow speed
Mach .068
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

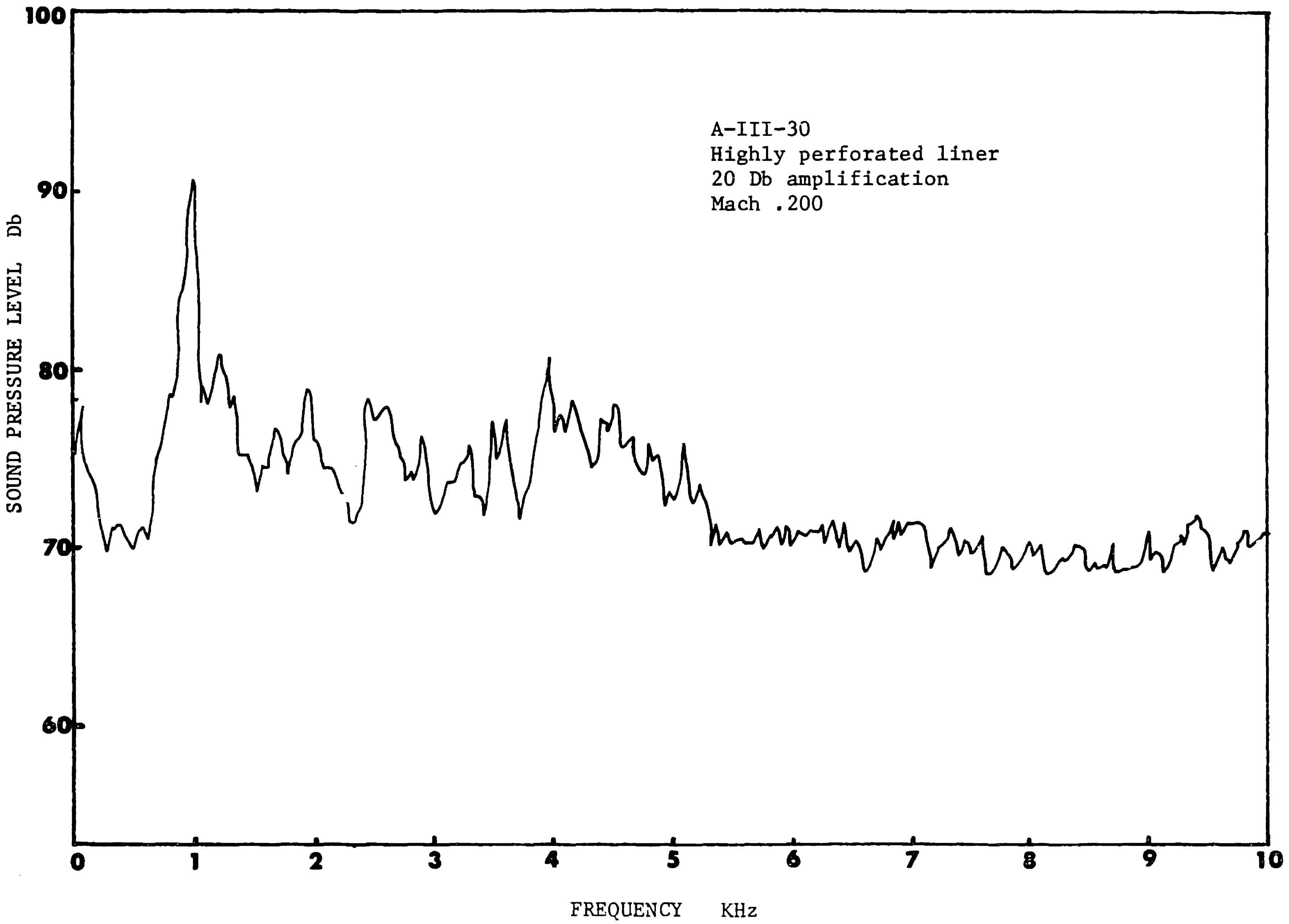

A-III-25
Slow increase in flow speed
Mach .069
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

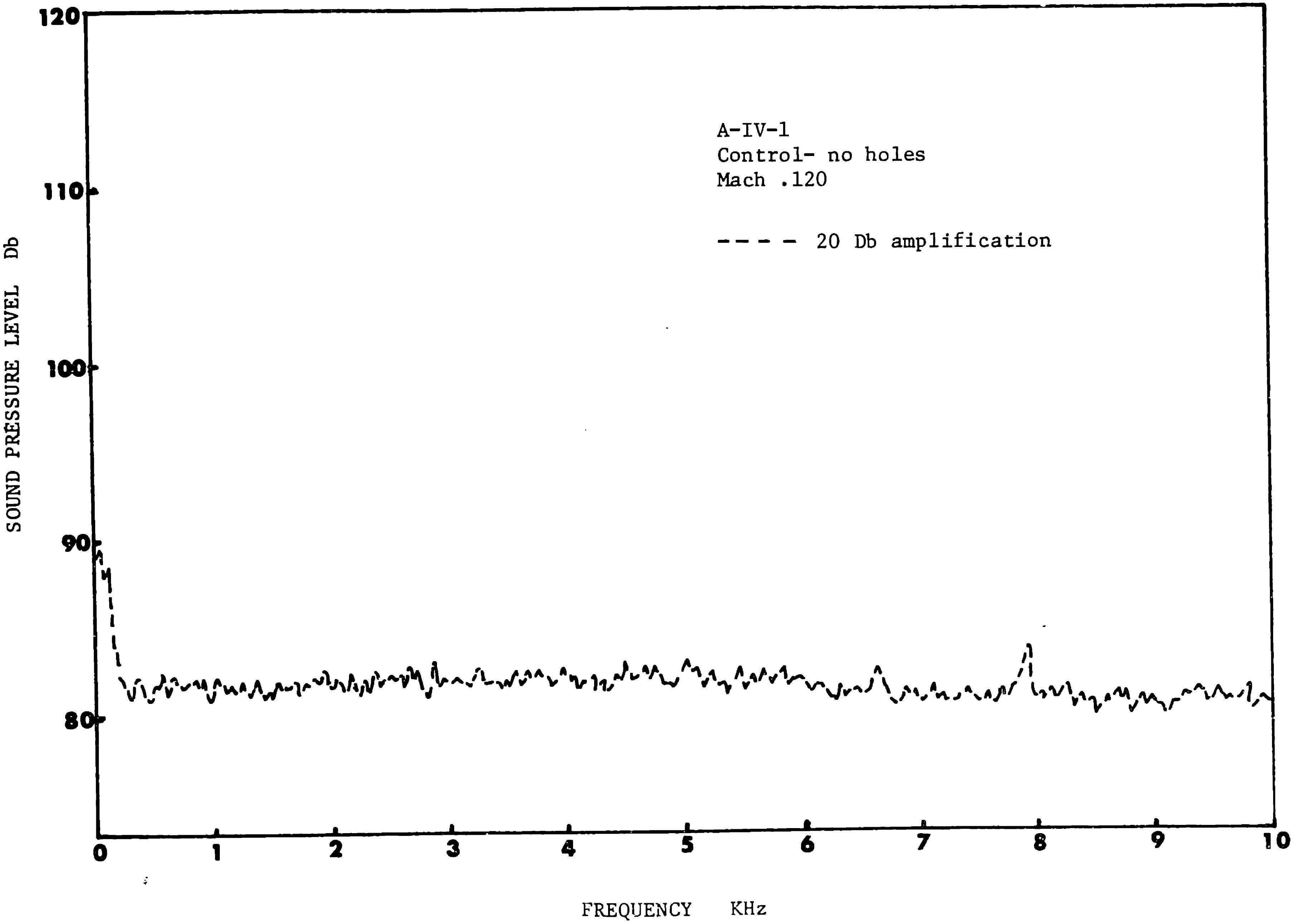

A-III-26
Slow increase of flow speed
Mach .070
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

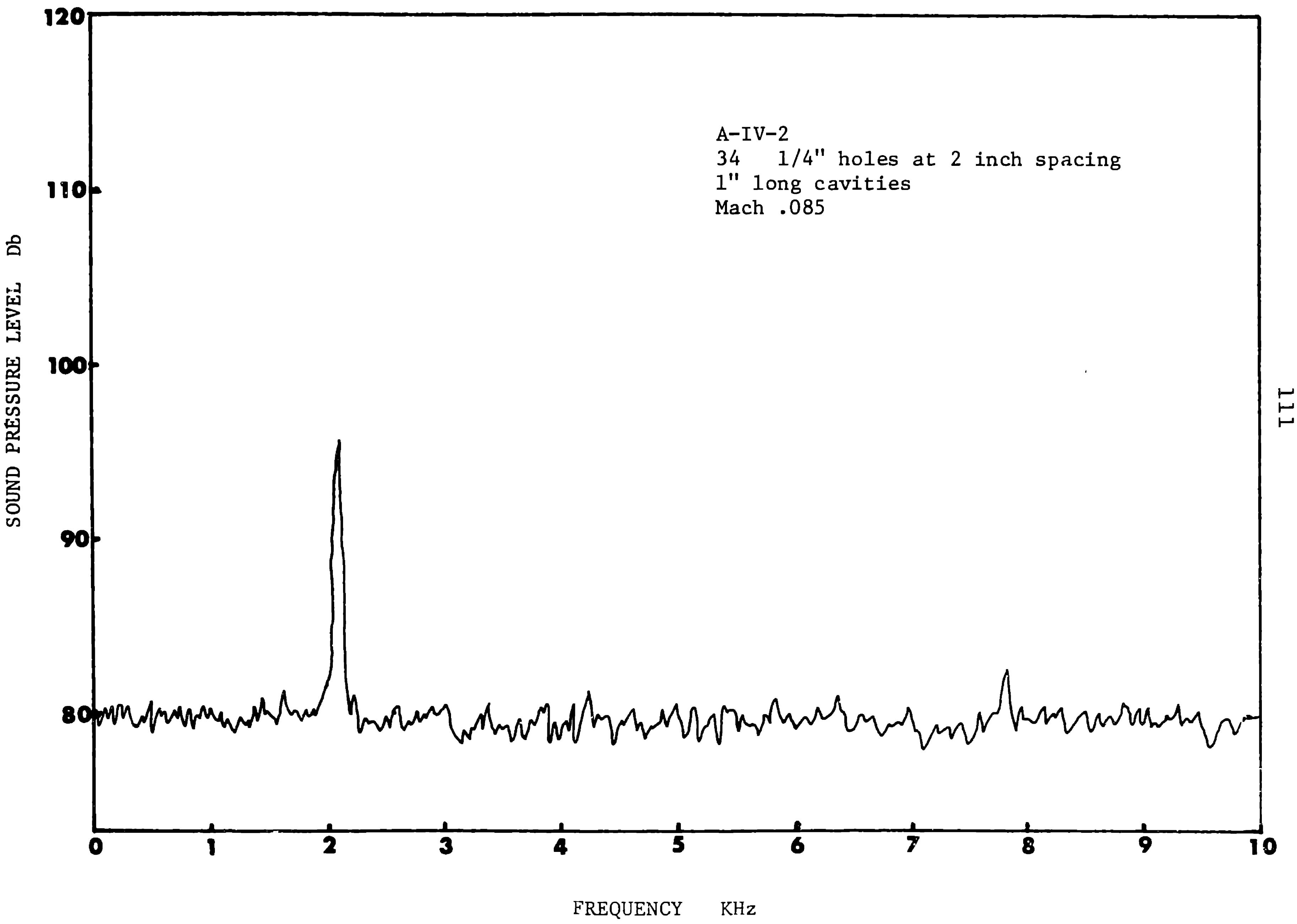

A-III-27
Slow increase of flow speed
Mach .073
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

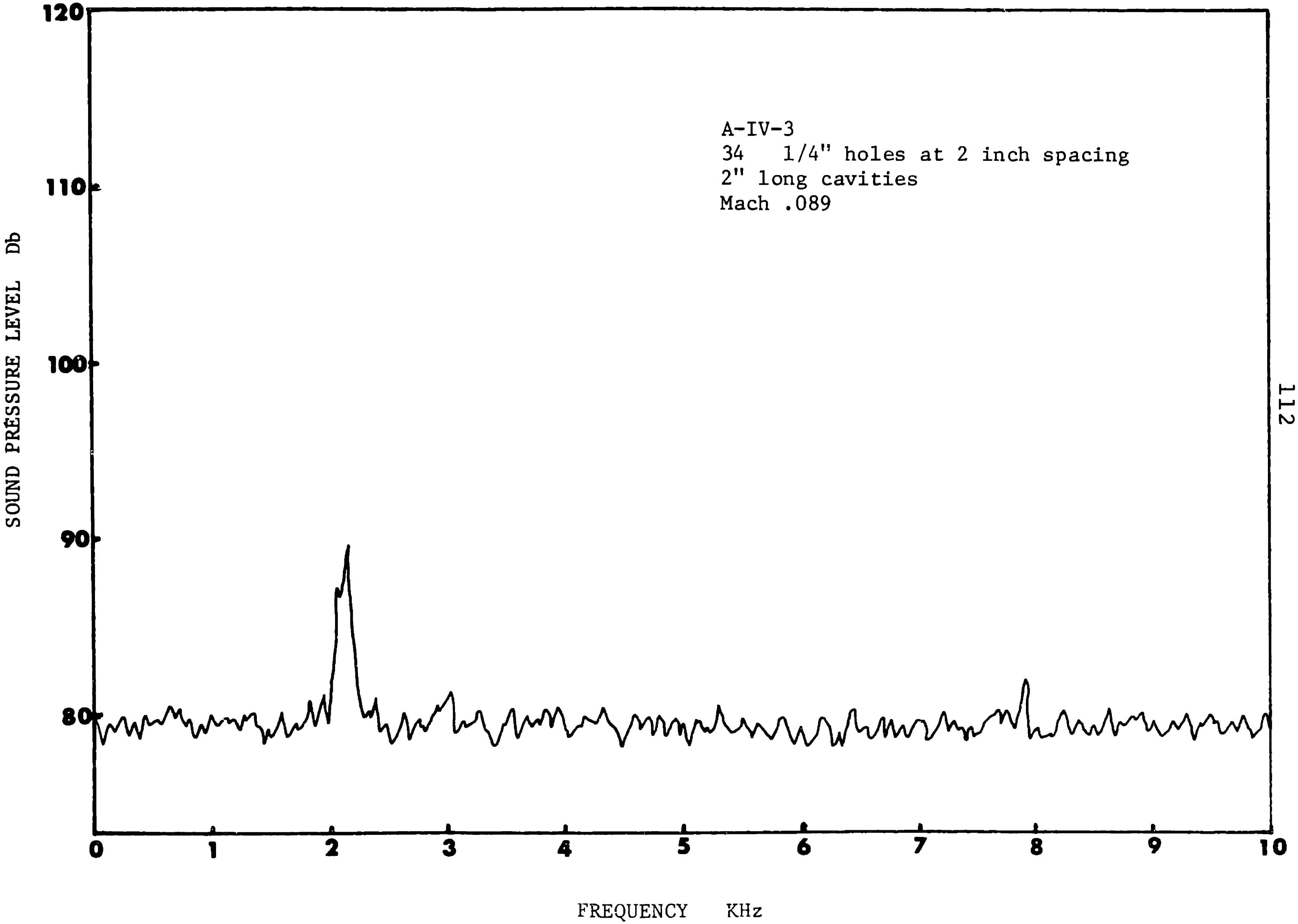

A-III-28
Highly perforated liner
20 Db amplification
Mach .127
SOUND PRESSURE LEVEL Db
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

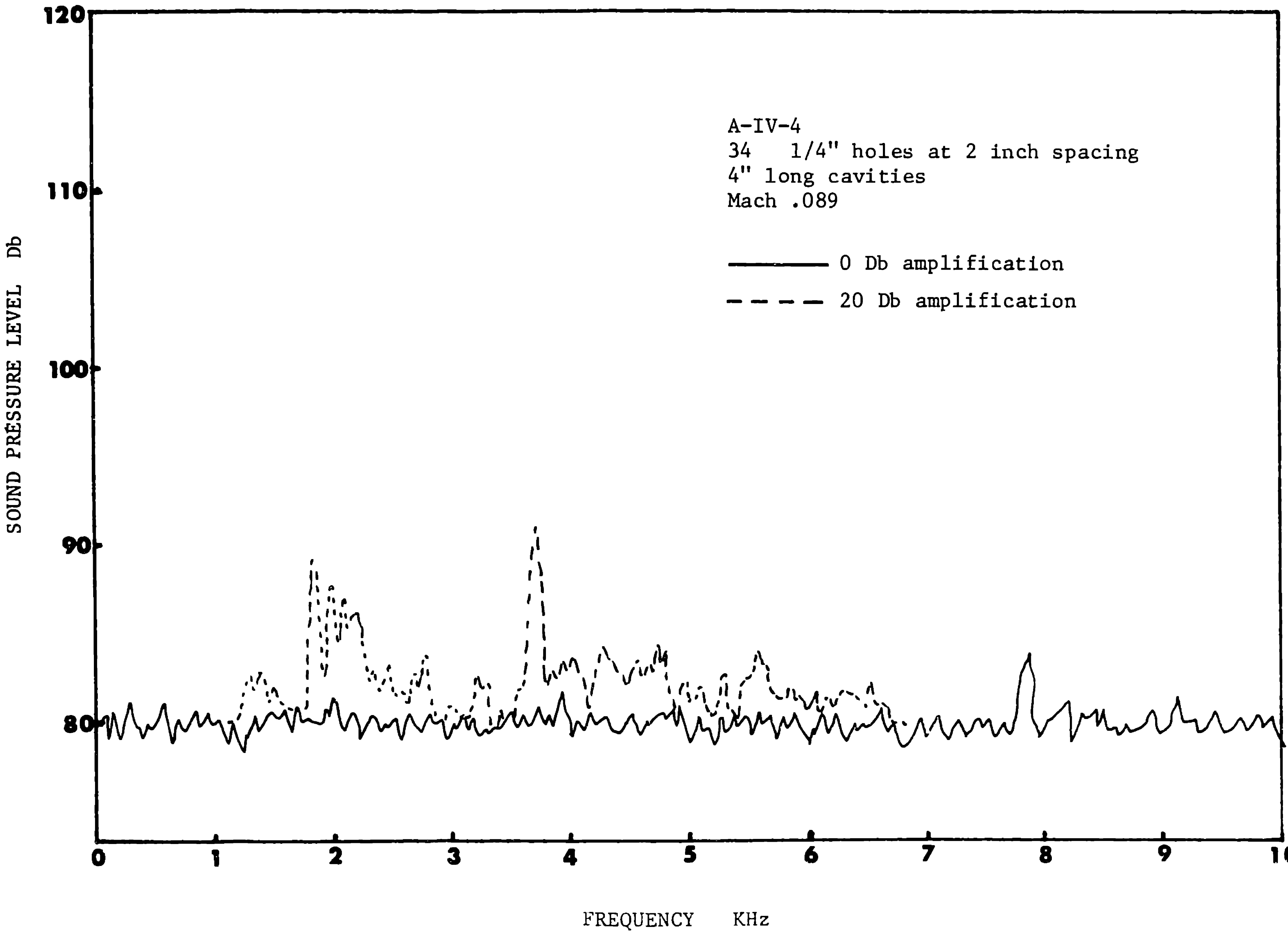

A-III-29
Highly perforated liner
20 Db amplification
Mach .164
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

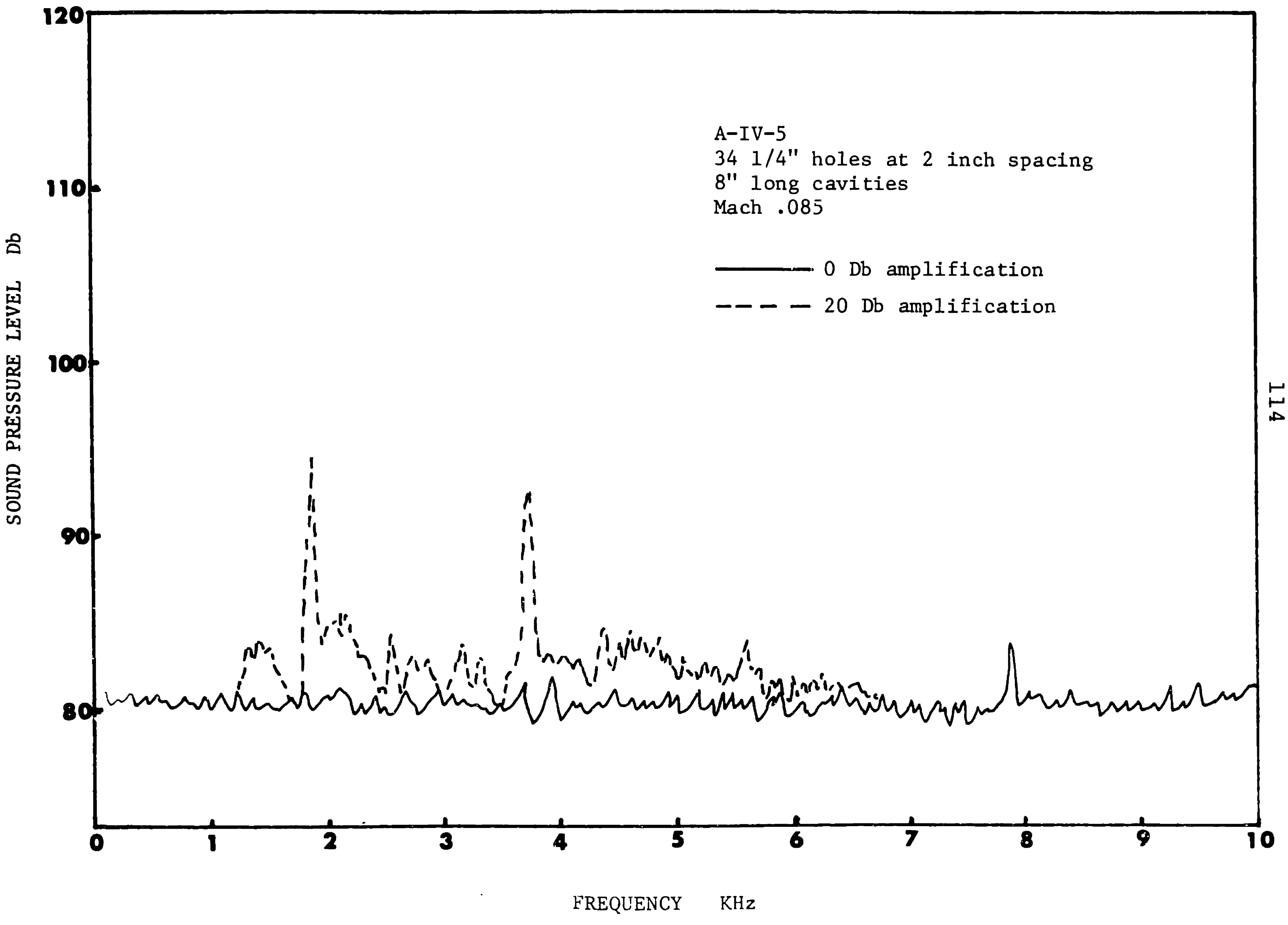

A-III-30
Highly perforated liner
20 Db amplification
Mach .200
SOUND PRESSURE LEVEL Db
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

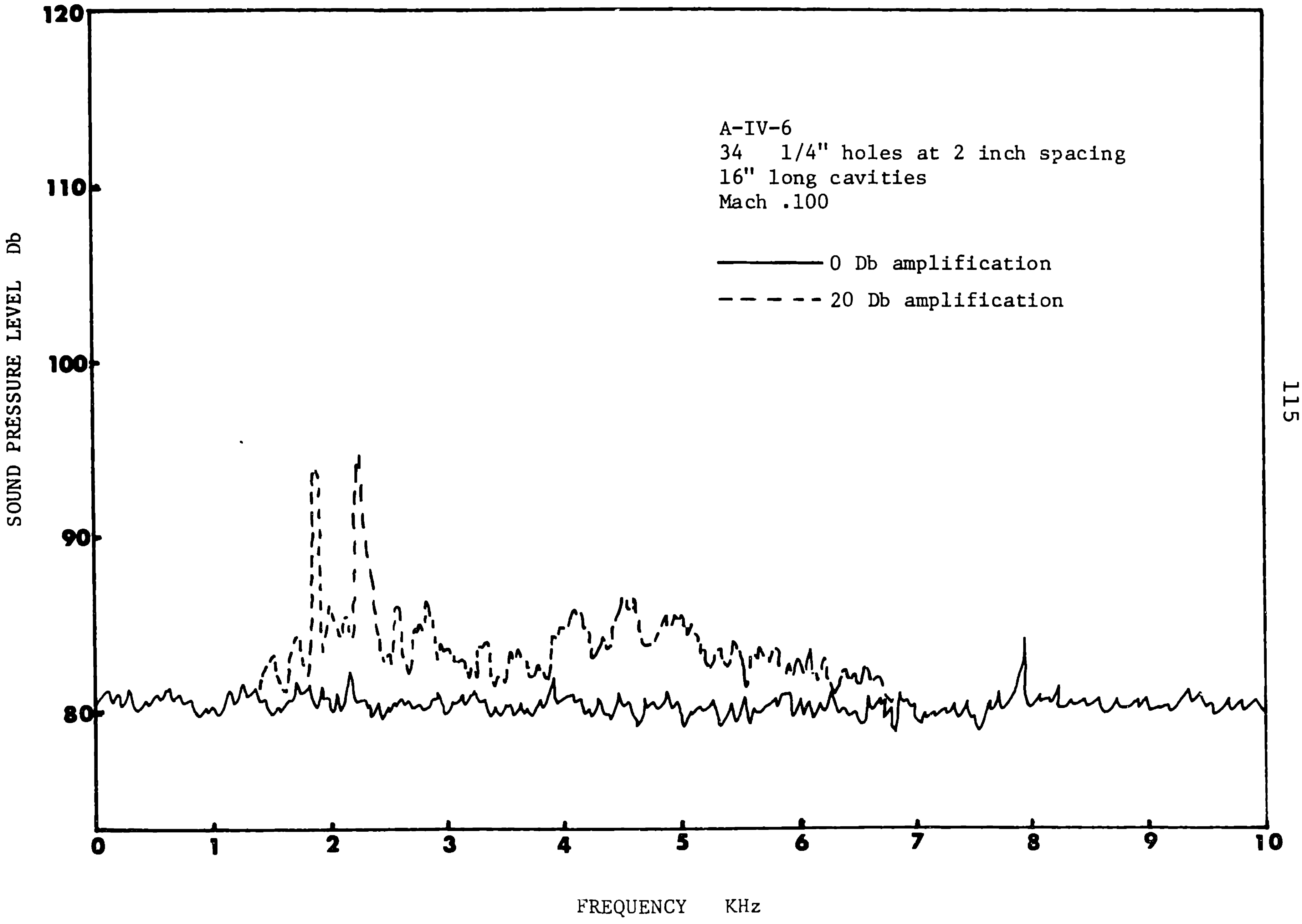

A-IV-1
Control- no holes
Mach .120
---- 20 Db amplification
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

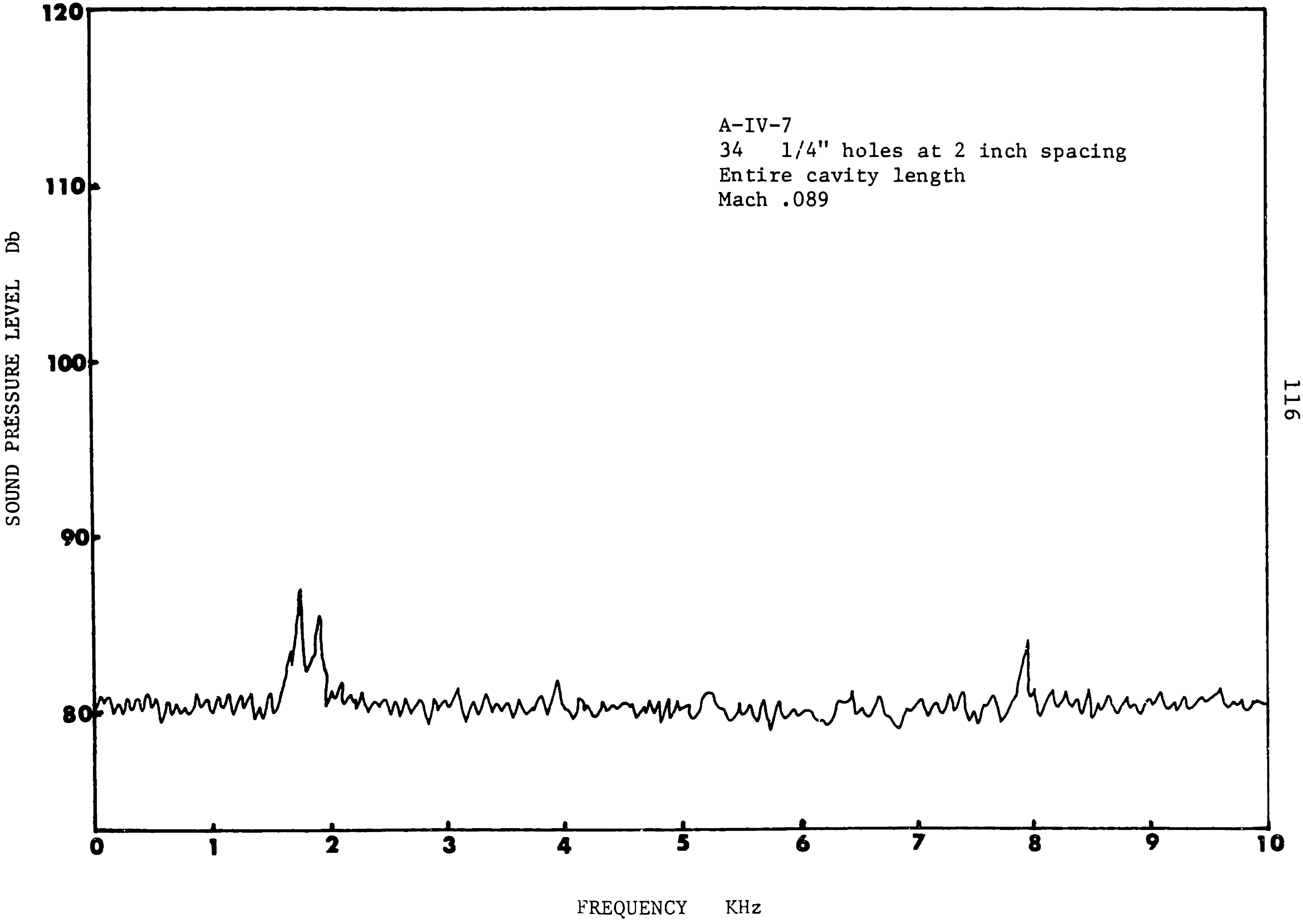

A-IV-2
34 1/4" holes at 2 inch spacing
1" long cavities
Mach .085
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

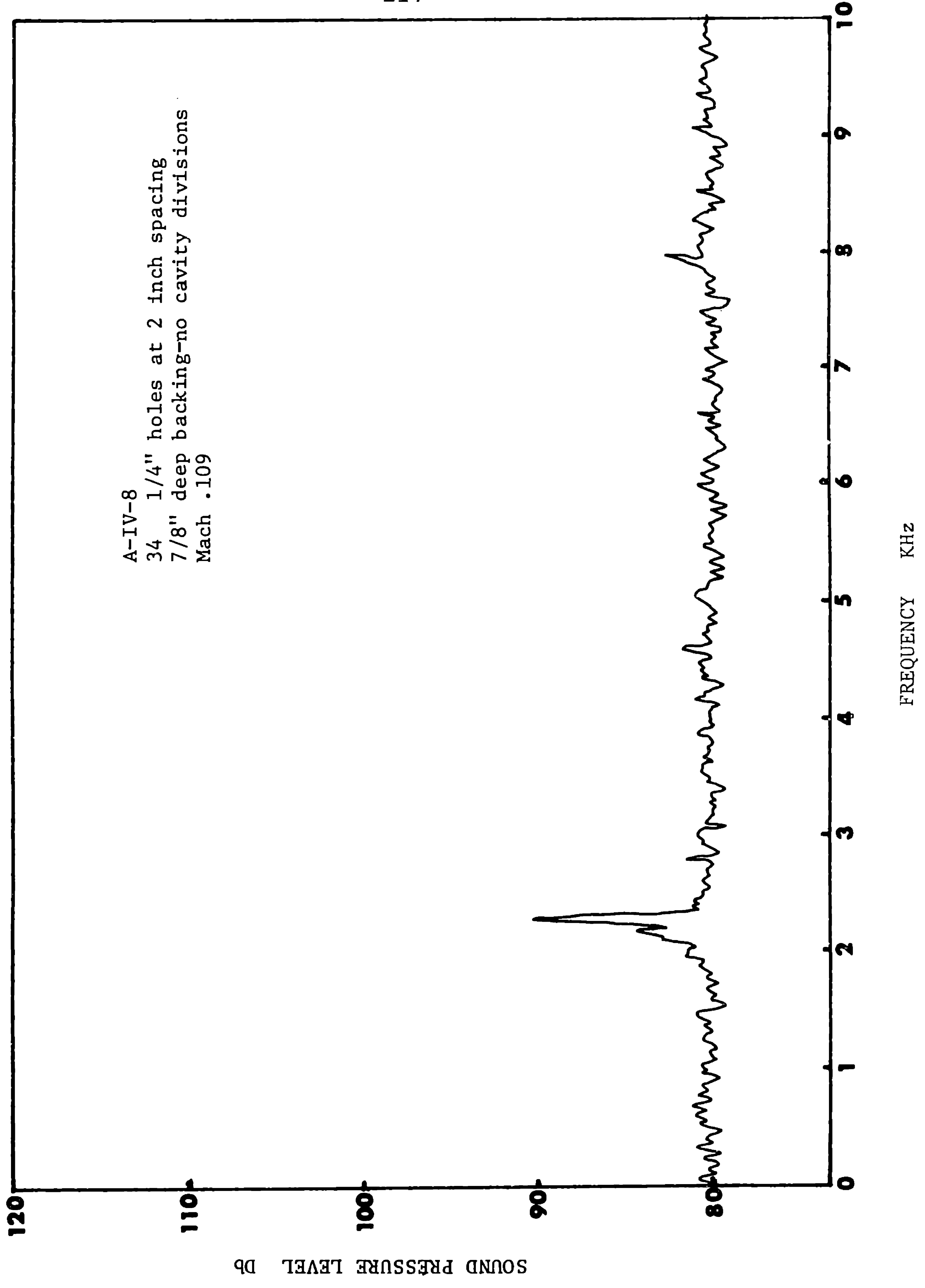

A-IV-3
34 1/4" holes at 2 inch spacing
2" long cavities
Mach .089
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

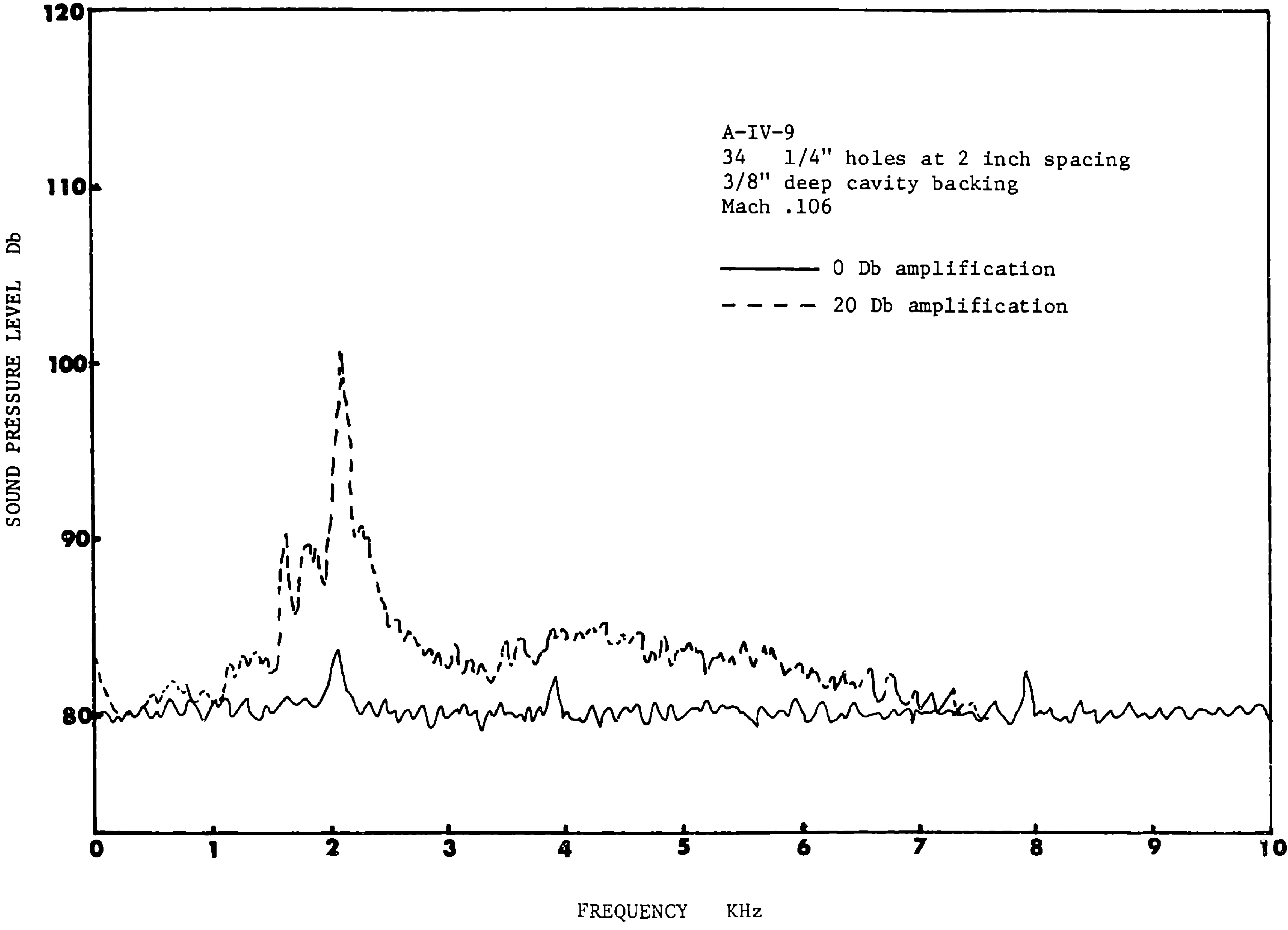

A-IV-4
34 1/4" holes at 2 inch spacing
4" long cavities
Mach .089
0 Db amplification
20 Db amplification
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

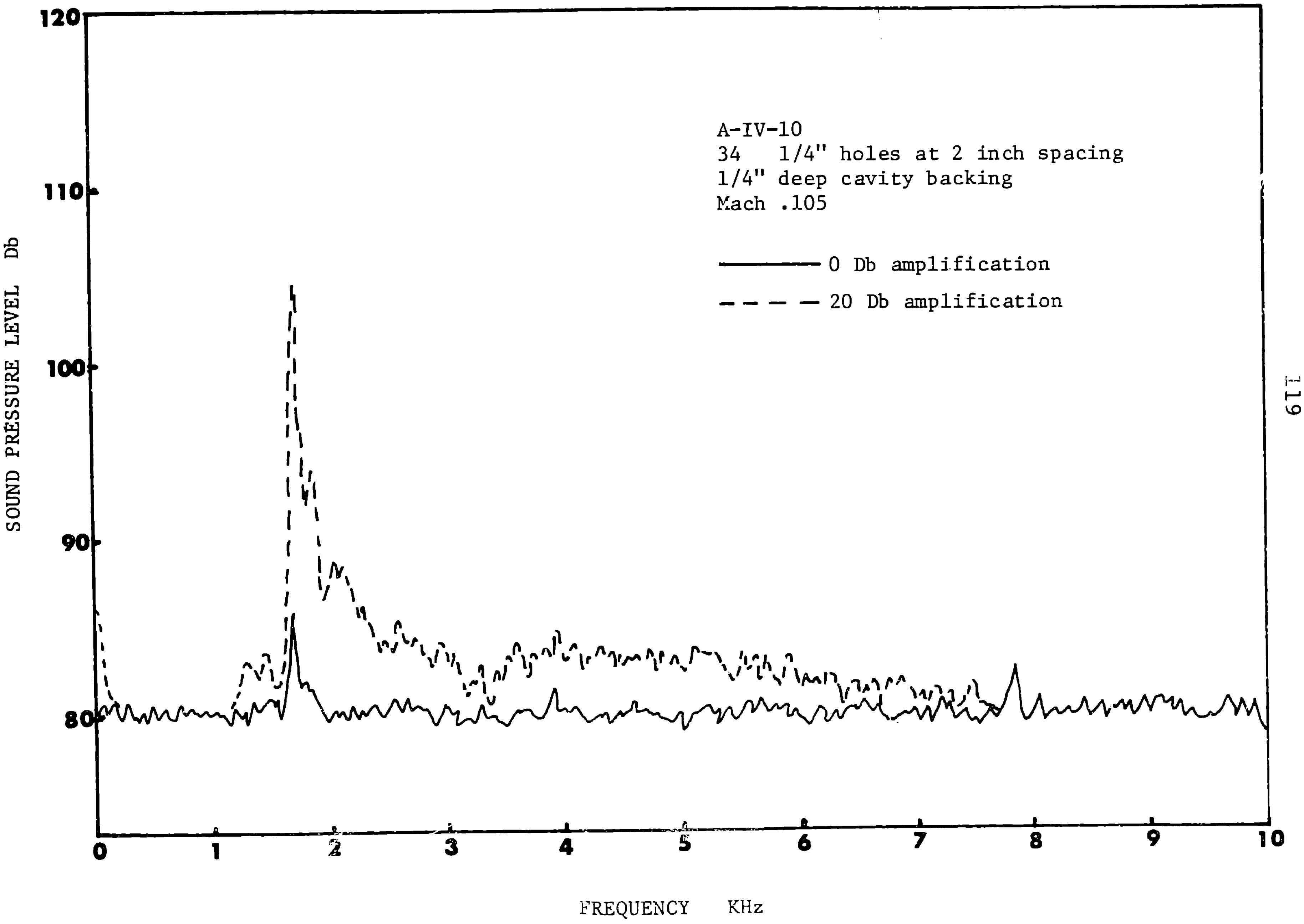

A-IV-5
34 1/4" holes at 2 inch spacing
8" long cavities
Mach .085
0 Db amplification
20 Db amplification
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

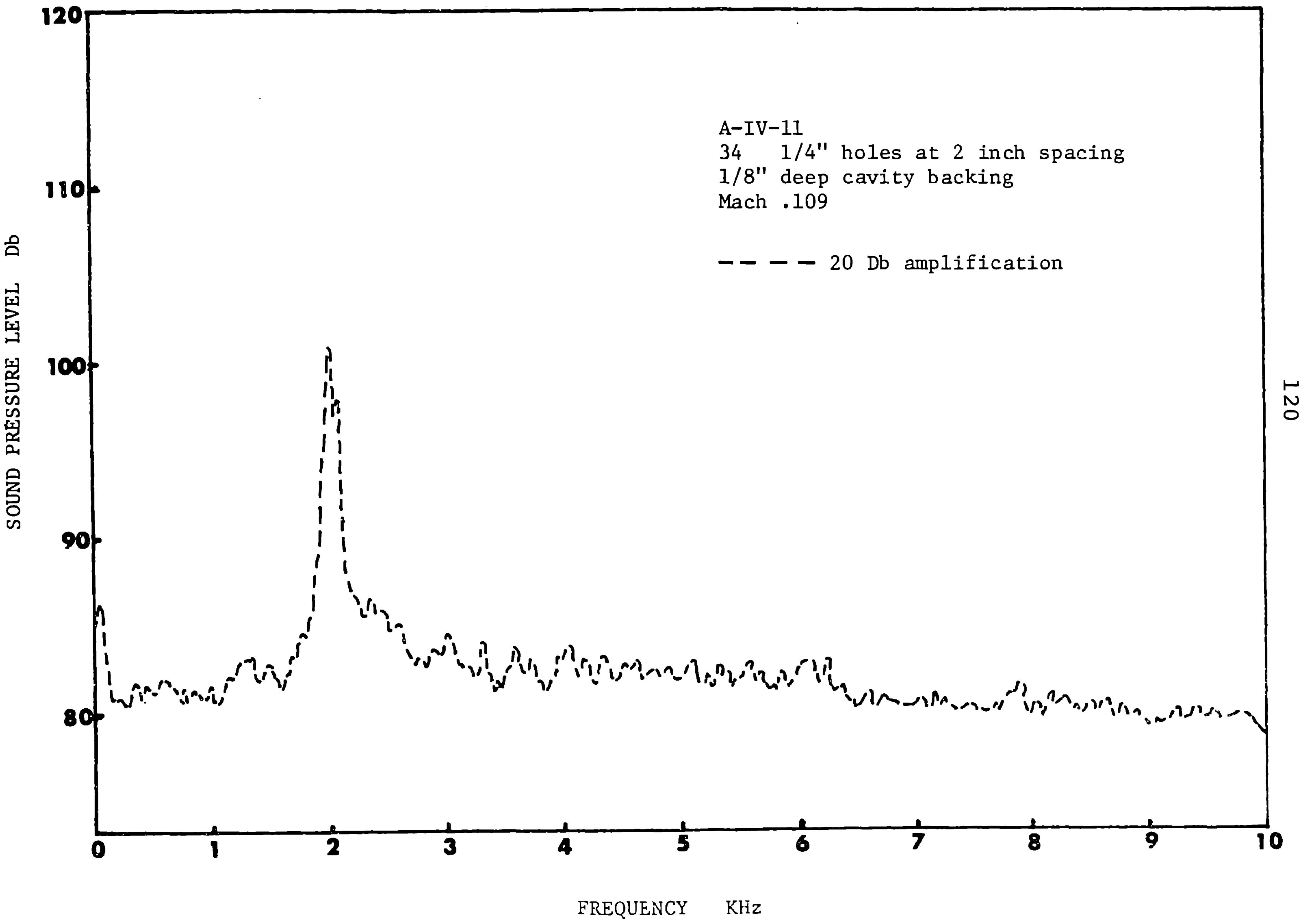

A-IV-6
34 1/4" holes at 2 inch spacing
16" long cavities
Mach .100
0 Db amplification
20 Db amplification
SOUND PRESSURE LEVEL Db
120
110
100
90
80
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

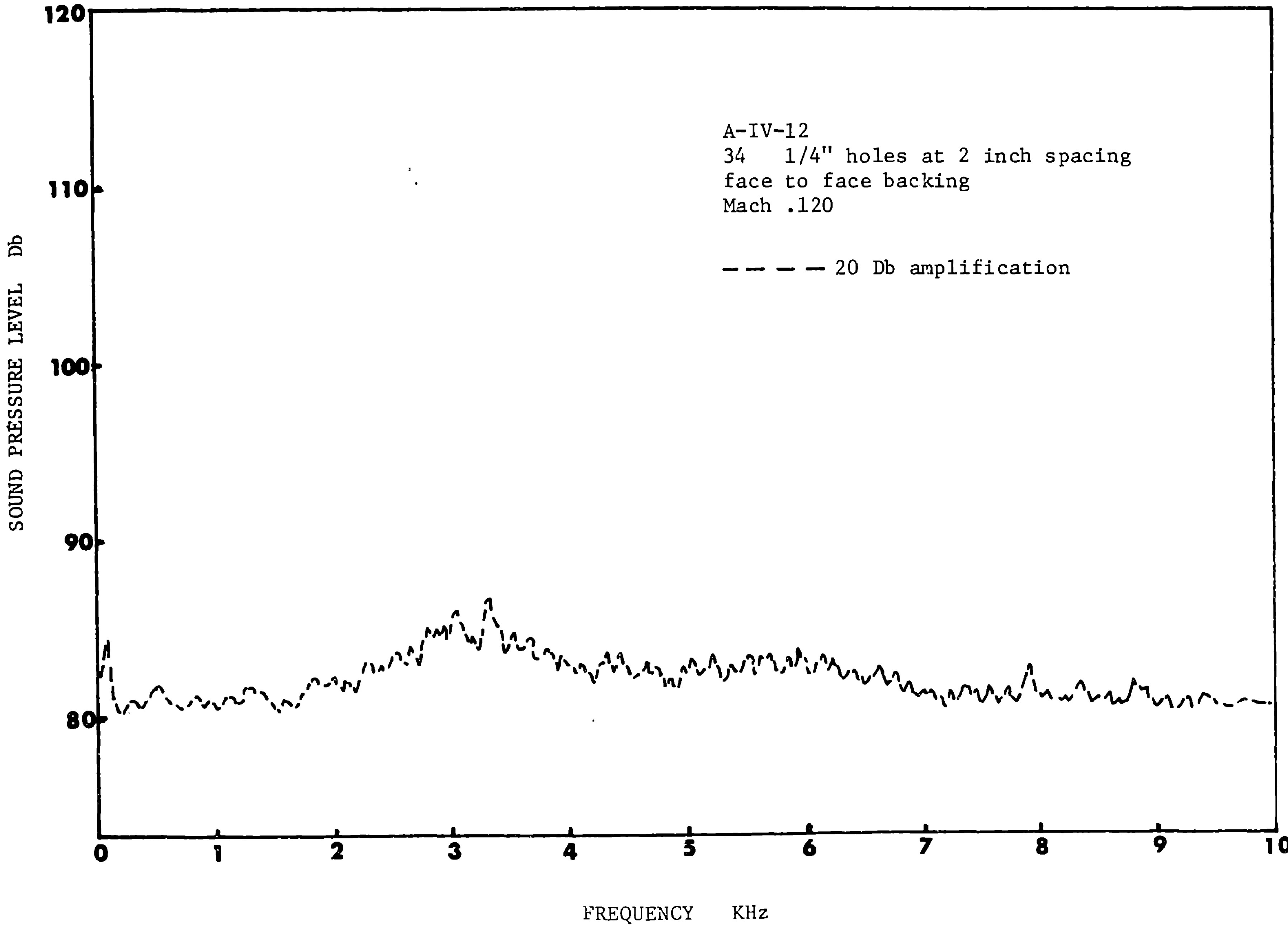

A-IV-7
34 1/4" holes at 2 inch spacing
Entire cavity length
Mach .089
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

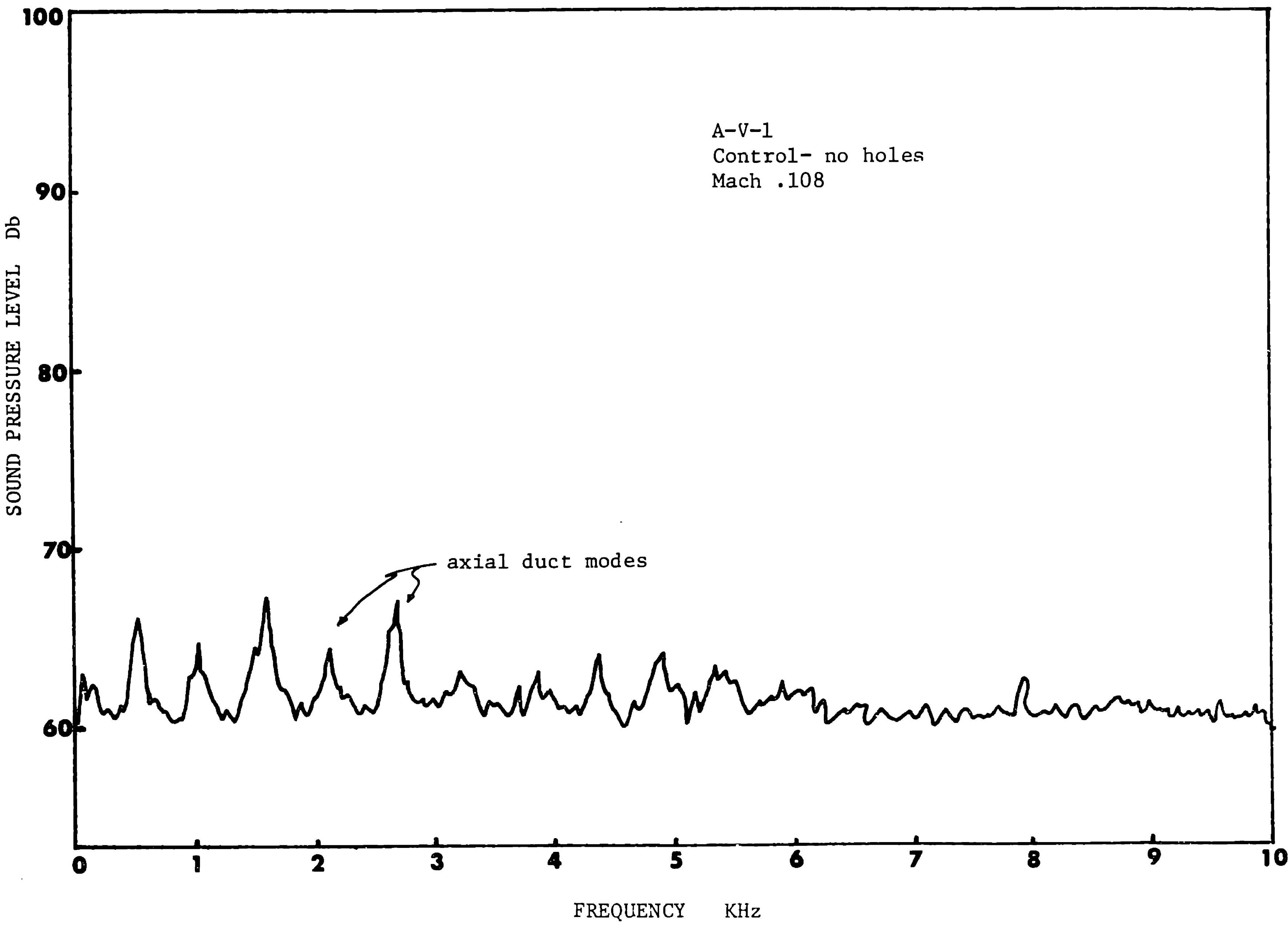

A-IV-8
34 1/4" holes at 2 inch spacing
7/8" deep backing-no cavity divisions
Mach .109
SOUND PRESSURE LEVEL Db
80
90
100
110
120
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

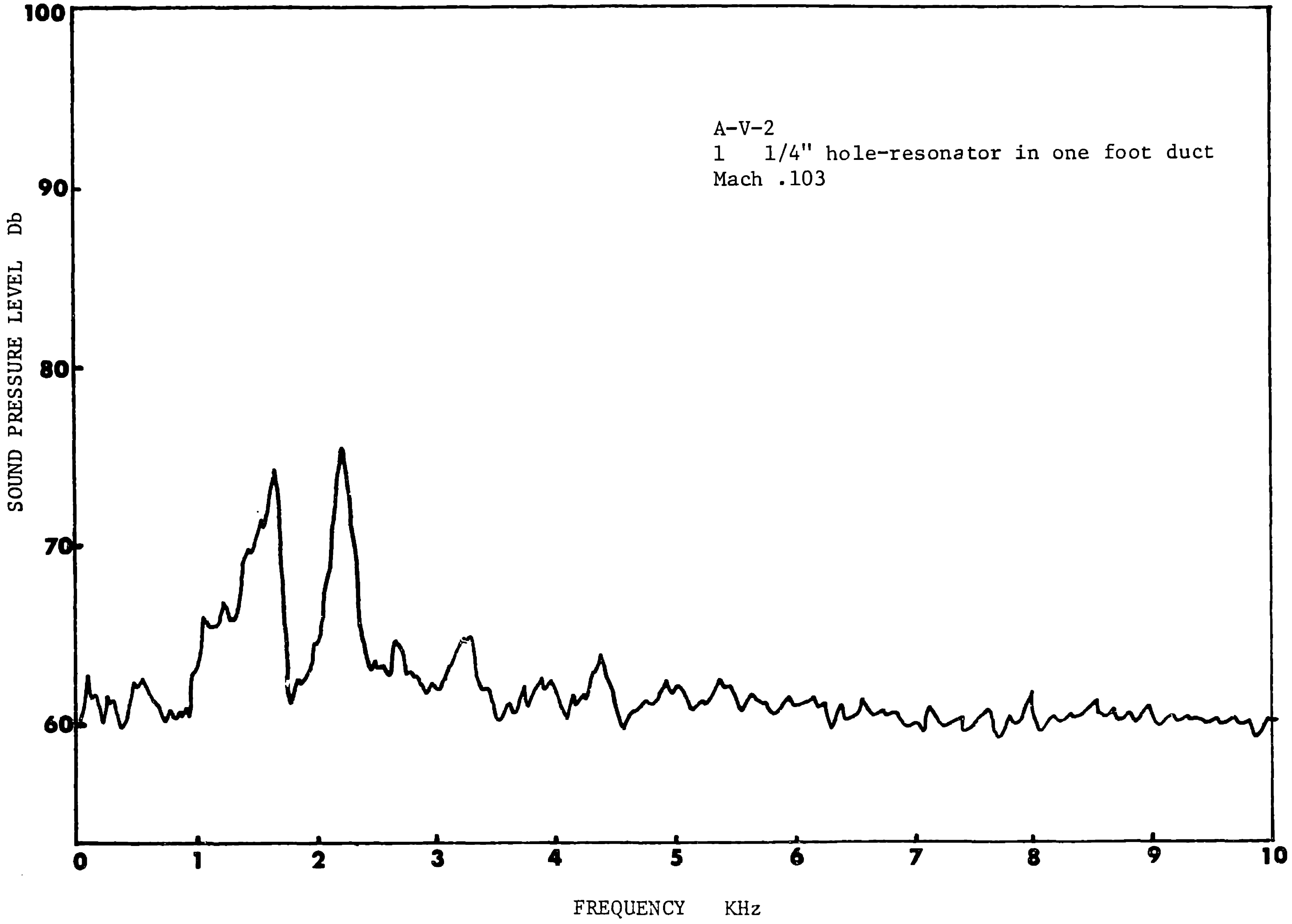

A-IV-9
34 1/4" holes at 2 inch spacing
3/8" deep cavity backing
Mach .106
0 Db amplification
20 Db amplification
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

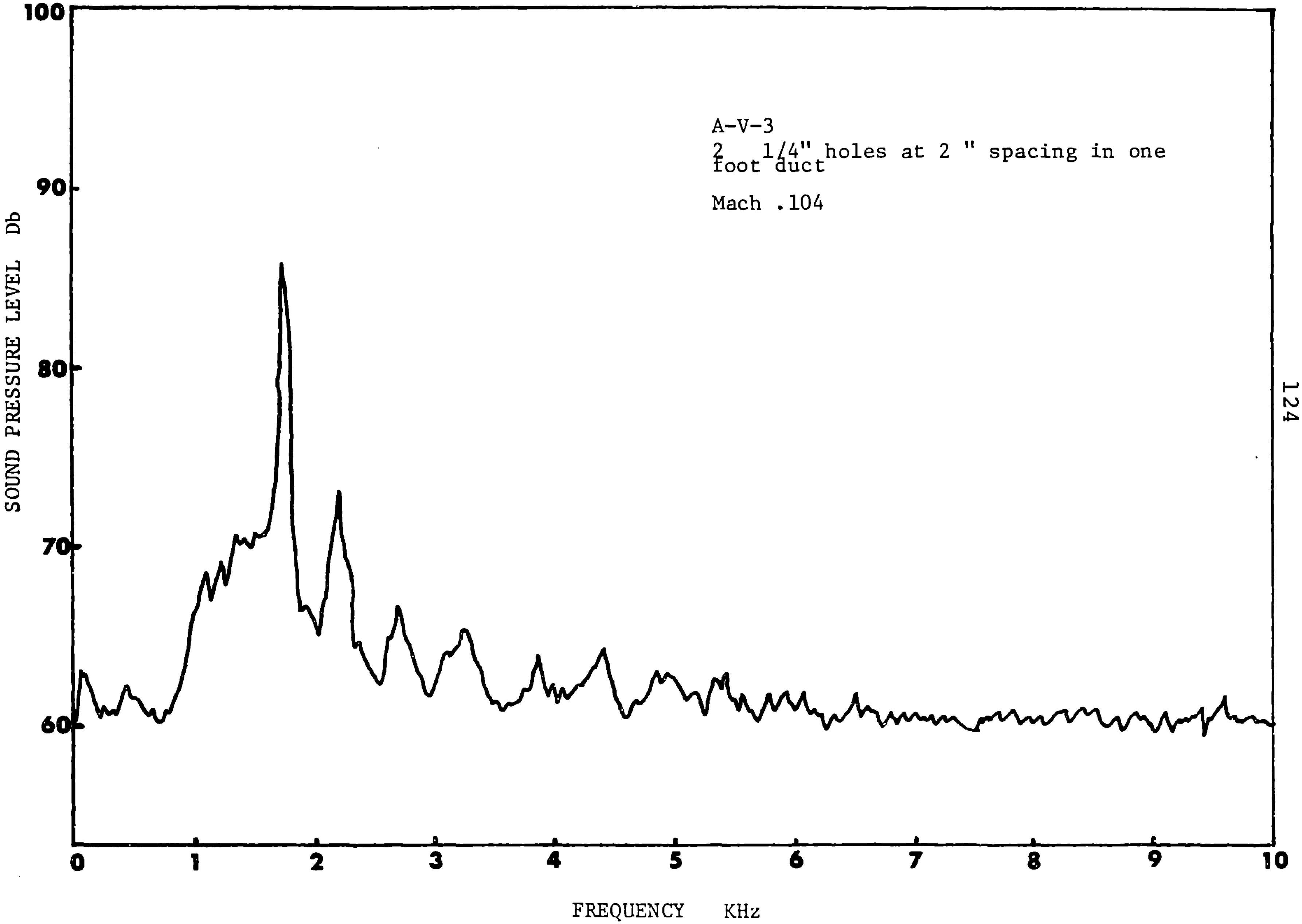

A-IV-10
34 1/4" holes at 2 inch spacing
1/4" deep cavity backing
Mach .105
0 Db amplification
20 Db amplification
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

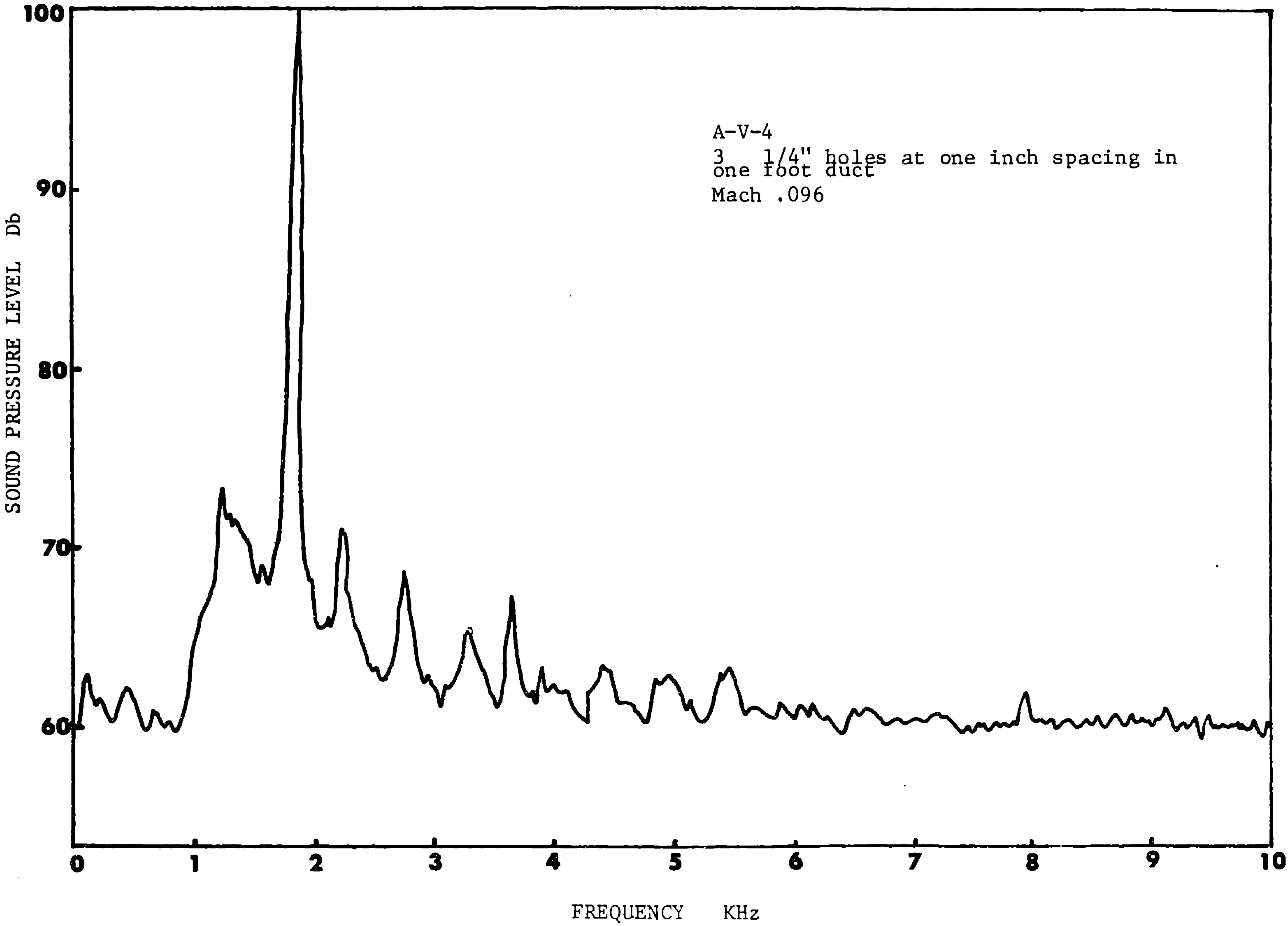

A-IV-11
34 1/4" holes at 2 inch spacing
1/8" deep cavity backing
Mach .109
— — — — 20 Db amplification
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

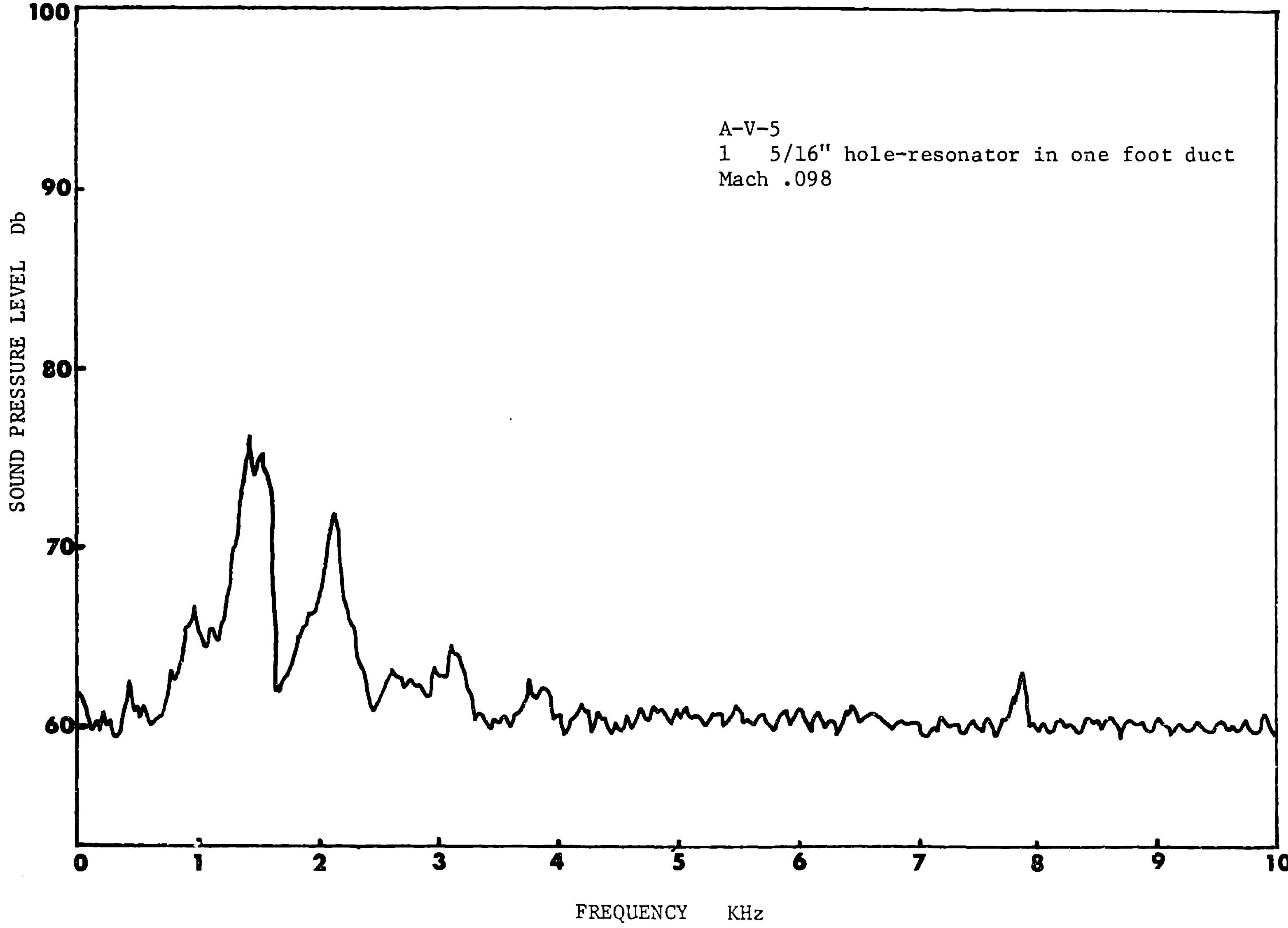

A-IV-12
34 1/4" holes at 2 inch spacing
face to face backing
Mach .120
– – – – 20 Db amplification
SOUND PRESSURE LEVEL Db
120
110
100
90
80
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

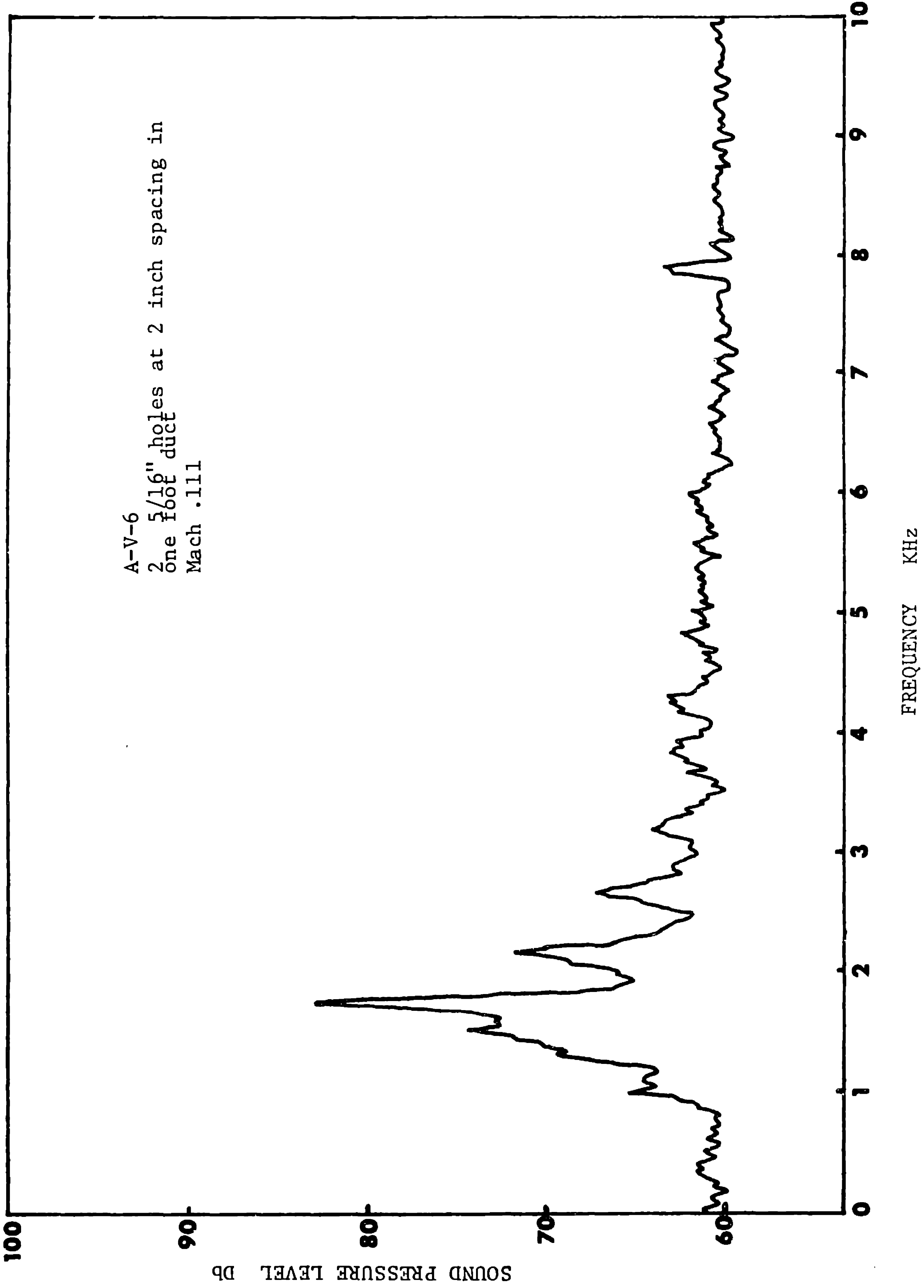

A-V-1
Control- no holes
Mach .108
axial duct modes
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz


A-V-2
1 1/4" hole-resonator in one foot duct
Mach .103
SOUND PRESSURE LEVEL Db
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

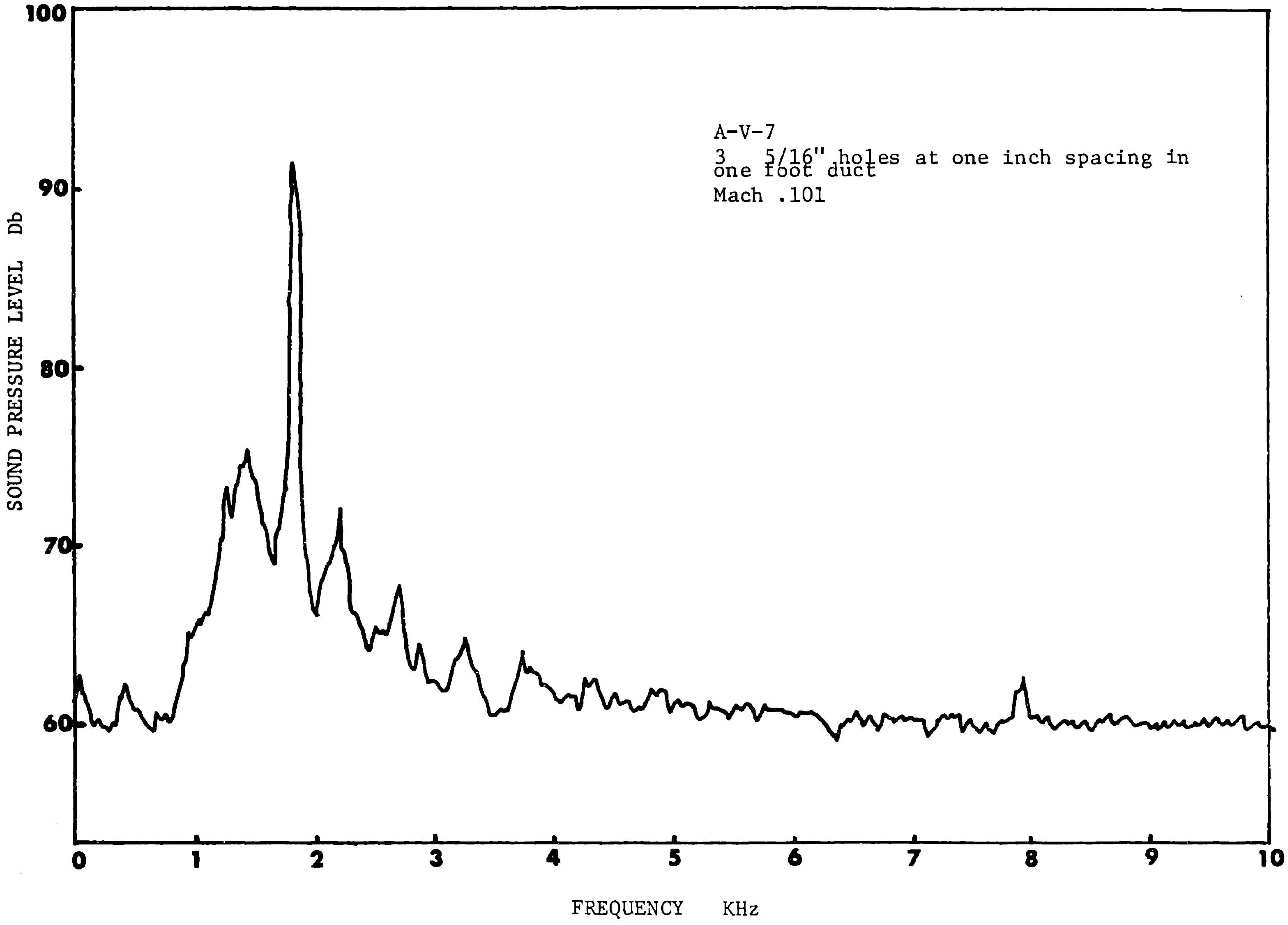

A-V-3
2 1/4" holes at 2 " spacing in one foot duct
Mach .104
SOUND PRESSURE LEVEL Db
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

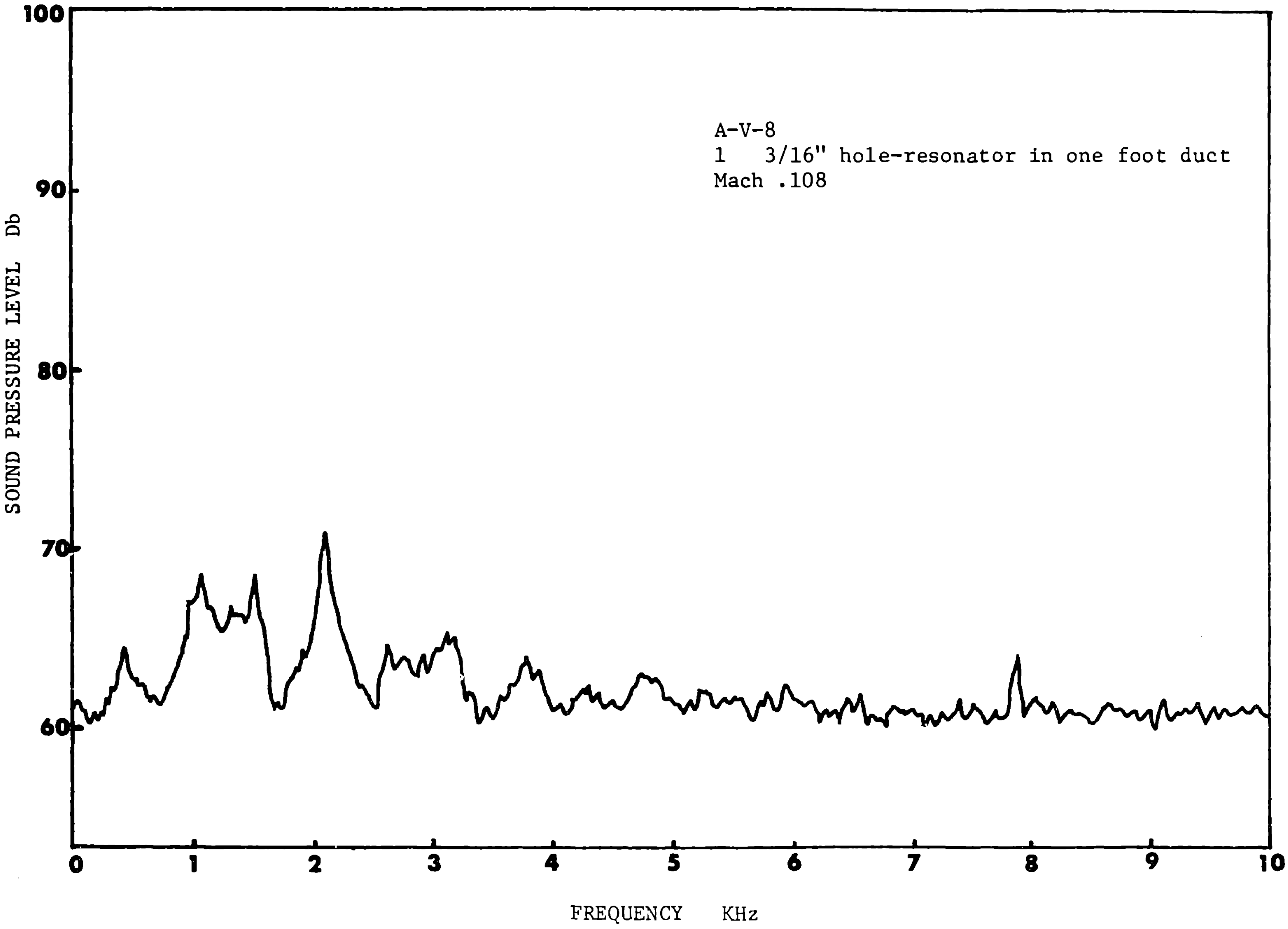

A-V-4
3 1/4" holes at one inch spacing in one foot duct
Mach .096
SOUND PRESSURE LEVEL Db
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

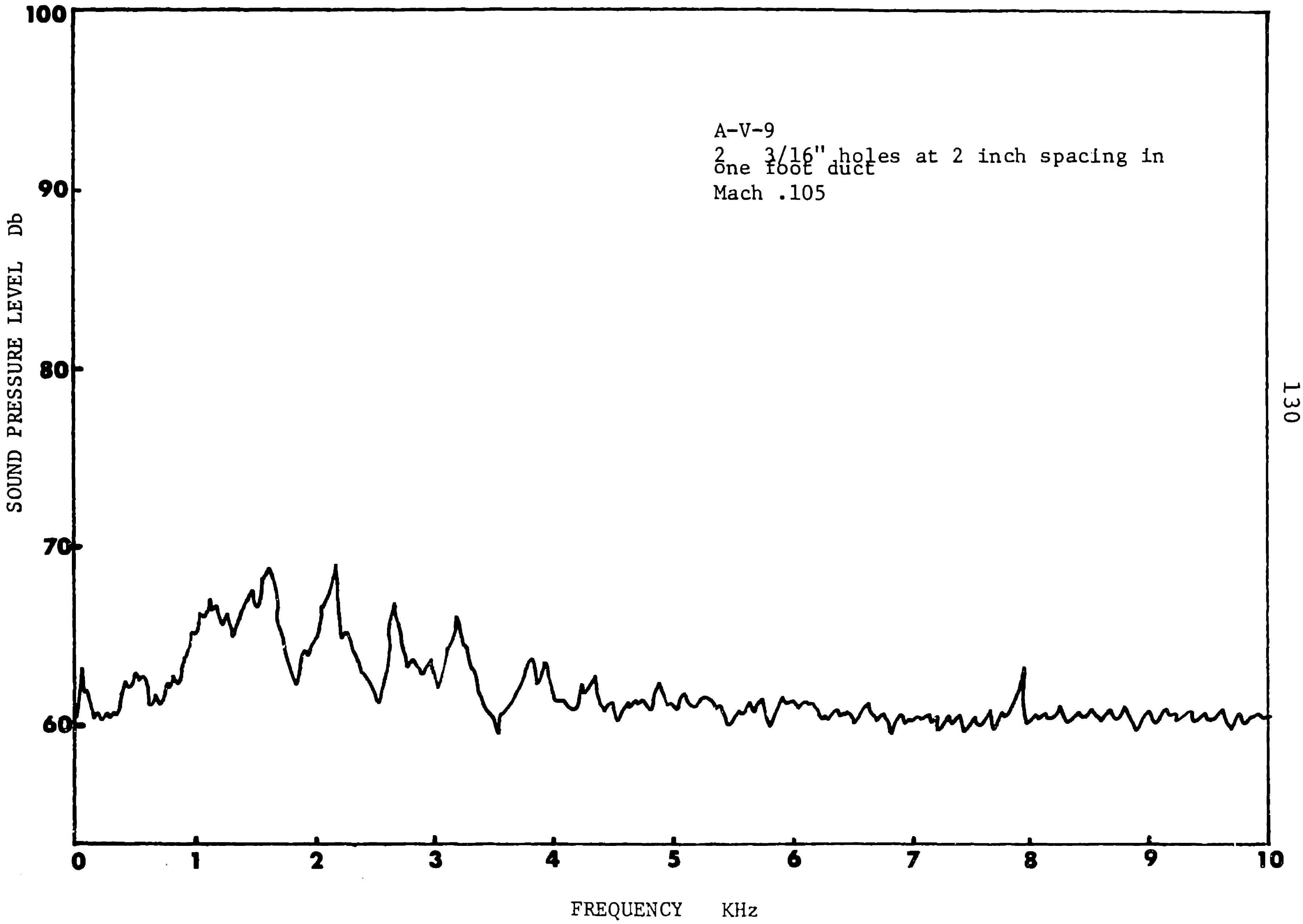

A-V-5
1 5/16" hole-resonator in one foot duct
Mach .098
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

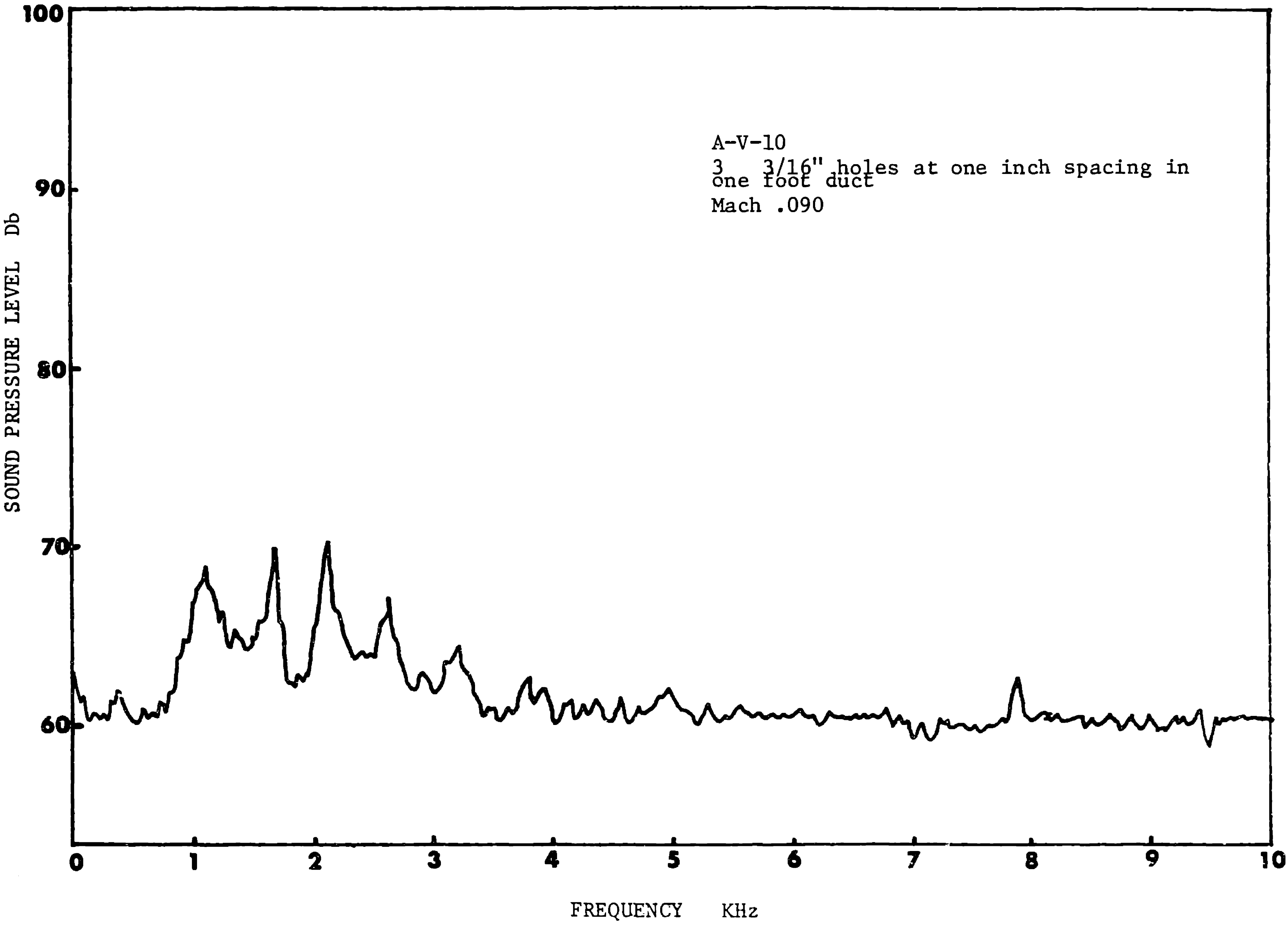


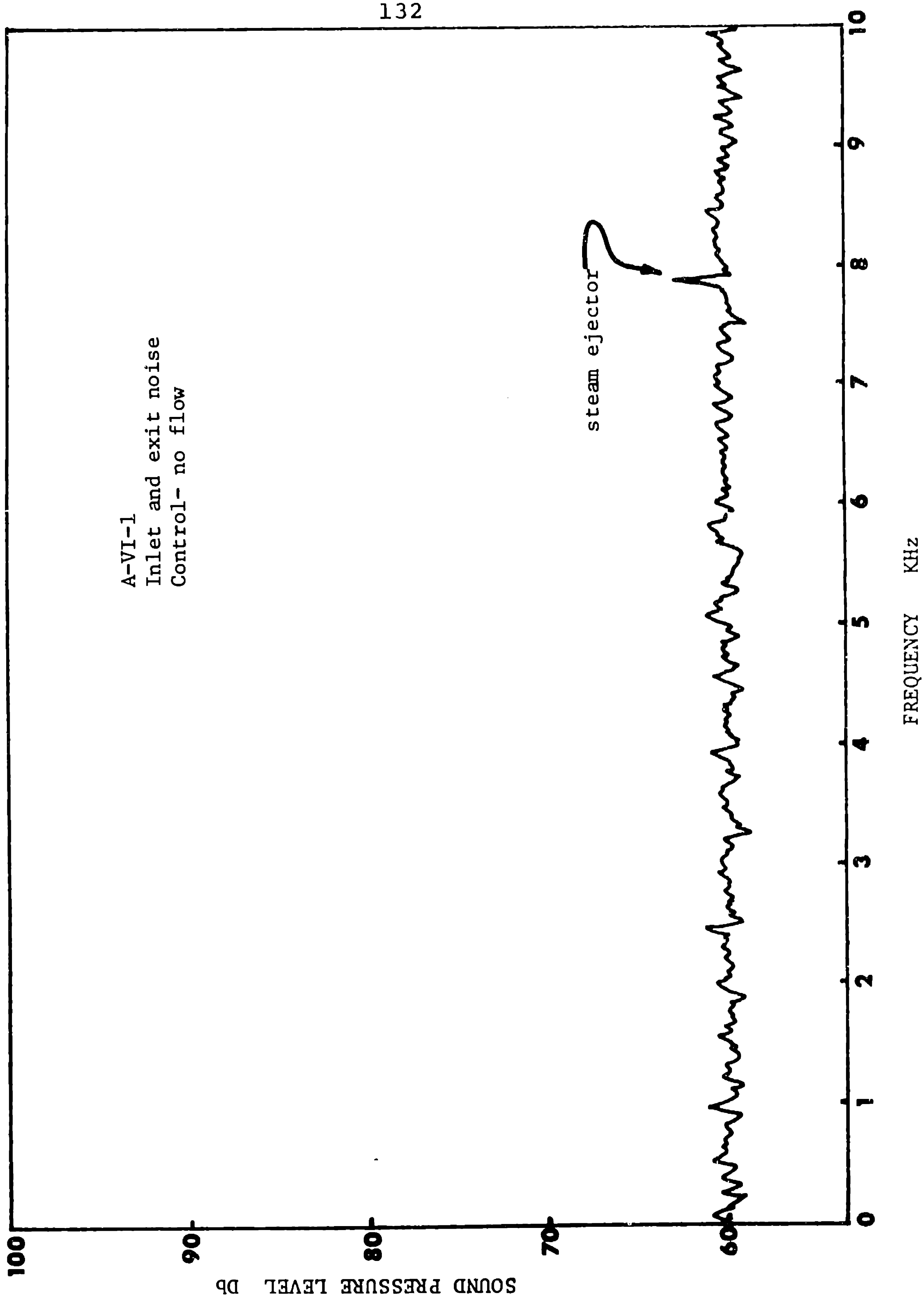
A-V-6
2 5/16" holes at 2 inch spacing in one foot duct
Mach .111

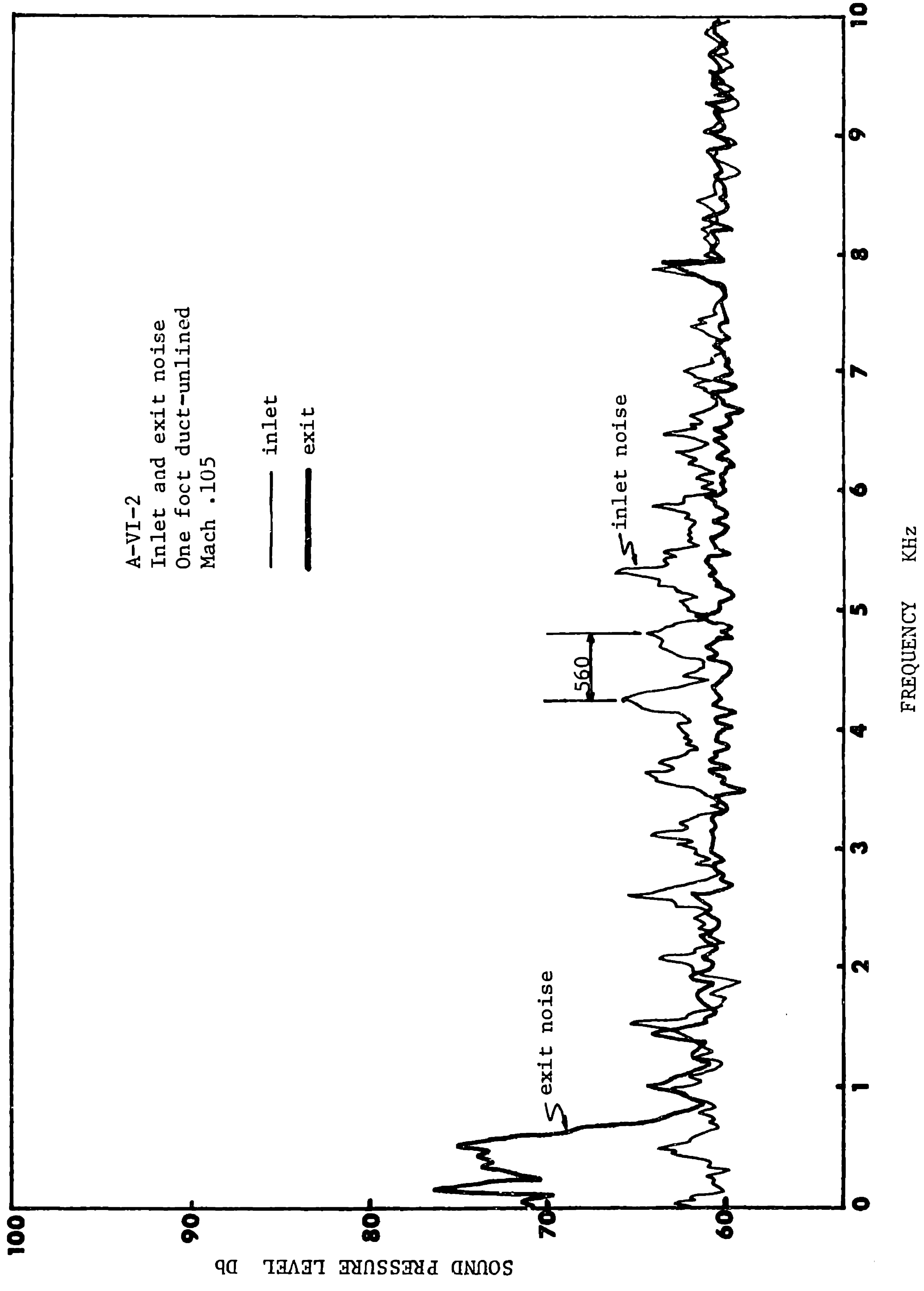

A-V-7
3 5/16" holes at one inch spacing in one foot duct
Mach .101
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

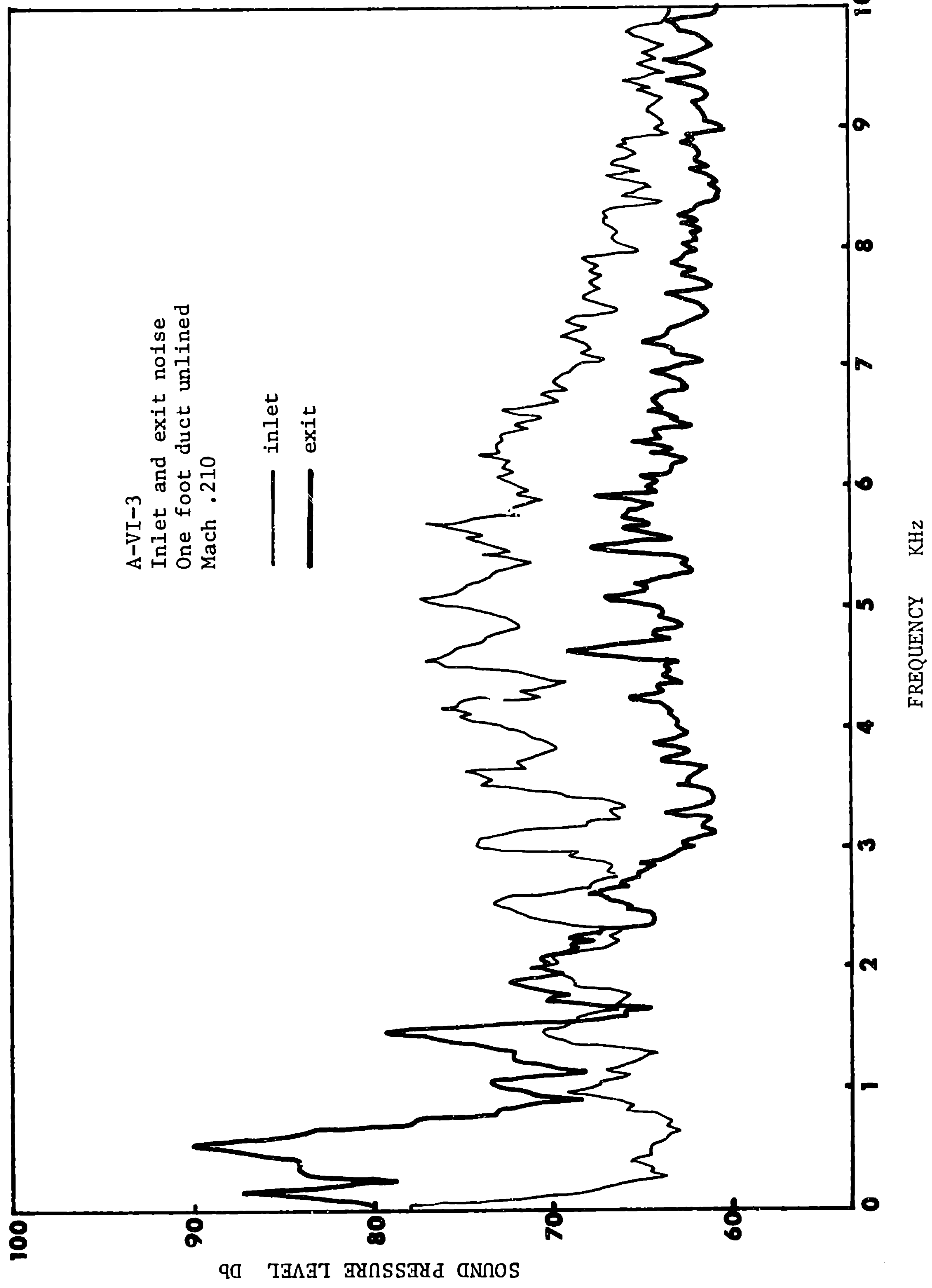

A-V-8
1 3/16" hole-resonator in one foot duct
Mach .108
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

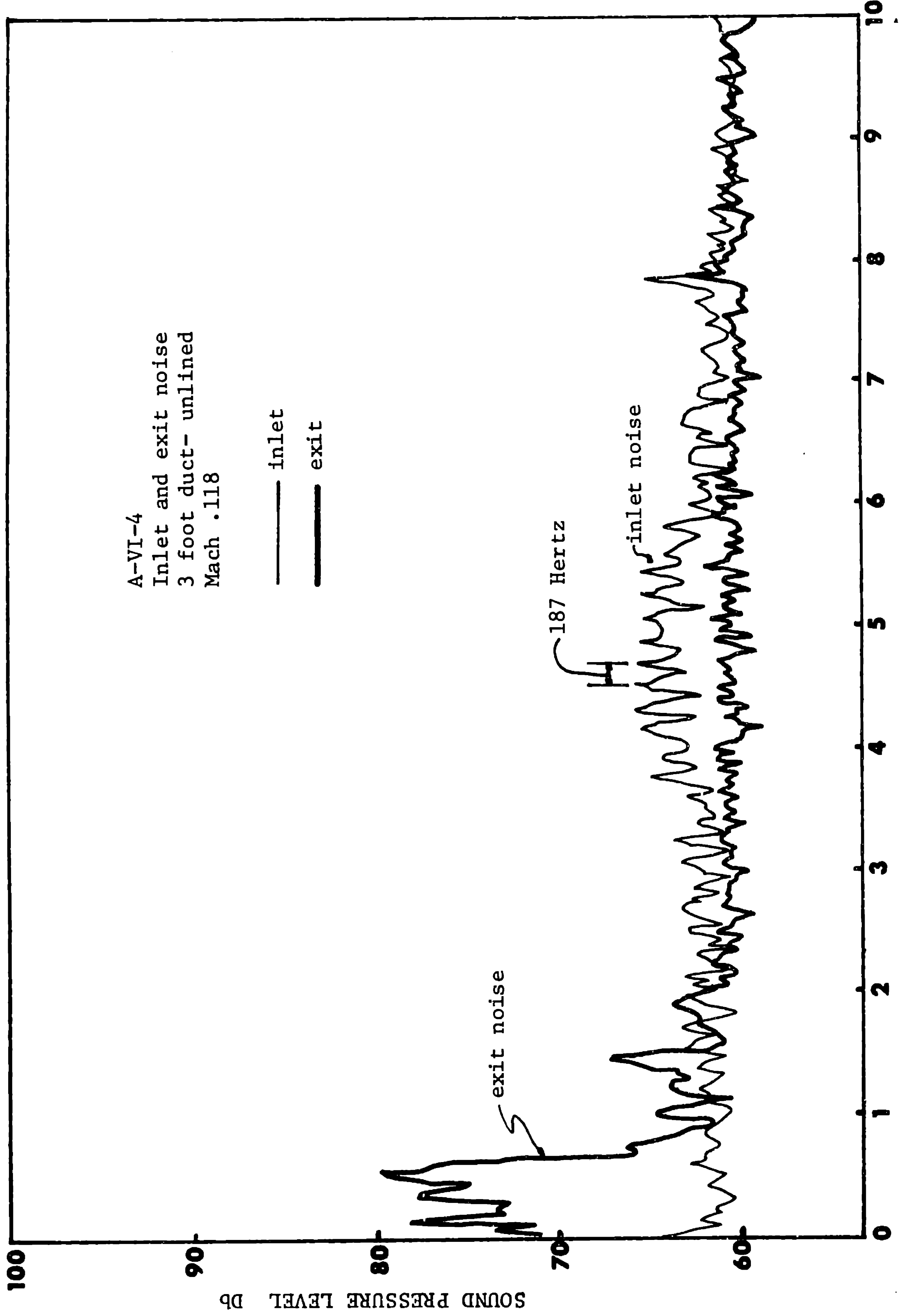

A-V-9
2 3/16" holes at 2 inch spacing in one foot duct
Mach .105
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

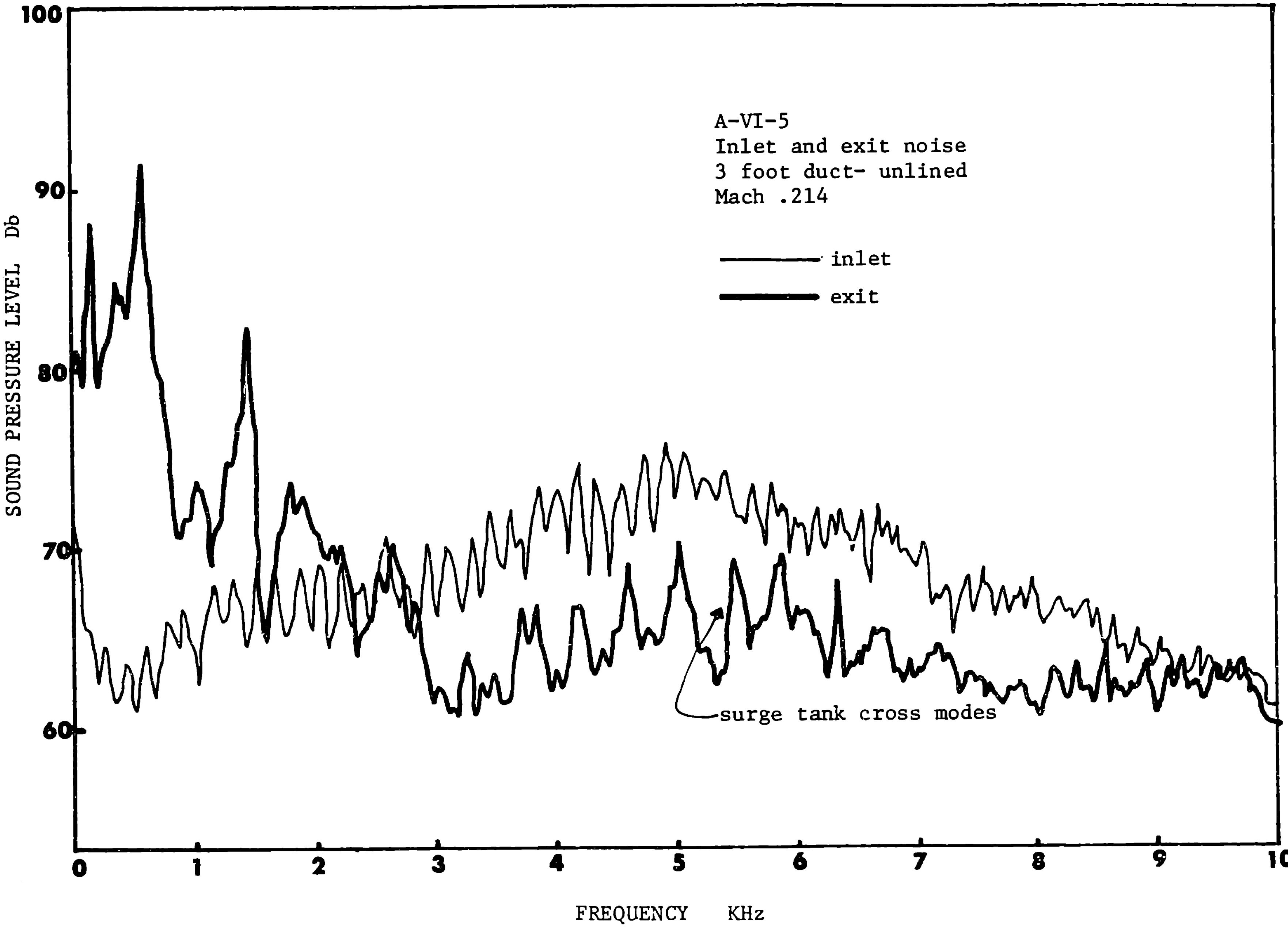

A-V-10
3 3/16" holes at one inch spacing in one foot duct
Mach .090
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

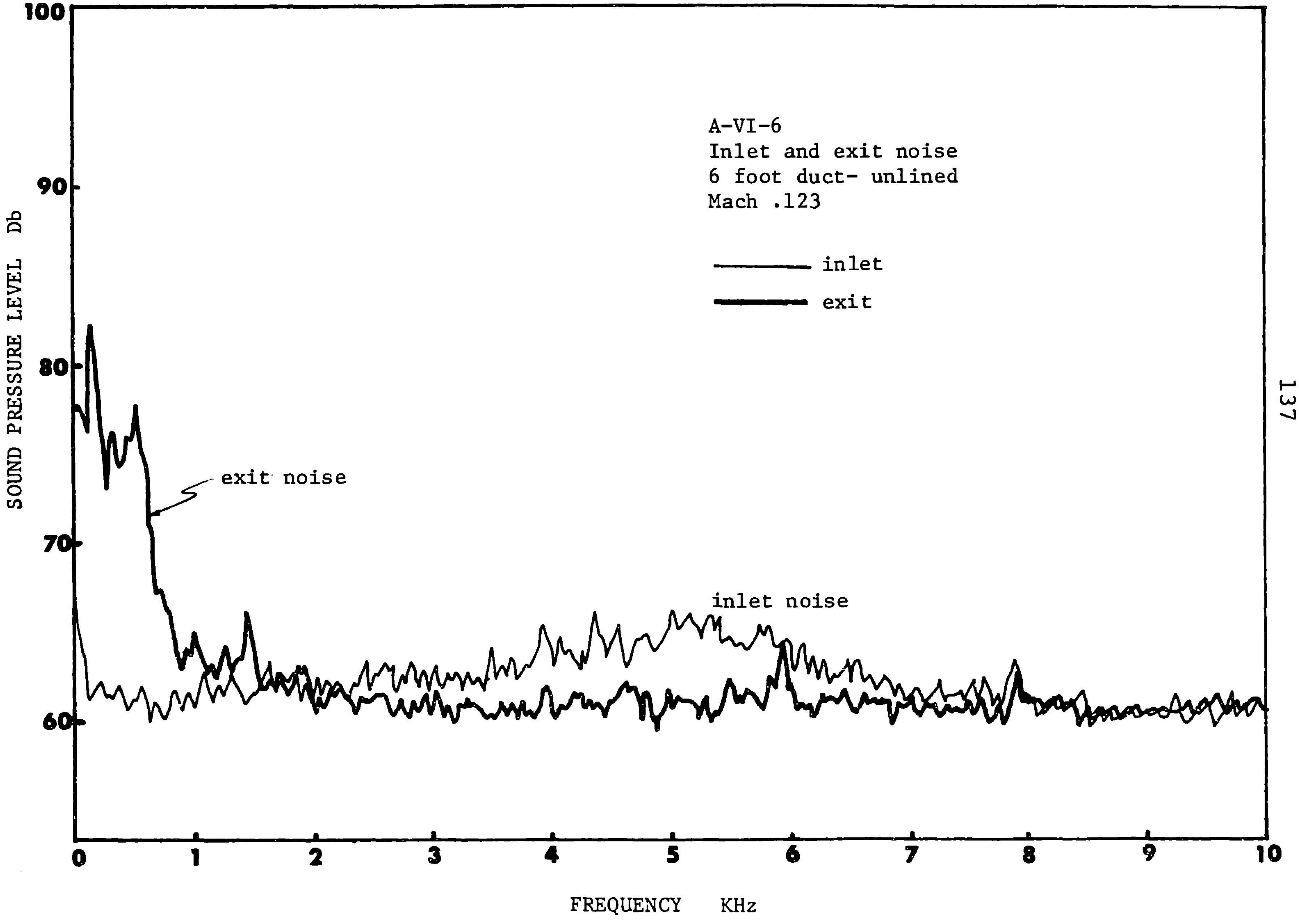

A-VI-1
Inlet and exit noise
Control- no flow
steam ejector
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10
SOUND PRESSURE LEVEL Db
60
70
80
90
100

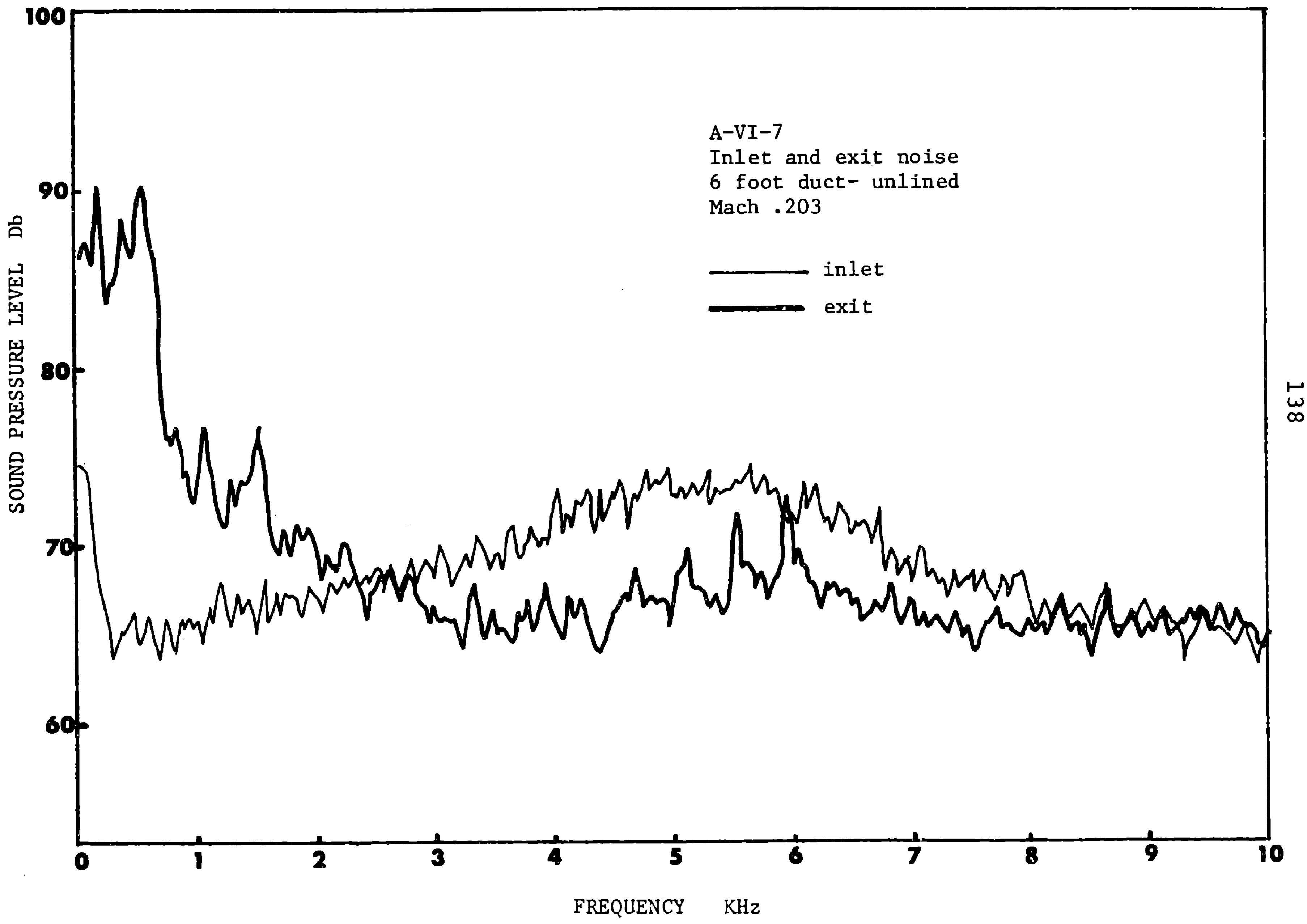

A-VI-2
Inlet and exit noise
One foot duct-unlined
Mach .105
inlet
exit
exit noise
inlet noise
560
SOUND PRESSURE LEVEL Db
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

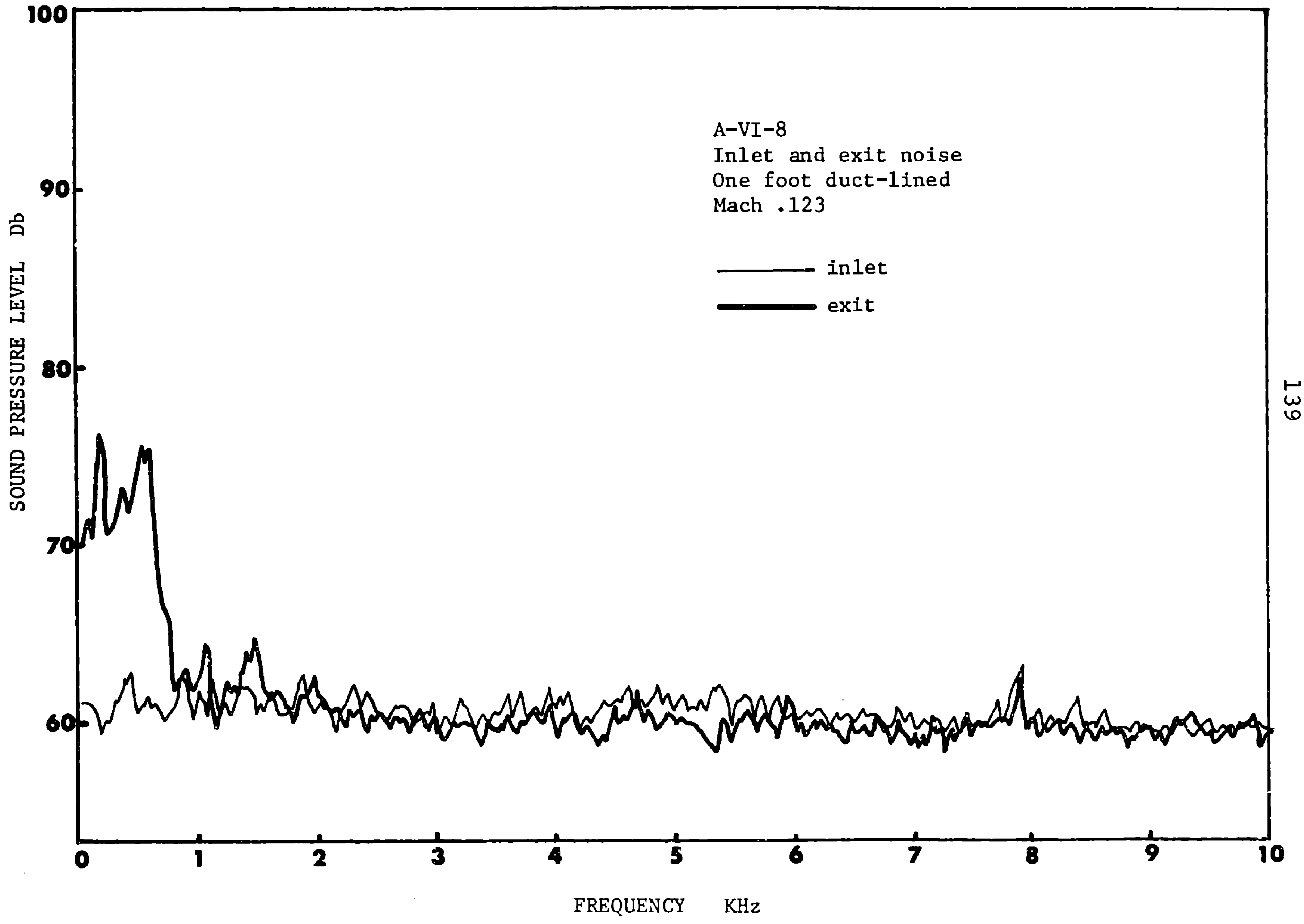

A-VI-3
Inlet and exit noise
One foot duct unlined
Mach .210
inlet
exit
SOUND PRESSURE LEVEL Db
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

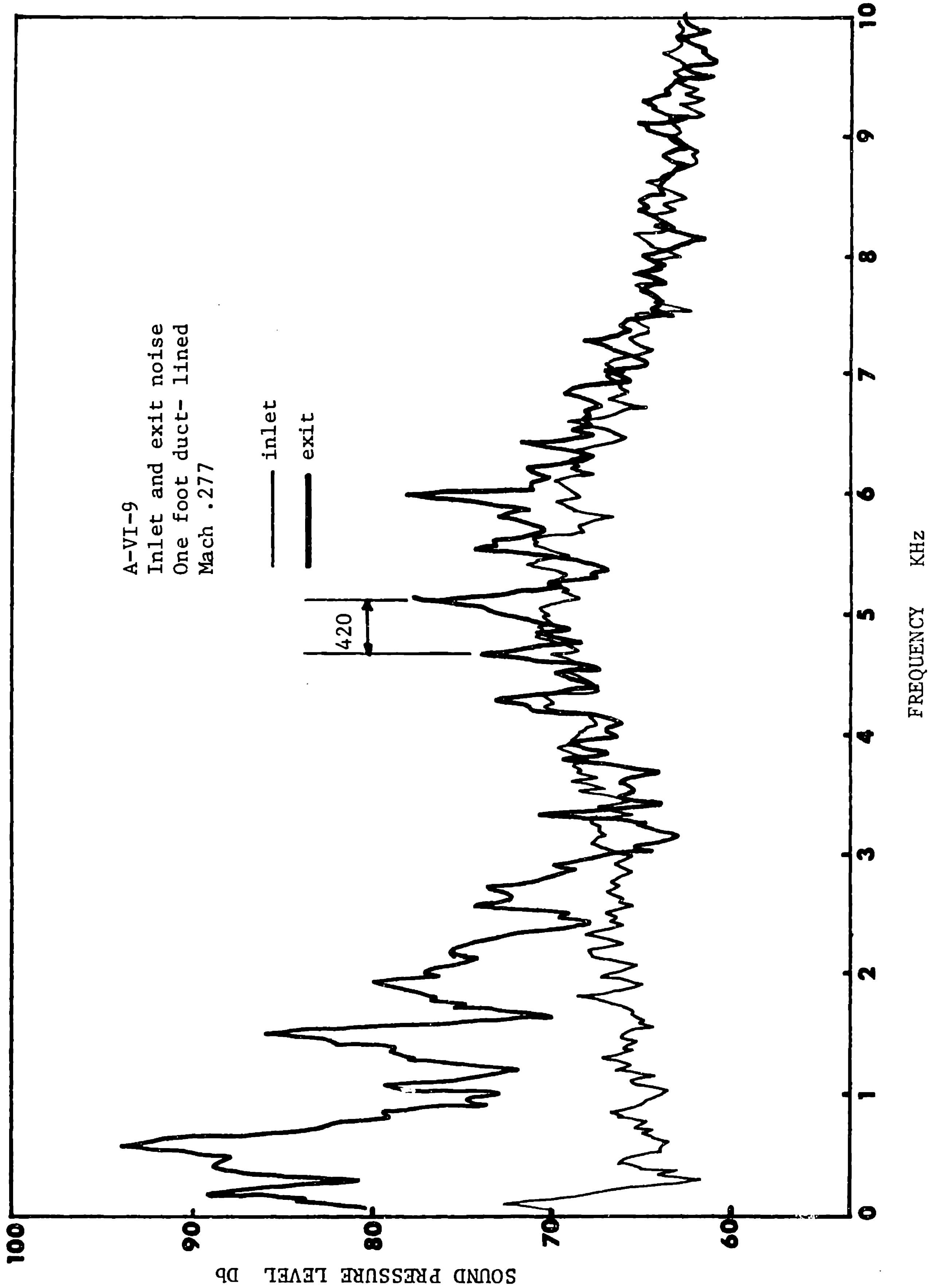

A-VI-4
Inlet and exit noise
3 foot duct- unlined
Mach .118
inlet
exit
187 Hertz
inlet noise
exit noise
SOUND PRESSURE LEVEL Db
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

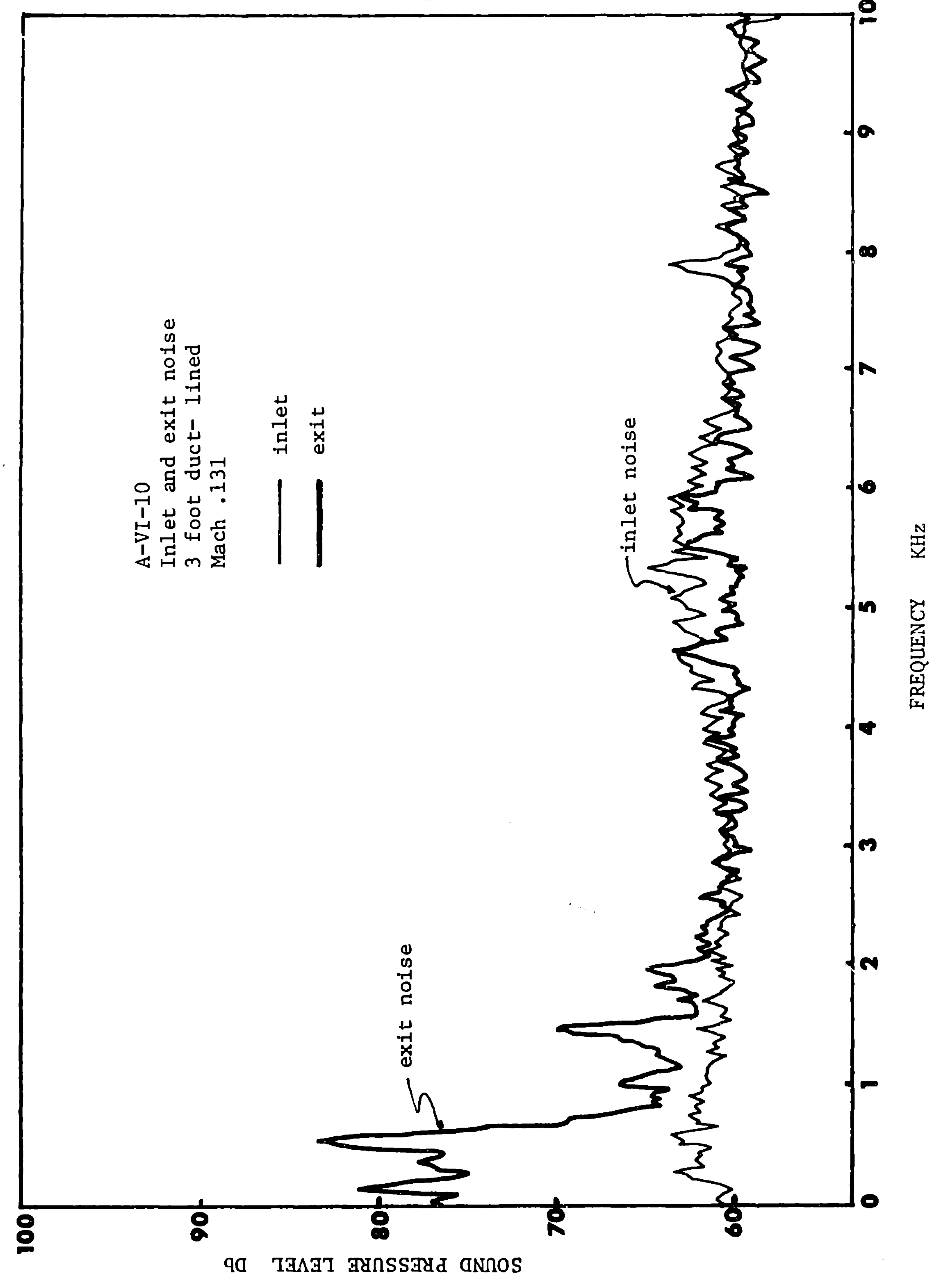

A-VI-5
Inlet and exit noise
3 foot duct- unlined
Mach .214
inlet
exit
surge tank cross modes
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

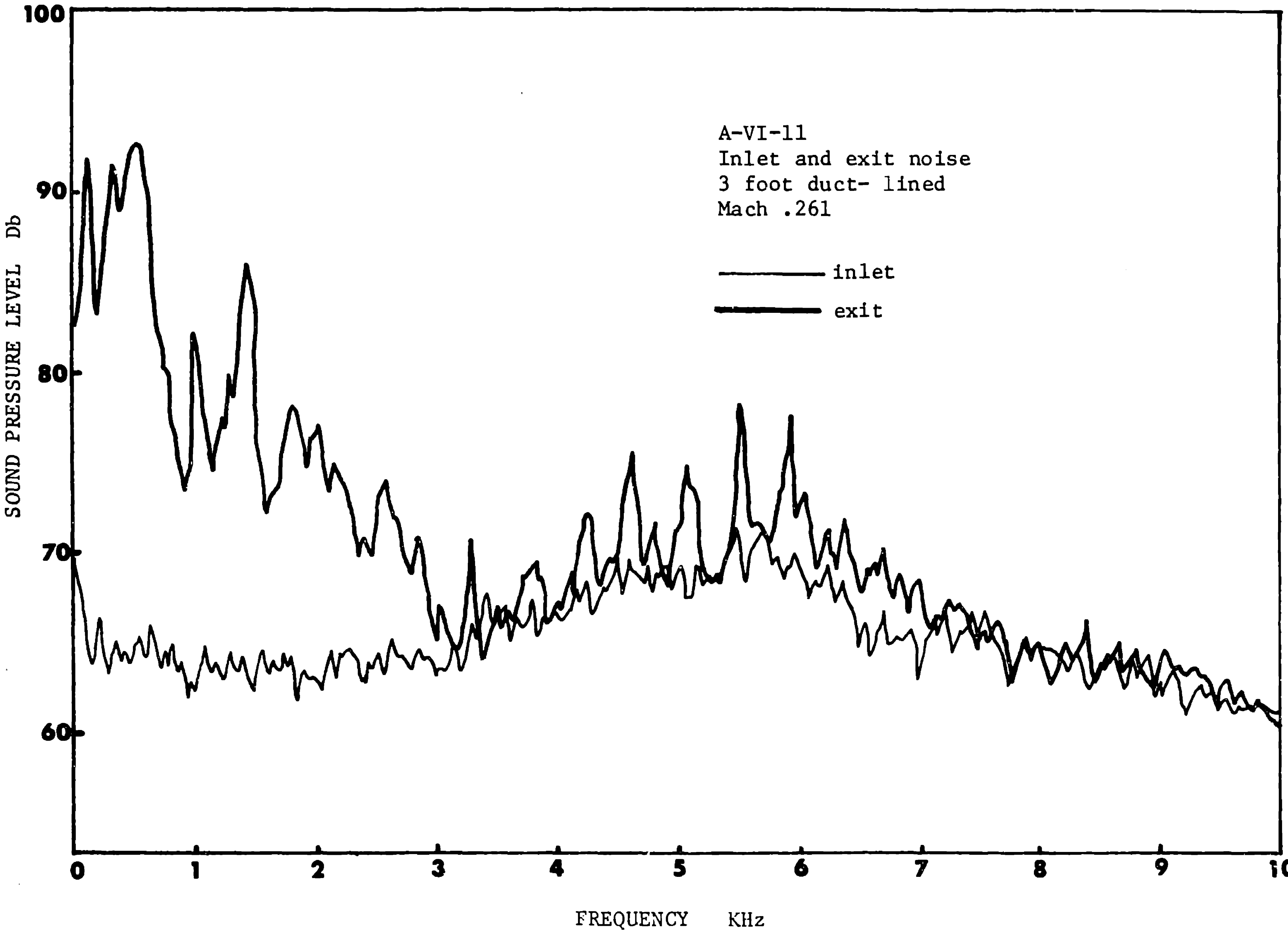

A-VI-6
Inlet and exit noise
6 foot duct- unlined
Mach .123
inlet
exit
exit noise
inlet noise
100
90
80
70
60
SOUND PRESSURE LEVEL Db
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

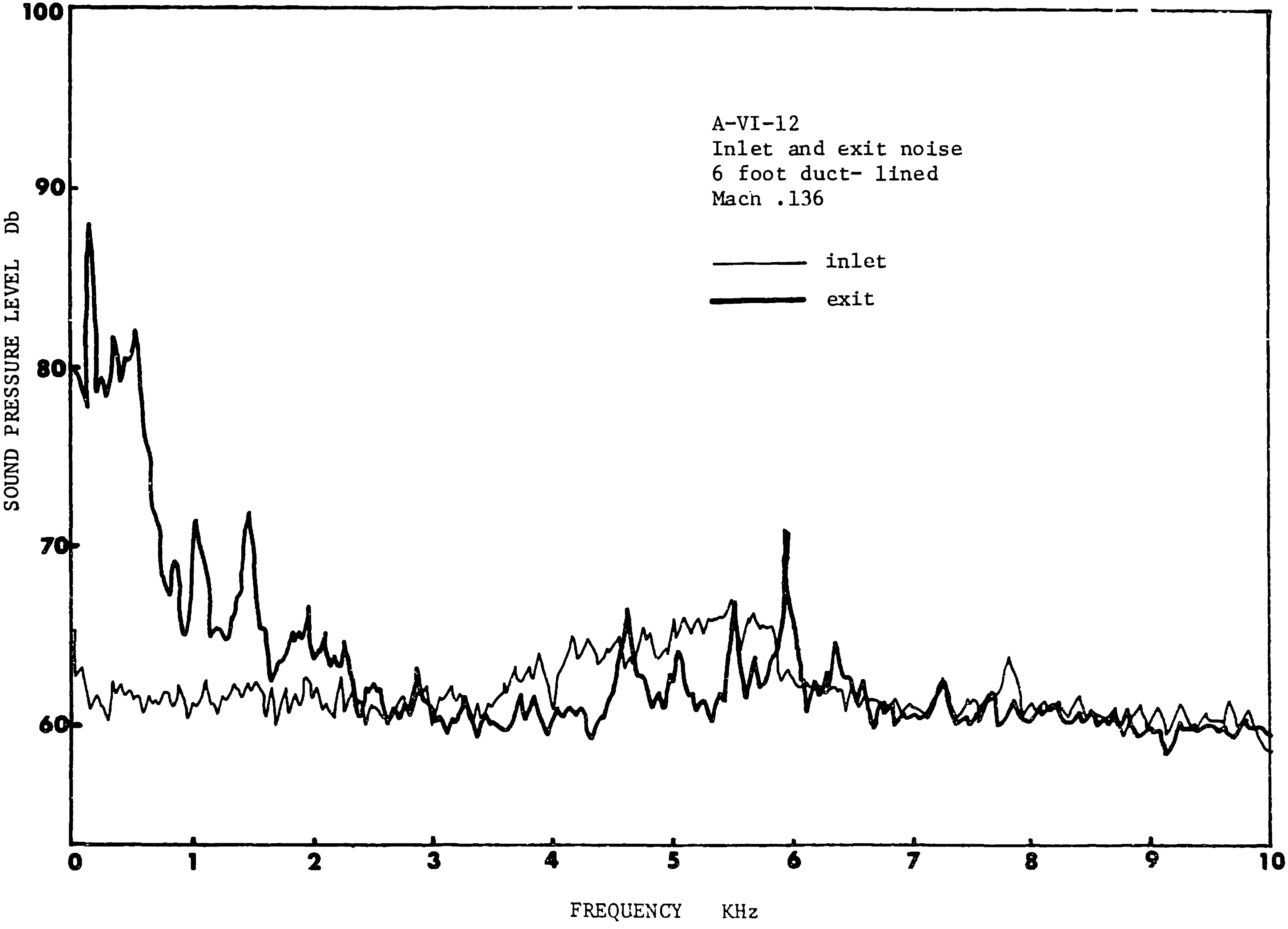

A-VI-7
Inlet and exit noise
6 foot duct- unlined
Mach .203
inlet
exit
100
90
80
70
60
SOUND PRESSURE LEVEL Db
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

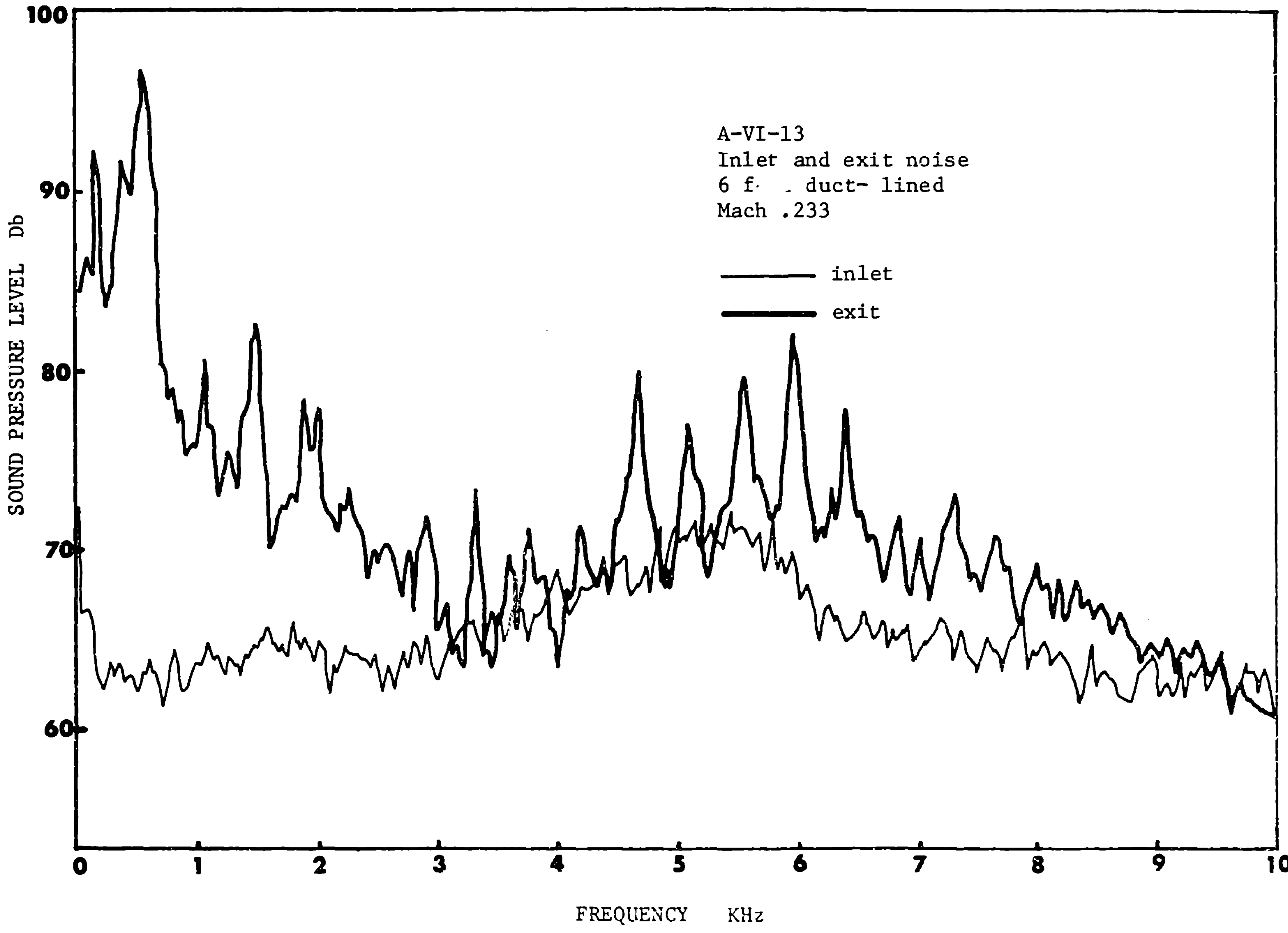

A-VI-8
Inlet and exit noise
One foot duct-lined
Mach .123
inlet
exit
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz

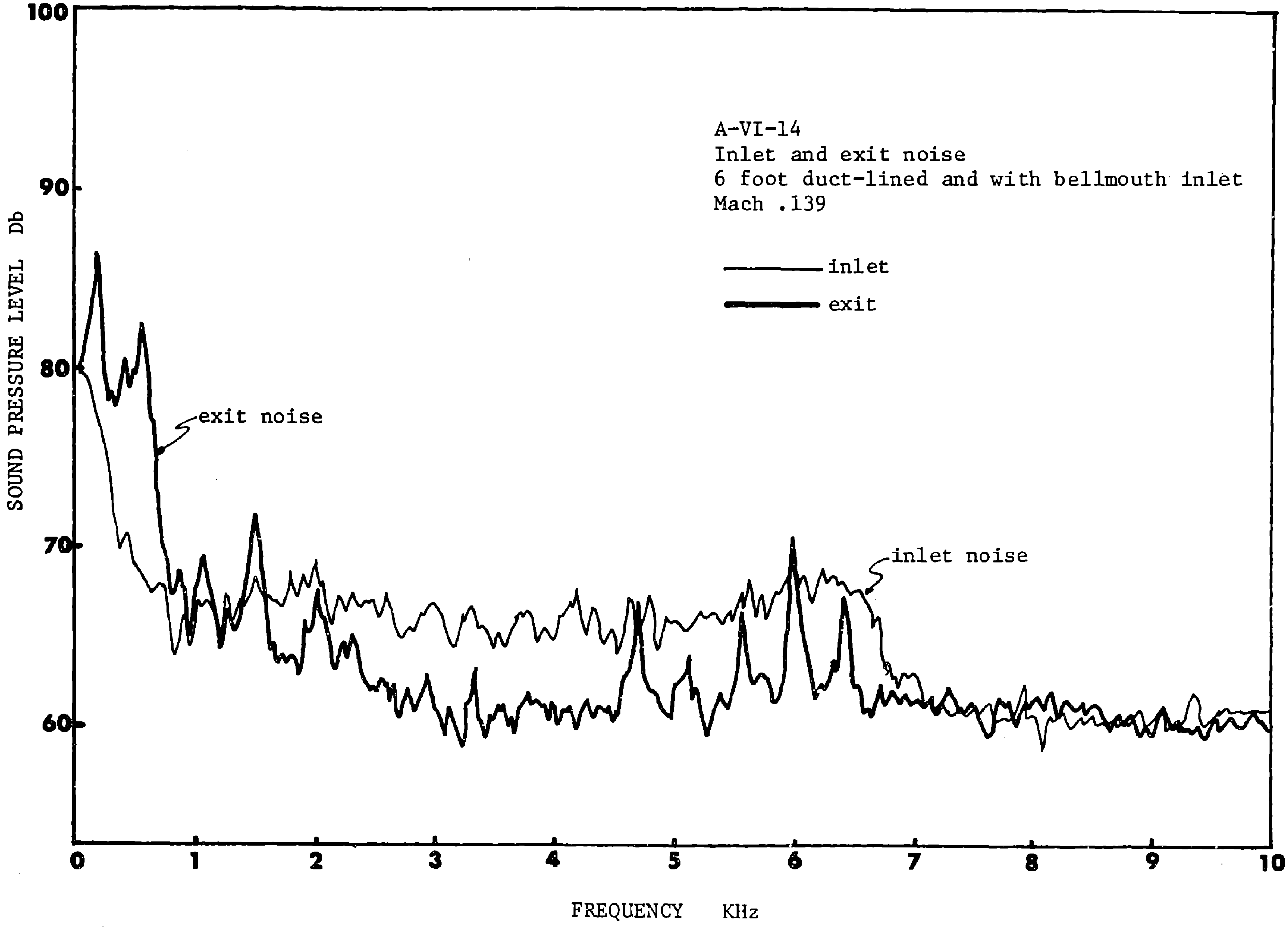

A-VI-9
Inlet and exit noise
One foot duct- lined
Mach .277
inlet
exit
420
100
90
80
70
60
SOUND PRESSURE LEVEL Db
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz


A-VI-10
Inlet and exit noise
3 foot duct- lined
Mach .131
inlet
exit
exit noise
inlet noise
SOUND PRESSURE LEVEL DB
100
90
80
70
60
FREQUENCY KHz
0
1
2
3
4
5
6
7
8
9
10

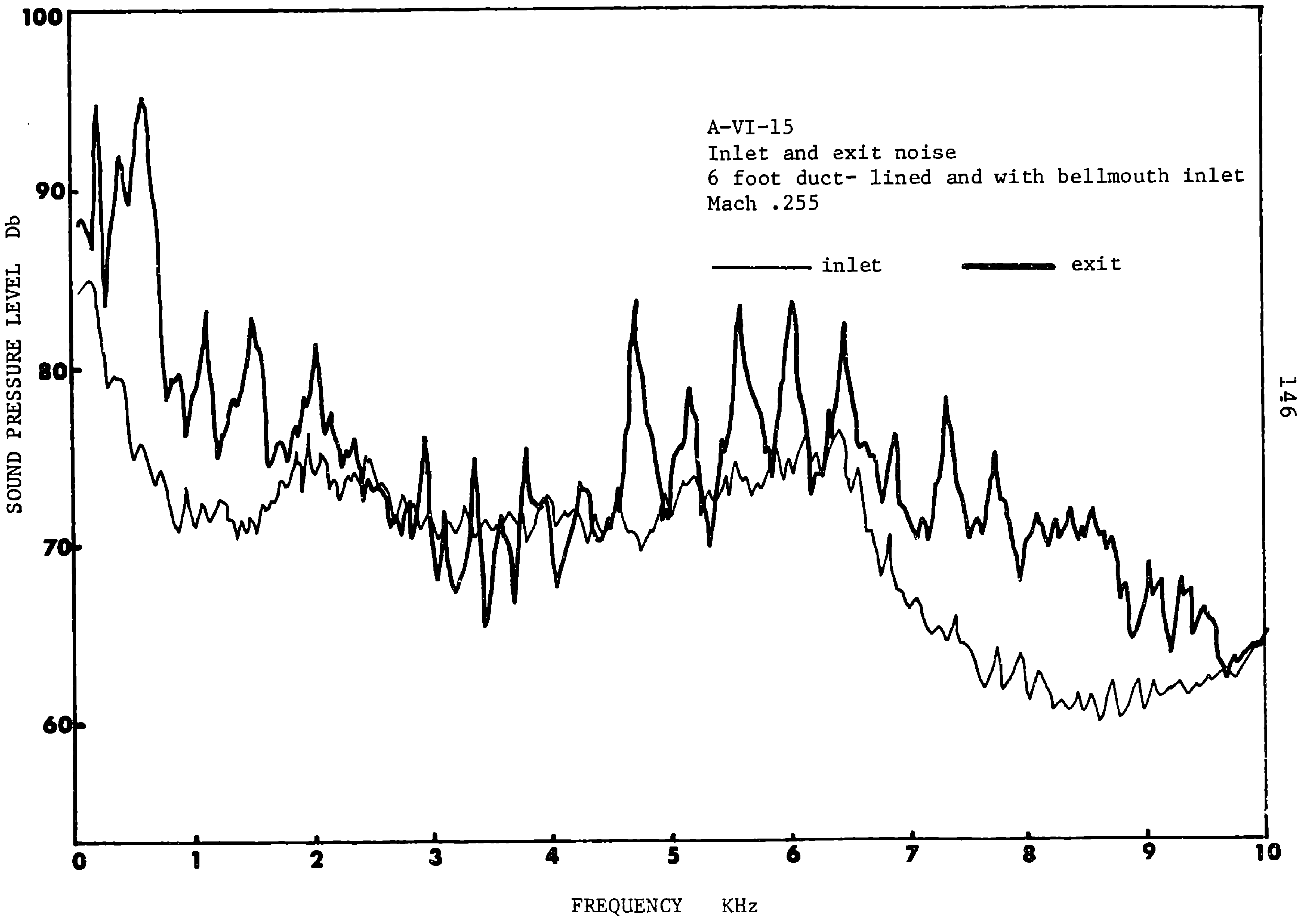

A-VI-11
Inlet and exit noise
3 foot duct- lined
Mach .261
inlet
exit
100
90
80
70
60
SOUND PRESSURE LEVEL Db
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz


A-VI-12
Inlet and exit noise
6 foot duct- lined
Mach .136
inlet
exit
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz


A-VI-13
Inlet and exit noise
6 f· . duct- lined
Mach .233
inlet
exit
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz



A-VI-14
Inlet and exit noise
6 foot duct-lined and with bellmouth inlet
Mach .139


A-VI-15
Inlet and exit noise
6 foot duct- lined and with bellmouth inlet
Mach .255
inlet
exit
SOUND PRESSURE LEVEL Db
100
90
80
70
60
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY KHz