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Effects of Acoustic Noise on Optical Tools

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ABSTRACT

Optical tools respond to internal vibration that can be excited by the external acoustic environment. The degree to which this occurs depends on many factors, but primarily the correspondence between the resonance characteristics of the tool and the frequency content of the acoustic environment in which it operates. Adverse noise environments, such as those often found in operating laboratories and microelectronics fabrication facilities, can affect the threshold of resolution achievable by the tool. This paper reviews the (typically somewhat inadequate) state of noise specification for optical tools, and the noise levels in typical spaces in which these are intended to operate. Manufacturer's noise specifications often overstate or understate the sensitivity of their tool when the noise sensitivity criterion is oversimplified. More precise and detailed criteria would be useful, for example, in the design of laboratories, or troubleshooting tool operational problems.

Keywords: optical tool environmental sensitivity, acoustic noise, vibration, specifications, criteria

1. INTRODUCTION

In addition to electromagnetic interference (EMI) and structure-borne vibration, acoustic noise can degrade the performance of optical tools, primarily by effectively increasing the size of the minimum resolvable image. Although the situation is still far from ideal, some tool manufacturers have recognized the need for detailed vibration specifications and provide realistic (i.e., experimentally derived) siting criteria. Based on a survey of published specifications, it is clear that knowledge about acoustic impact to optical tools is less universal and, indeed, that the terms of specification are often confused or misleading. This paper is, in effect, a call for improvement of the state of acoustic noise specification for high-resolution optical and other metrology and inspection tools.

2. THE MECHANISM BY WHICH ACOUSTIC NOISE INTERFERES WITH OPTICAL TOOLS

Among other things, the achievable resolution of an optical tool is a function of differential vibration between critical elements in the tool, say, between a lens and the observed target. Vibration of elements within a tool can be stimulated by (1) vibration sources within the tool (motors, pumps, servo mechanisms, etc.); (2) external vibration sources (other machines, people, traffic, etc.), transmitting to the tool via its support structure; and (3) acoustic noise in the laboratory environment that causes vibration of exposed elements of the tool (casing panels, mechanical elements, etc.), which is then passed on to sensitive internal elements via the tool structure. Type (1) vibration sources must be controlled by the manufacturer at the outset in order to achieve the desired resolution during the tool design stage in the factory[1]. Type (2) vibration impact is addressed with the provision of siting specifications[2]. It is acoustic noise impacts of Type (3), which can also be addressed by detailed site specifications, that are discussed herein.

The simplest and probably most common means by which acoustic noise causes vibration impact to tools is by excitation of the tool casing panels. For example, Figure 1 illustrates vibration induced in an 560 x 710 x 0.4 mm thick steel panel due to the presence of five different levels of acoustic noise. Part (c) of this figure shows the impinging sound pressure levels (in dB re 20 micropascals) measured near the panel, in octave bands of frequency. Parts (a) and (b) show the corresponding noise-induced vibration velocity levels (in dB re 1 microinch/second) measured at the center of the panel in narrow and octave bands of frequency, respectively. There is, clearly, a direct (linear) relationship between the sound pressure level impinging on the panel and the vibration level measured on the panel.

The amount of vibration induced in a structure is not only a function of the noise level, but also the frequency. Structures will tend to respond more readily to impinging noise at their modal or natural frequencies, determined by the properties and dimensions of the structure. This can be especially dramatic in low-damped structures excited at their fundamental, or “low order,” resonance frequencies, when these frequencies are high enough that the size of the structure equals or exceeds the acoustic wavelengths[3]. Figures 2 and 3 show the results of noise levels impinging on a 210 x 350 x 6 mm thick aluminum plate. The plate was exposed to broadband noise throughout the range of 0 to 2000 Hz. Figure 2 shows the sound pressure level impinging on the plate, measured in both narrowband and one-third octave bands of frequency, and Figure 3 shows the corresponding induced vibration level at plate center. There is a significant amount of vibration at several of the plate modal frequencies (275, 750, 785, 960, and 1370 Hz), but at other frequencies relatively little vibration is induced.

In general terms, we can assess the likelihood of acoustic impact to structures by dividing the impinging noise into three frequency regions. At low frequencies, where the acoustic wavelength is significantly longer than the dimensions of the tool structures, coupling between the two is relatively inefficient. In the mid to high frequency range, especially at the “coincidence” frequency and above (where the acoustic and structural bending wave speeds are equal), the structure is more likely to be excited by acoustic energy. As with the aluminum plate example, the “middle” frequency range might also contain easily excitable low order resonance frequencies. However, in the high frequency region, acoustic excitation of structures is often less of a concern due to fact that there is usually less acoustical energy available with increasing frequency (see Figure 4), among other reasons. It is in the “middle” frequency range, say 50 to 10,000 Hz for common structures, that structures are most likely to be excited by acoustic noise.

3. TYPICAL LABORATORY AND CLEANROOM NOISE LEVELS

Environments in which optical tools operate are often noisy, especially if the environment is classified as “clean.” The noise levels in cleanrooms are necessarily high because of the high air volumes required to maintain air cleanliness and the fact that acoustically absorptive materials are incompatible with the need to control particles, out-gassing, and contamination. More recent designs employing local clean environments, often called “mini-environments,” usually do not significantly reduce the noise levels to which a tool is subject. Even though mini-environment fans handle relatively low volumes of air, they are located closer to the tools. In practice, we find that the vibration and noise in most types of clean and non-clean laboratory environments often approaches the limits of operability of the most sensitive optical tools.

On the other hand, consideration of human comfort will typically place a limit on the amount of noise in a working environment. Excessive noise exposure (high noise levels for extended periods of time) has been shown to cause fatigue, changes in pulse and respiration rate, changes in work efficiency and, in extreme cases, hearing damage. In addition, noise can interfere with communication. Thus, in lieu of the presence of exceptionally noise-sensitive tools, HVAC system design noise levels for operating cleanrooms are commonly set at the frequency-based noise criterion (NC) level NC-60 (or the equivalent) or lower. (The addition of tools to these spaces often increases the noise level above the HVAC design criterion.)

Table 1 lists the octave band sound pressure levels measured in a number of operating laboratories and cleanrooms (each of which contains optical tools). The NC levels, as well as the overall dB, dBA, and dBC levels, are calculated for each. Note the wide range of noise levels in which the tools must operate, the highest being noise levels which might be uncomfortable for a human operator to work in for extended periods. Figure 4 shows a statistical summary of these data, with the minimum, maximum, mean, and mean-plus-one-standard-deviation levels calculated for each octave band of frequency.

4. REVIEW OF TYPICAL CURRENT OPTICAL TOOL NOISE CRITERIA

The aluminum plate resonance example in Section 2 demonstrates the importance of tool component resonances in the determination of acoustic sensitivity. A noise specification for a tool for which acoustic sensitivity has been determined experimentally will often contain several “valleys” in the allowable noise versus frequency spectrum, corresponding to structural resonances of one or several critical components.

However, a review of the current state of optical tool noise specifications reveals a far less developed state. We reviewed manufacturer’s published noise specifications for 101 different optical tools (scanning electron microscopes, optical microscopes, inspection systems, focussed ion beam instruments, etc.) and found the following:

> No noise specification is given for 69 of the tools reviewed. It is assumed that either the noise sensitivity is not known to the manufacturer, or the tool has been observed to operate without interference in the laboratory or fabrication environments in which it is installed (this is typical of relatively low-resolution tools), and thus it is effectively not sensitive to acoustic noise.
>
> For 22 of the tools, “single-number” overall noise level indices, such as dBC (the most common), dBA, or unweighted dB, are specified. Although it is often not stated, it is assumed that these dB units are relative to the common reference acoustic pressure of 20 micropascals[4].
>
> Five of the specifications are qualitative or senseless, e.g., “2 dB,” “quiet,” “no audible sounds are allowed.”
>
> Only four of the tools have specifications expressed as frequency spectra based on test data.
>
> (There is one remaining tool for which an *estimated* frequency spectrum curve is provided.)

The accuracy of simple single-number specifications is questionable in this situation. By definition, dBA and dBC levels are a summation of noise in the 10 to 20,000 Hz frequency range[5]. For reasons discussed above, these overall criteria extend well above and below the frequency range of acoustic sensitivity of typical tools and mechanical devices. Thus the noise sensitivity of a tool may be significantly overstated using one of these indices. This can lead to costly over-design of the air handling systems serving the laboratory.

More importantly, these simple indices do not represent critical resonance information about the tool. Inadequate noise specifications make evaluation of tool problems difficult and uncertain. For tools with no specification, or one of doubtful accuracy, it is no simple matter to evaluate an interference problem that may be due to noise, vibration, EMI, or some combination of the three. For new installations, it would be useful to know with certainty whether operation of the tool will be affected by the ambient noise in the laboratory, before it is delivered to the site.

To clarify why single number specifications are often inadequate, consider Figure 5. Shown in part (a) of this figure is a hypothetical tested noise sensitivity curve for an optical tool. Superimposed upon this are the sound pressure spectra from two different laboratories (A and B), each of which sums up to 70 dBC (re 20 micropascals), a common manufacturer’s noise criterion level. Even though a measurement of the overall noise level in these two rooms will produce the same dBC rating, the tool is more likely to operate without acoustic interference in Lab A than in Lab B. This is because the noise in Lab B has a strong component in the 63 Hz band, corresponding to an acoustically excited tool resonance (indicated by a dip in the noise sensitivity curve) in the same band.

Another way to show this is that several rooms that meet a particular frequency-based HVAC design noise spectrum can have a wide range of overall noise level values. Figure 5(b) shows the measured noise level in four of the laboratories and cleanrooms from Table 1, each of which just meets the standard frequency-based noise criterion curve NC-60. However, the C-weighted overall noise rating for these NC-60 areas varies by 11 dBC.

Finally, we wish to point out another practice that can cause overstatement of tool sensitivity: providing a measure of the noise environment in the manufacturer’s demonstration facility as a criterion level. The noise levels in the manufacturer’s facility are often lower than those in an operating production area, due to differences in scale, cleanliness, etc. It is therefore unreasonable to expect the acoustic environment of a production area to match that of a development area, if this is not warranted by actual test specification data.

5. CONCLUSIONS

In this paper we have put forth arguments in favor of improving the state of noise specification for optical tools, using frequency-based sensitivity testing. It is shown that simple and estimated criteria can overstate or understate the actual acoustical sensitivity of tools. Over- or under-design of the noise environment in a laboratory or cleanroom can be costly, especially in comparison with the relatively simple sensitivity testing procedure[6].

The frequency-based tool specifications should be expressed in the standard octave bands, or preferably, one-third octave bands. While tool sensitivity spectra developed using pure tones are certainly acceptable (even preferred in some cases), the testing procedure necessary to develop this spectrum might be considered as unnecessarily time-consuming.

NOTES AND REFERENCES

1. However, there is a new class of tools, the photolithography scanner, for which support structure stiffness requirements are often specified, to help control the effects of the tool's internal forces on vibration-sensitive internal components.
2. These specifications vary widely in their usefulness, in direct proportion to their accuracy and detail. For more information, see Colin G. Gordon "Generic Criteria for Vibration-Sensitive Equipment" *SPIE Proceedings* Volume 610, November 1991.
3. This case is somewhat different from that illustrated in Figure 1. The panel illustrated in Figure 1 has a relatively high degree of internal structural damping, and in addition, most of the data shown are well above its fundamental frequency of about 5 Hz. In the relatively high frequency region, a high modal density tends to obscure single resonances.
4. It is important to note that the single-number dBA and dBC noise indices, as well as certain frequency-based criteria such as NC, NCB, and RC, are based on human perception of various noise environments, and thus inherently contain frequency "weighting" (essentially, filtering networks) that correspond to normal human hearing. The use of these indices may be questioned in the case of non-human mechanisms.
5. American National Standards Institute ANSI S1.4-1983 "Specification for Sound Level Meters"
6. For details on how this type of test might be carried out, see Colin G. Gordon and Thomas L. Dresner "Methods of Developing Vibration and Acoustic Noise Specifications for Microelectronics Process Tools" *SPIE Proceedings* Volume 2264, July 1994.

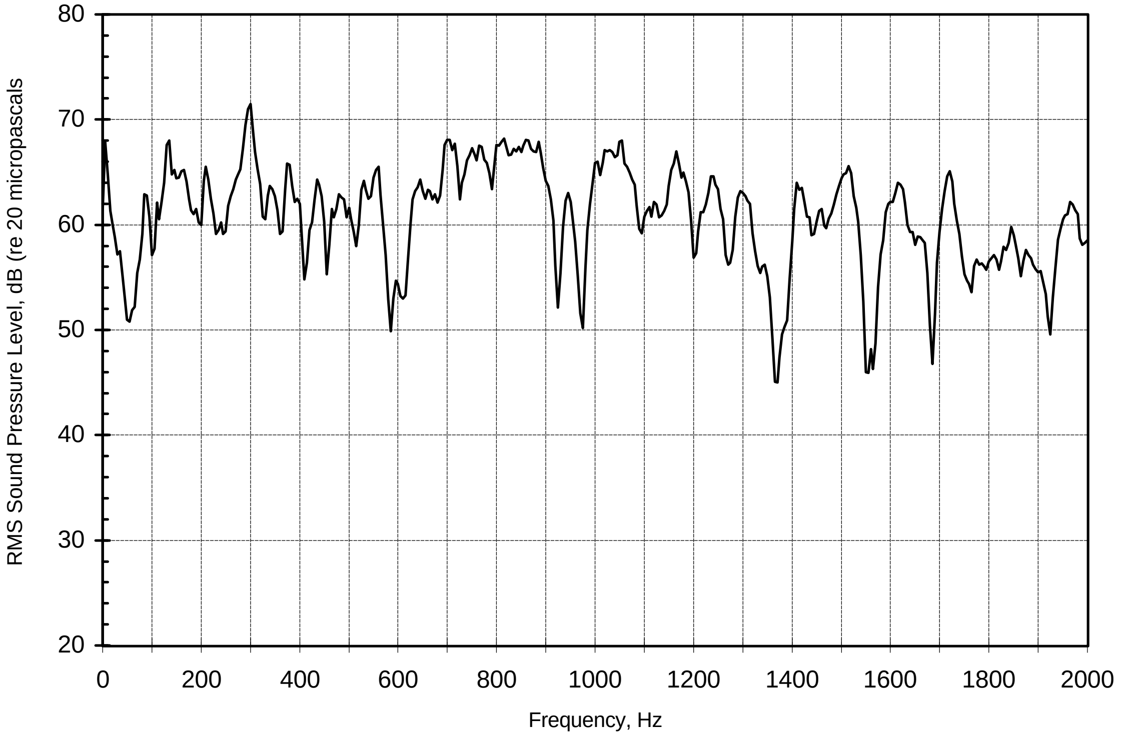
Table 1: Measured operational cleanroom and laboratory noise levels

Nr	Room Type	Sound Pressure Level (dB re 20 uPa) vs. Octave Band Center Frequency (Hz)									NC	dB	dBA	dBC
		31.5	63	125	250	500	1000	2000	4000	8000				
1	cleanroom	67	65	69	63	61	58	54	46	37	58	73	63	72
2	cleanroom	67	69	71	66	64	60	57	53	48	61	75	66	75
3	cleanroom	67	73	69	65	64	61	60	55	52	61	76	67	75
4	cleanroom	73	69	71	67	64	59	55	49	43	61	77	65	76
5	cleanroom	68	70	71	67	65	62	61	56	49	62	76	68	76
6	cleanroom	72	71	71	69	66	63	62	60	56	63	78	70	77
7	cleanroom	66	70	68	67	67	64	61	57	51	64	75	69	75
8	cleanroom	67	72	72	68	65	64	63	56	50	64	77	69	76
9	cleanroom	76	74	73	71	66	61	57	50	43	65	80	68	79
10	cleanroom	73	77	82	72	68	66	64	58	41	74	84	72	84
11	cleanroom	74	78	81	71	64	61	56	51	42	73	84	69	83
12	cleanroom	75	77	80	73	70	70	65	64	54	71	84	74	83
13	cleanroom	74	79	84	74	67	62	58	54	43	76	86	72	86
14	cleanroom	71	71	70	67	64	61	57	55	46	61	77	67	76
15	cleanroom	74	73	69	67	65	60	58	56	49	62	78	67	77
16	cleanroom	73	71	70	68	67	64	62	58	48	64	78	69	77
17	cleanroom	74	73	71	67	67	65	59	56	48	64	79	69	77
18	cleanroom	69	71	68	64	65	60	56	53	48	62	75	66	74
19	cleanroom	73	76	74	69	67	63	60	53	50	64	80	69	79
20	cleanroom	72	75	72	68	67	63	57	53	47	64	79	68	78
21	cleanroom	68	68	74	64	66	62	57	53	49	64	77	67	76
22	cleanroom	69	68	74	65	65	60	56	53	47	64	77	66	76
23	cleanroom	69	67	67	64	63	58	53	46	41	60	74	64	73
24	cleanroom	70	68	67	64	63	58	52	46	42	60	74	63	73
25	cleanroom	70	67	67	65	63	58	53	47	42	60	74	64	73
26	cleanroom	68	67	68	68	65	60	56	52	47	62	75	66	74
27	cleanroom	68	66	67	66	65	60	56	51	46	62	74	66	73
28	cleanroom	70	67	69	70	66	61	55	51	46	64	76	67	75
29	laboratory	70	66	66	62	61	59	54	50	41	58	73	63	72
30	laboratory	58	58	53	51	52	49	45	39	31	48	63	54	62
31	laboratory	60	58	54	49	50	49	45	40	33	48	63	53	62
32	laboratory	59	59	54	55	56	56	53	47	39	55	65	60	64
33	laboratory	55	56	60	60	57	57	53	47	37	56	66	61	66
34	laboratory	54	60	67	65	62	59	55	50	41	59	71	64	70
35	laboratory	58	57	61	61	63	56	51	46	36	60	68	63	68
36	laboratory	57	59	63	61	64	56	51	47	36	61	69	63	68
37	laboratory	63	63	60	65	67	67	65	64	57	66	74	72	74
38	laboratory	75	78	64	61	55	50	45	42	33	59	80	58	79
39	laboratory	66	68	65	68	61	57	53	51	54	64	73	64	73
40	laboratory	67	65	62	63	59	63	54	49	41	65	72	65	71
41	laboratory	70	69	68	66	65	64	62	63	55	70	76	70	75
42	laboratory	58	59	50	51	46	44	39	34	26	49	62	49	61
43	laboratory	60	65	54	56	49	49	41	35	28	50	67	53	66
44	laboratory	59	59	54	56	50	44	40	37	31	52	64	52	63
45	laboratory	58	58	55	54	51	45	43	45	37	53	63	53	62
46	laboratory	55	49	49	53	51	49	46	43	36	54	60	54	59
47	laboratory	64	71	58	60	51	46	41	37	31	55	72	55	71
48	laboratory	52	55	52	58	54	51	46	40	31	56	62	56	62

Note: The cleanrooms represented in this table are Class 1. The laboratories have no clean classification.
All data are from operating production environments, containing mechanical equipment, HVAC, and optical and other tool noise sources.

Figure 2: Noise induced vibration in a 210 x 350 x 6 mm thick aluminum plate

a) Narrowband (effective bandwidth = 7.5 Hz)



b) One-third octave band

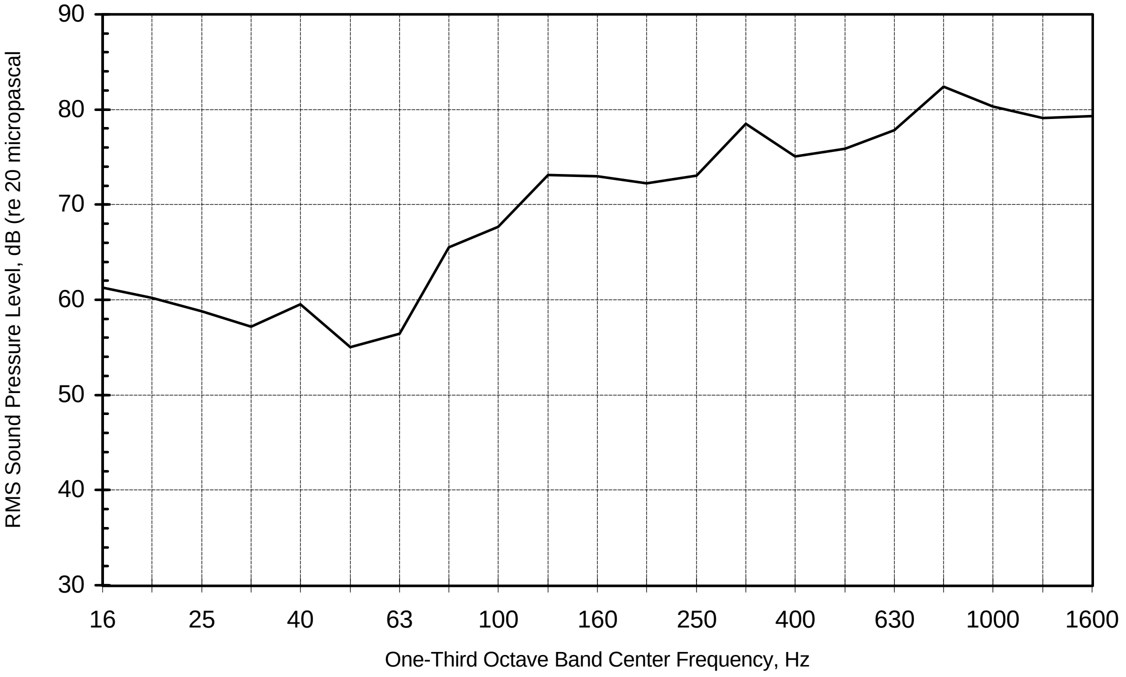
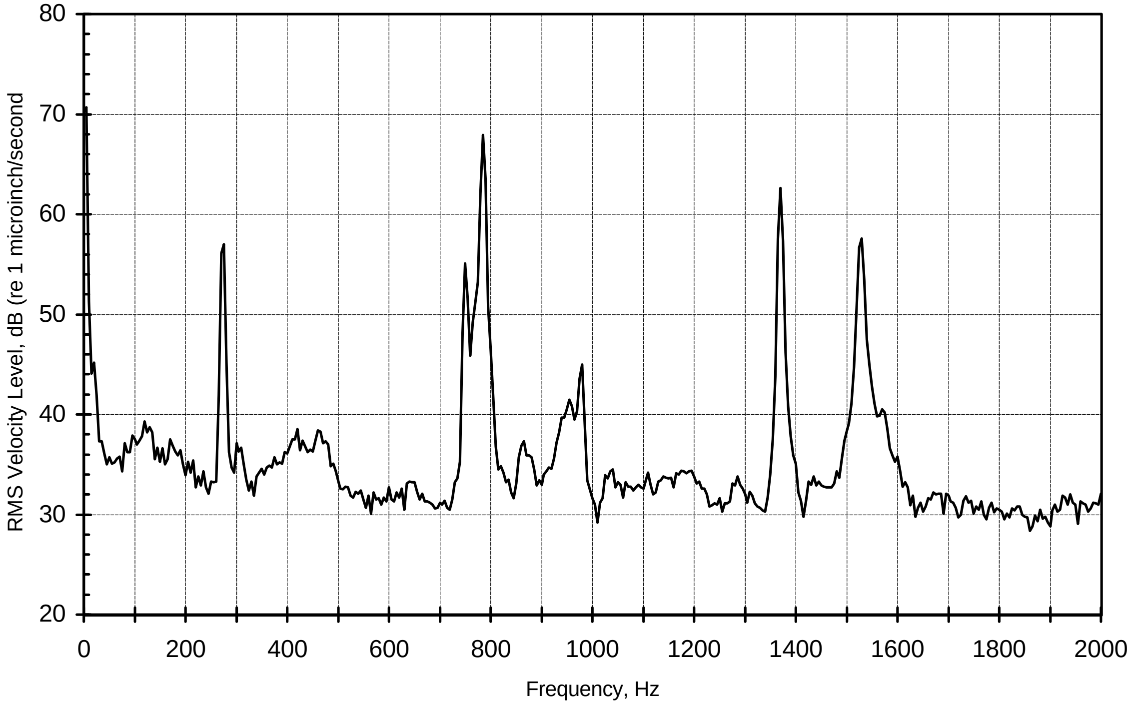


Figure 3: Noise induced vibration in a 210 x 350 x 6 mm thick aluminum plate - induced vibration levels

a) Narrowband (effective bandwidth = 7.5 Hz)



b) One-third octave band

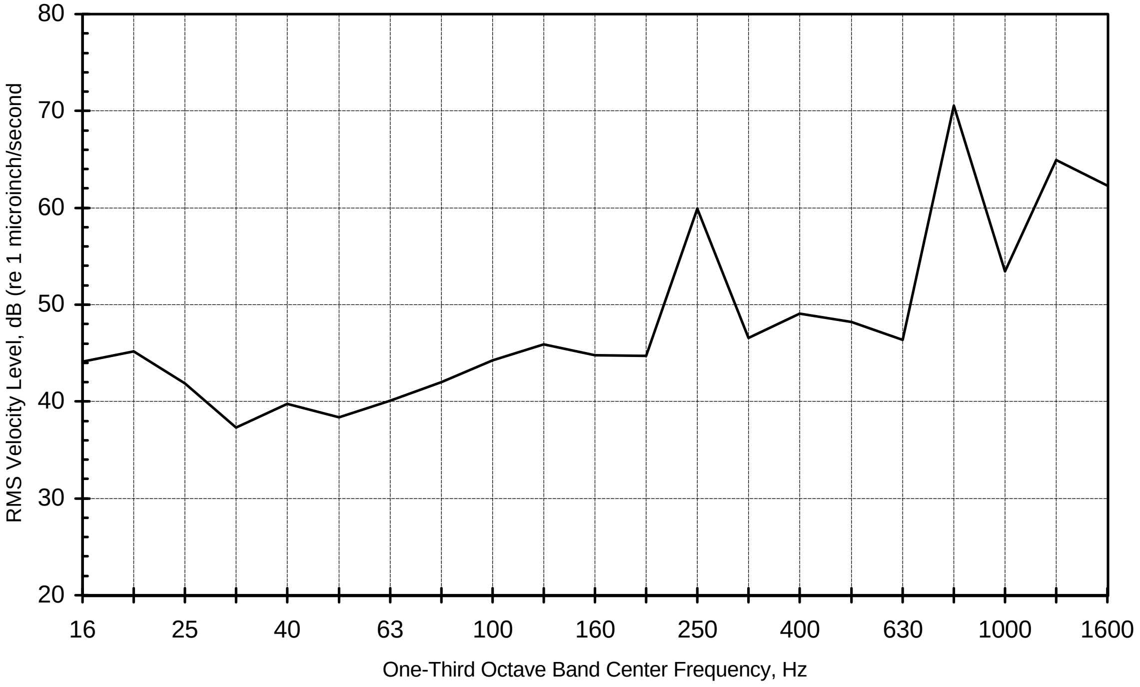
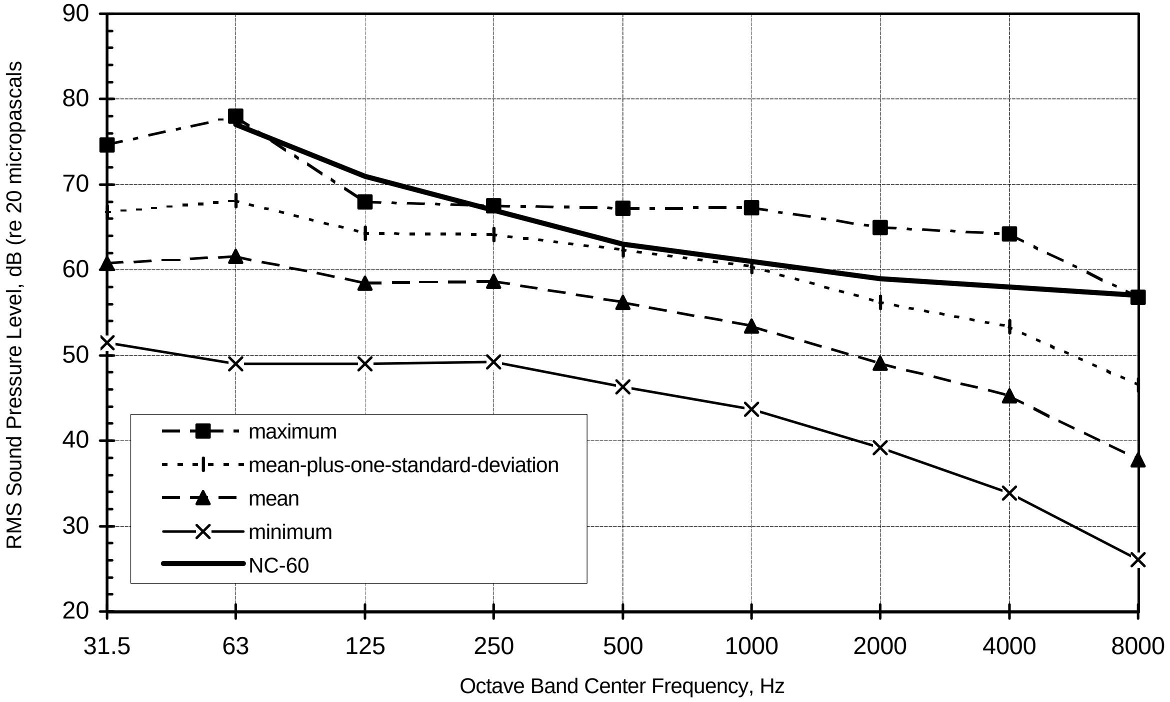


Figure 4: Statistical distribution of measured operational non-clean laboratory and cleanroom noise levels (each data record is a space-averaged 20-second Leq, with "slow" time constant and no frequency weighting)

a) Laboratories (20 data records)



b) Cleanrooms (28 data records)

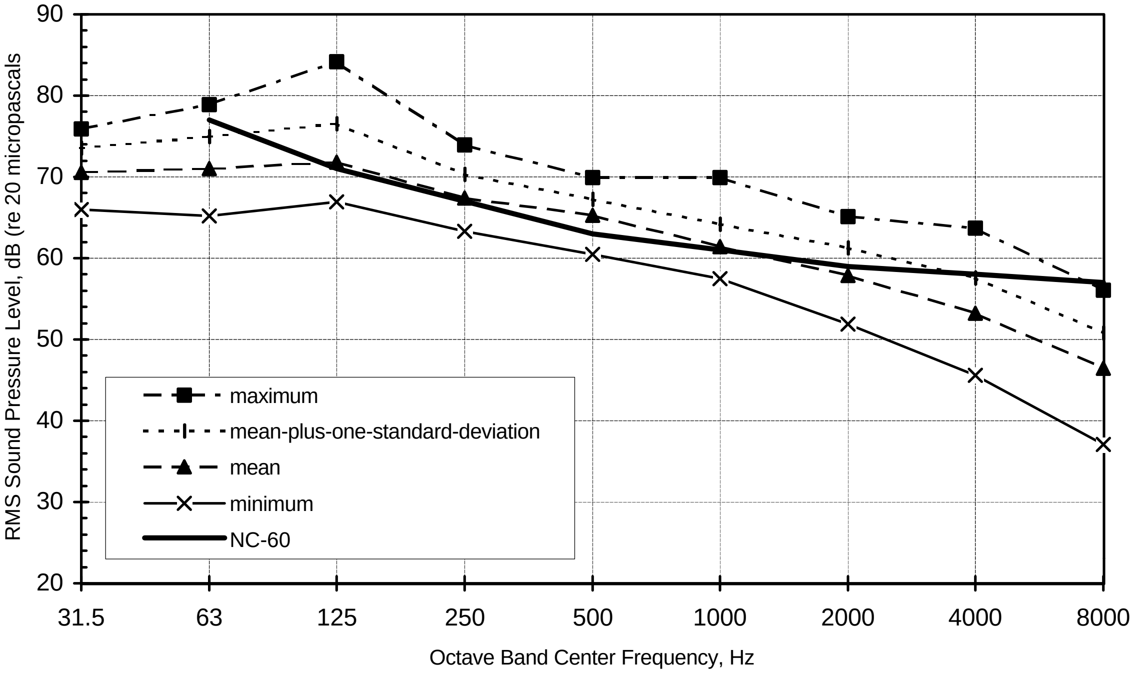
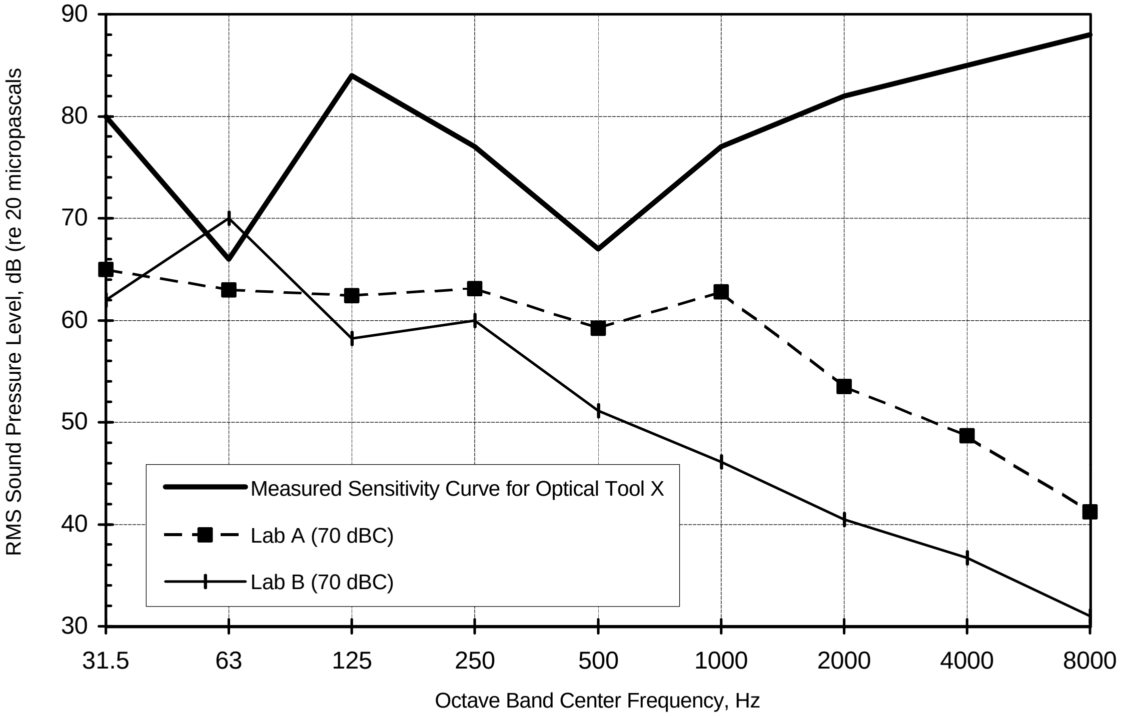


Figure 5: Optical tool sensitivity is not well represented by overall noise indices such as dBC

a) An optical tool that probably functions better in one 70 dBC laboratory (Lab A) than in another 70 dBC laboratory (Lab B)



b) Four cleanrooms or laboratories from Table 1 that meet the NC-60 HVAC design criterion, with a spread in dBC values of 11 dBC