Specification of the 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 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 article 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.

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[1] However, there are tools, for example photolithography scanners and laser drills, 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.

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 machine panel due to the presence of five different levels of acoustic noise. Part (a) of this figure shows the impinging sound pressure levels (in dB re 20 micropascals) measured near the panel, in octave bands of frequency. Parts (b) and (c) show the corresponding noise-induced vibration velocity levels (in dB re 1 micrometer/second) measured at the center of the panel in octave and narrow (1.875 Hz) 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] Figure 2 shows the results of noise levels impinging on a freely-supported 210 x 350 x 6 mm thick aluminum plate. The plate was exposed to broadband noise throughout the range of 0 to 2000 Hz. In the figure, the narrowband sound pressure level impinging on the plate is compared with 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. Exceptionally, very low frequency pressure fluctuations may interfere with tools with open beams (some interferometers, atomic force microscopes, etc.). In the mid to high frequency range, especially at the "coincidence" frequency (where the acoustic and structural bending wave speeds are equal) and above, 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. 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 3), among other reasons. For enclosed optical tools, it is in the "middle" frequency range 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.

Figure 3 summarizes the octave band sound pressure levels measured in a number of operating laboratories and cleanrooms (each of which contains optical tools). 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.

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[3] This case is somewhat different from that illustrated in Figure 1. The panel illustrated in Figure 1 has a relatively high degree of 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. 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 have reviewed manufacturer's published "siting" noise specifications for 101 different optical tools (scanning electron microscopes, optical microscopes, inspection systems, focused 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 characteristic of relatively low-resolution tools), and thus it is effectively not sensitive to typical levels of acoustic noise.

- For 22 of the tools, one of the "single-number" overall noise level indices dBC (the most common), dBA, or unweighted dB, is specified.[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 noise specifications based on test data, setting different limits at different frequencies. (For one tool, an *estimated* frequency spectrum curve is provided.)

The usefulness of simple single-number specifications is highly 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 may 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 which 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 4. 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

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[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"

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 4(b) shows the measured noise level in four of the laboratories and cleanrooms summarized in Figure 3, 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 article 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.

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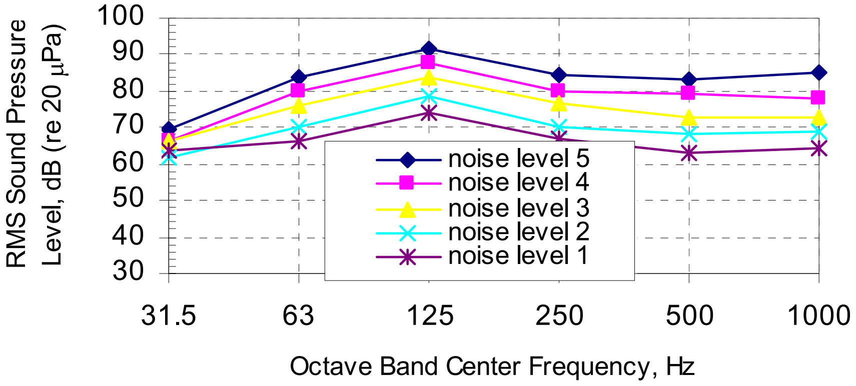
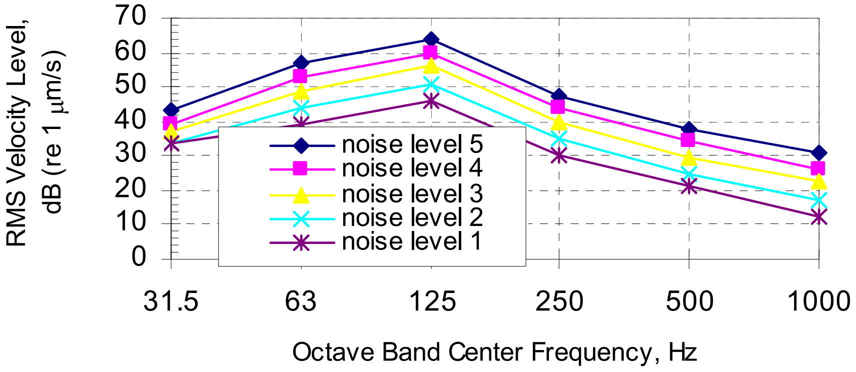
[6] For details on how this type of test might be carried out, see Colin G. Gordon and Thomas L. Dresner "Methods of Developing Vibration and Acoustic Noise Specifications for Microelectronics Process Tools" *SPIE Proceedings* Volume 2264, July 1994.

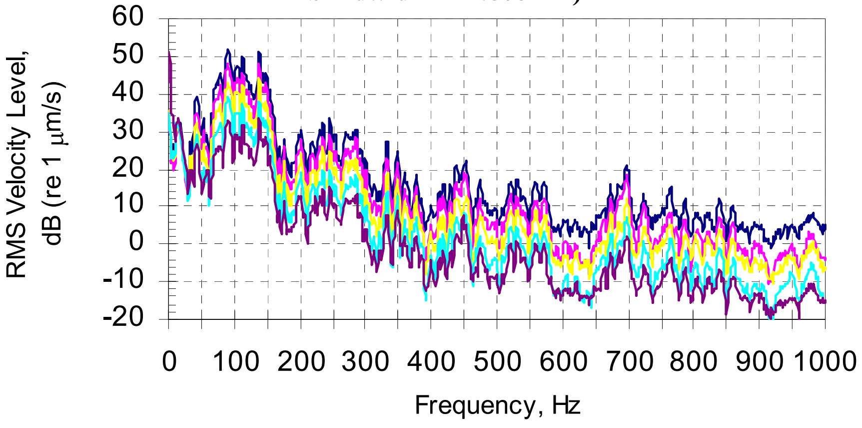
Figure 1: Noise induced vibration in a 560 x 710 x 0.4 mm thick steel panel



a) Impinging noise levels, unweighted, "slow" time constant, 20-second L_{eq}



b) Noise induced panel vibration: octave band



c) Noise induced panel vibration: narrowband (effective bandwidth = 1.875 Hz)

Figure 2: Noise induced vibration in a 210 x 350 x 6 mm thick aluminum plate (bandwidth = 7.5 Hz)

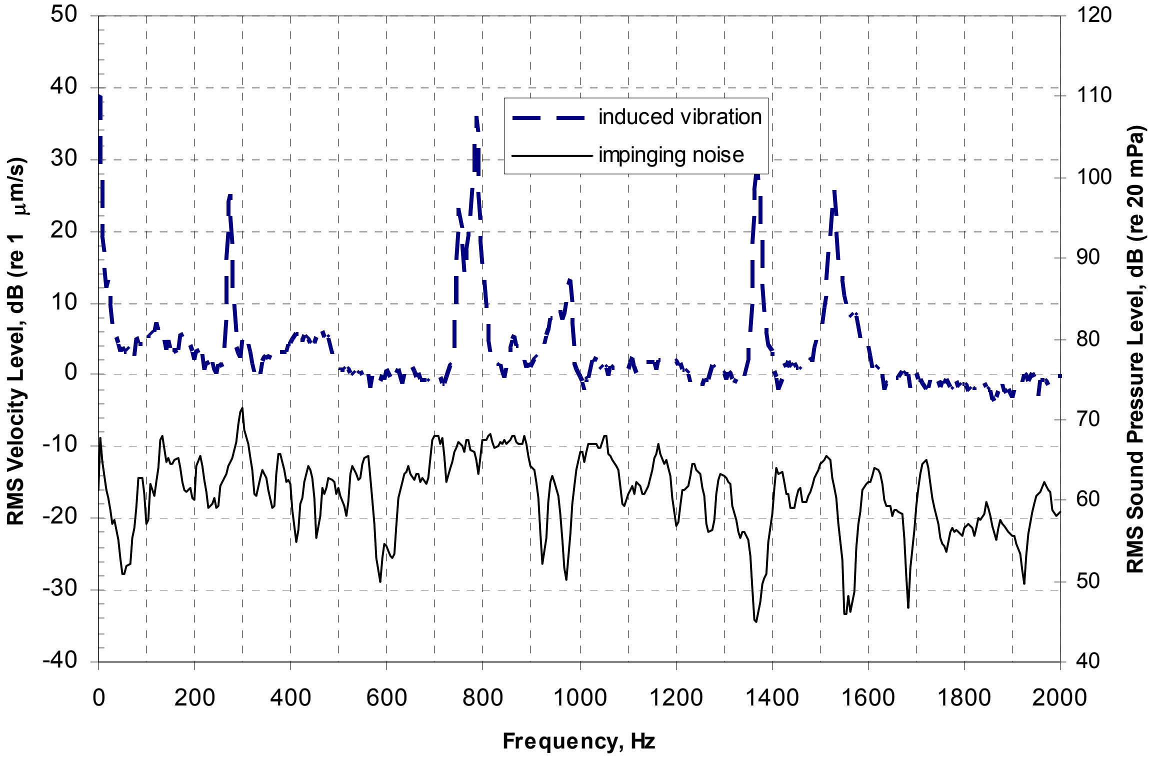
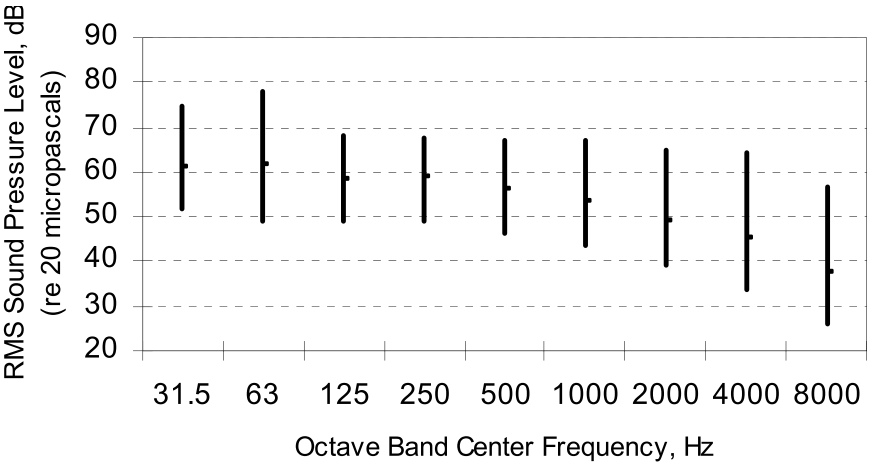


Figure 3: Statistical distribution of measured operational non-clean laboratory and cleanroom noise levels (each data record is a space-averaged 20-second Leq, with "slow" time constant and no frequency weighting)

a) Laboratories (20 data records)



b) Cleanrooms (28 data records)

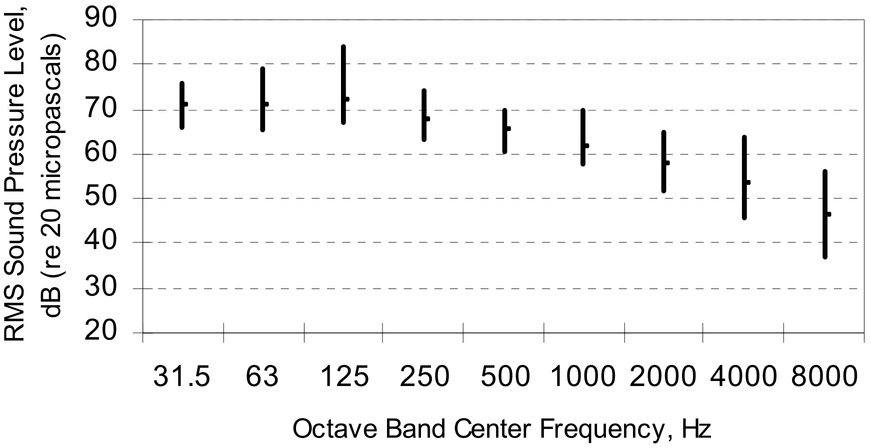
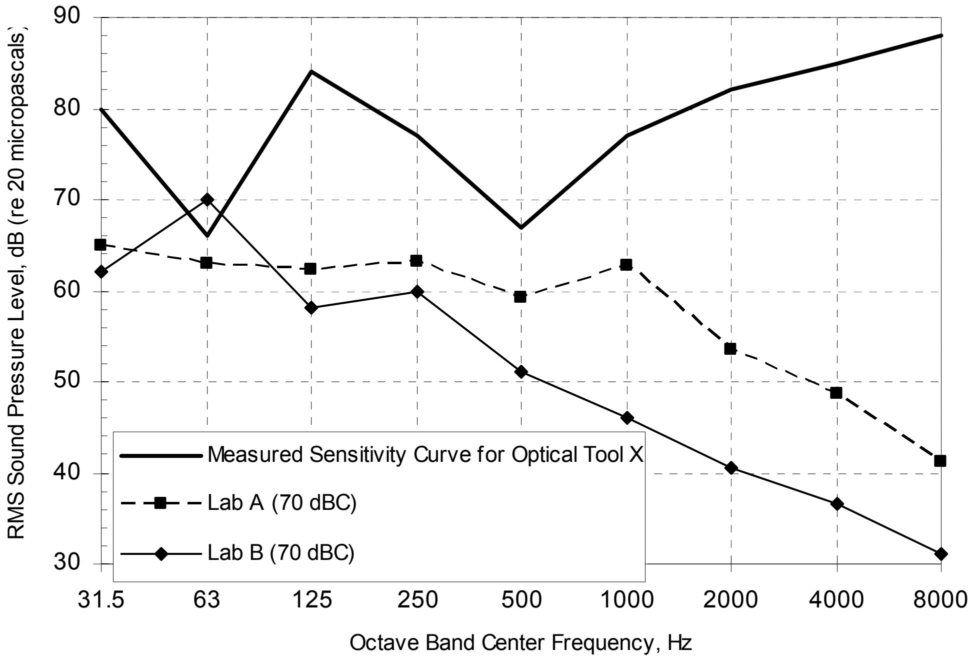


Figure 4: Optical tool sensitivity is not well represented by overall noise indices such as dBC

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