Bulletin 53
(Part 1 of 4 Parts)

Reprinted From

THE SHOCK AND VIBRATION BULLETIN

Part 1

Welcome, Keynote Address,
Invited Papers, Pyrotechnic Shock, and
Shock Testing and Analysis

MAY 1983

A Publication of
THE SHOCK AND VIBRATION
INFORMATION CENTER
Naval Research Laboratory, Washington, D.C.

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

Office of
The Under Secretary of Defense
for Research and Engineering

ELIAS KLEIN MEMORIAL LECTURE
VIBRATION CHALLENGES IN MICROELECTRONICS MANUFACTURING

Eric E. Ungar and Colin G. Gordon
Bolt Beranek and Newman, Inc.

The manufacture of smaller, more tightly packed, integrated circuits requires facilities designed to meet stringent vibration requirements. Vibration control is complicated by the need for extensive process support equipment and some service personnel in the vicinity of the sensitive machines.

Facility criteria that have been developed on the basis of earlier facility experience have tended to be unrealistic and inadequately defined. The present paper delineates the shortcomings of these criteria and indicates how better criteria may be defined.

Information on vibration levels that are permissible for critical items of optical equipment is essential to the development of realistic facilities criteria. The limitations of some of the available data are discussed, together with suggestions for overcoming them and for improving optical equipment items from the standpoint of their structural dynamics.

INTRODUCTION

An integrated circuit "chip" basically consists of a substrate on which there are deposited a series of extremely thin layers of various materials. The patterns and materials of these layers, and the connections between them, are designed to accomplish the desired circuit functions.

There has been a continuing trend toward chips with more and faster data processing capability, implying smaller and more tightly packed circuit elements—and thus establishing a need for greater precision in the patterns in which the material layers are deposited.

The production of these patterns involves a series of steps that are essentially photographic. The image sharpness in these steps and the registration of successive patterns atop each other determine the circuit density that can be obtained. Some limits on the attainable image sharpness are established by the basic properties of the light or other radiation that is used for the photographic exposure; newly developed technology, in fact, makes use of electron beams whose wavelengths are shorter than those of light, in order to capitalize on the resulting reduced diffraction and increased resolution. However, it appears that other limits result from wobbling of the optical systems occurring during the photographic exposures.

An idea of how stable microelectronics manufacturing equipment needs to be may be obtained by noting that current production chips have line widths of 5 to 7 μm, that in the near future production of chips with line widths of 1.5 to 2 μm is expected, that efforts toward production of line widths of 0.5 to 1.0 μm are in progress—and that registration requirements typically are of the order of ten percent of the line width. (Note: 1 μm = 1 micron $\approx 4 \times 10^{-5}$ in $\approx$ 0.04 mils.)

The aforementioned wobbling—or, more precisely, the corresponding motion of the light (or other radiation) beams across the image surface—is associated with vibratory relative deflections of the optical system. It is these vibrations that are the primary concern of the present paper.

This paper represents an attempt to provide a broad overview of the major problem areas, in part from a historical perspective, in order to present some challenges and guidance to vibration specialists. However, delineation of specific problem solutions has been omitted and identification of specific facilities and equipment items has been avoided for three reasons: (1) requirements for different facilities may differ greatly, depending on numerous equipment, usage and environmental factors, (2) rapid change in microelectronics technology leads to continuous changes in equipment and to updating of its performance data, and (3) much of the specific data is proprietary.

FACILITIES

Effects of Process Requirements on Configuration

Facilities for the manufacture or development of integrated circuits tend to be complex, largely because of the many different items of equipment that are required. The photographic processes themselves typically involve multiple stages of chemical treatment—such as coating, baking, developing, etching and stripping implying the need for extensive piping systems to bring gaseous and liquid chemicals to the areas where they are used. Additional piping is needed to support the rinsing, washing, scrubbing and drying operations, as well as to provide fuel (and oxidants) for various process furnaces. The many chemicals that are used require the installation of hoods for the removal of fumes and the provision of wastewater treatment and waste chemical disposal means.

All of the microcircuit production steps need to be carried out in a clean, controlled atmosphere, requiring not only that temperature and humidity be maintained within tight limits, but also that particulate contamination be kept to an acceptable level. The control of particulate contaminants typically is achieved by means of "clean room" systems that produce controlled uni-directional (non-turbulent) flow of thoroughly filtered air in the working spaces. These systems, as well as the more conventional heating and air conditioning systems, again require extensive ducts and piping serving the processing areas.

Because of all these support requirements, integrated circuit manufacturing facilities tend to be designed as arrays of modular spaces, with each space housing perhaps a dozen major pieces of production-related equipment and about four to six workers. Each work space is surrounded by support equipment areas or "service aisles", in which maintenance of strict particulate contamination control is not required. A typical space configuration is illustrated by the architectural sketch of Fig. 1. The work spaces and support equipment areas communicate with each other via a multitude of conduits, ducts and pipes that provide power and that supply and remove various gases and liquids.

Sources of Vibration

The aforementioned support systems tend to include equipment items that may generate significant vibrations. Typically, the major sources of vibrations consist of the numerous large fans that supply air to the clean rooms, the turbulent air flows within the duct systems, the pumps and chillers that generate and circulate chilled water for air conditioning and process equipment cooling, and the flow of water and of other liquids in pipework.

Some relatively small support equipment items, such as vacuum pumps, tend typically to be located in the service aisles, in close proximity to the areas they serve—and thus may cause appreciable vibrational disturbances in spite of their small size. Traffic of vehicles (e.g., electric or unpowered carts along these aisles transporting heavy compressed-gas cylinders and the like) also may constitute a source of potentially disturbing vibrations in the work area. In many instances, however, the activities of personnel—particularly walking—in or near the work areas tend to constitute a major source of problematic vibrations, in addition to the mechanical equipment mentioned earlier, whereas external sources, such as nearby road or rail traffic, typically are of lesser importance at reasonably selected plant sites.

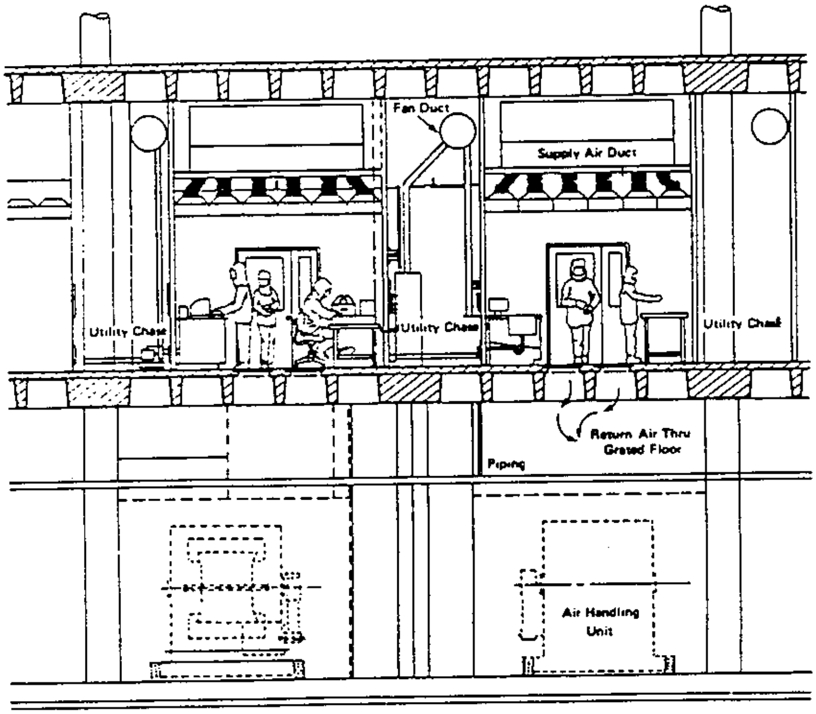

Fig. 1 — Typical "clean room" arrangement for microelectronics manufacture.

Vibration Criteria Considerations

The floor of a microelectronics manufacturing area must provide a vibration environment that permits the sensitive equipment housed in that area to perform satisfactorily. Manufacturing facilities also need to be flexible, in order to be able to accommodate changes in the technology and advances in the state of the art. Facility users rarely will accept specific areas designed only for specific equipment items, and they tend unhesitatingly to state that they want their facilities to be suitable for tomorrow's equipment, which is not yet invented, but which is bound to have tighter requirements as line widths become smaller.

Because some of the suppliers of microelectronics fabrication equipment have not provided adequate specifications of the maximum floor vibrations to which given items of equipment may be exposed during operation (as discussed later in this paper), facility engineers have been left without much guidance. For some early facilities, they thus have simply and naively set forth the requirement that the absolute displacement of the facility floor not exceed the desired line width resolution (or image displacement) at all frequencies below a certain value. This sort of criterion is unrealistic, even if one ignores the very low frequencies, where such phenomena as tidal and atmospheric effects make it practically impossible to meet this requirement. It does not take account of the fact that the image movement results from a relative displacement between structural components of the equipment, and that this relative displacement may differ considerably from the absolute displacements of the equipment's support points. At low frequencies, where the equipment behaves dynamically essentially as a rigid body (as one may conclude from basic structural dynamics considerations), the relative displacements may be several orders of magnitude smaller than the absolute input displacements.

Some facility specifications, as illustrated in Fig. 2, have deviated from frequency-independent displacement limits, perhaps on the basis of empirical experience with some specific items of equipment. It is unlikely, however, that the stringent requirements implied by these specifications at the low end of their frequency range ever were met.

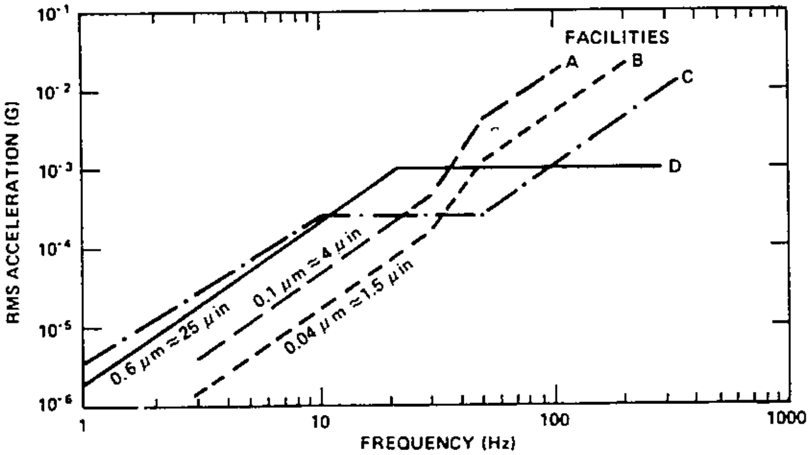

Fig. 2 — Some recent microelectronics facilities floor vibration criteria specified by facility users. (Slanted lines with μm labels are lines of corresponding constant displacement amplitude.)

An approach based entirely on empirical facility vibration data has more recently been taken by facilities engineers. They have simply measured the vibration environments in areas where various equipment items are operating satisfactorily and have set forth the requirement that the vibrations at every frequency in the newly designed facility be less by a given factor than the most severe corresponding vibrations in the areas where measurements were taken. The purpose of the reduction factor was to provide an additional margin of safety and to account for the expected greater vibration sensitivity of newer equipment.

Unfortunately, the bandwidths used for the aforementioned environmental data analyses are rarely indicated, often resulting not only in the unwitting combination of data corresponding to different bandwidths, but also in a lack of definition of the bandwidths applicable to a specification.

However, this empirically based approach has some shortcomings, even if the measurement bandwidths are fully identified. For example, a particular vibration environment, which may be unacceptable because of the effect of only one of its frequency components, in this approach would lead to the setting of restrictive limits on all other frequency components— resulting in potentially costly over-conservatism.

Fully realistic and sensible criteria also must take proper account of the combined effects of different excitation components. For example, if an acceleration a_1 at frequency f_1 is barely acceptable if this vibration component is present by itself, and if an acceleration a_2 at frequency f_2 similarly is barely acceptable, both according to some criterion curve developed on the basis of a series of narrow-band excitations—then, is an environment satisfactory if it contains both of these components? Intuitively, the answer depends on the separation between the two frequencies: components with widely different frequencies are likely to act independently and to affect different equipment modes preferentially, so that their simultaneous presence is likely to be acceptable, whereas components that do not differ much in frequency may have additive effects. Perhaps the best means for coping with this problem consists of defining criteria in tems of bandwidths that are typical of equipment response bandwidths, so that measurement in these bandwidths takes account of the combination of the frequency components present in the environment approximately as does the equipment response.

Furthermore, in the setting criteria it is not sufficient merely to establish boundaries on the vibration levels as a function of frequency, in specified bandwidths. One also needs to delineate the time interval(s) over which measurements are to be carried out, as well as the statistics (amplitude distribution) of the vibration levels. Of course, any given data sample must extend over several periods of the lowest frequency component of interest, so that one can analyze that component adequately.

In addition, however, practical considerations for a manufacturing facility make it necessary to characterize the vibration environment encountered during an entire working day, so that one ideally should measure this environment over several such days. In establishing a meaningful criterion in relation to long-term environmental vibrations, one needs to consider how significantly microelectronic manufacturing equipment is affected by occasional disturbances. For equipment or processes that must continue without interruption for extended periods, one requires that the environment exceed the disturbing levels only extremely rarely, whereas for others, more frequent disturbances may be acceptable. It often turns out that the equipment items that are most sensitive to vibrations do not operate continuously and that some of the most sensitive items include control systems that prevent photographic exposure if the image is inadequately sharp. It thus often is useful to state criteria in terms of percentile levels—i.e., the vibration levels which are exceeded a given percent of the time during defined periods of the working day.

Design Considerations

In view of the extreme vibration-sensitivity of the equipment, it is important that a relatively vibration-free site be selected for a microelectronics facility. For this purpose, performance of a vibration survey is generally recommended as part of the site evaluation process. such a survey should include measurements during the quietest (most vibration-free) times and during the most active times, and ideally should extend over long enough periods so that meaningful statistical discussion. For example, one may want to evaluate the vibration amplitudes in each one-third octave band that are exceeded 50, 20, 10 and 5 percent of the time, so that one can calculate what percentage of the time the site vibrations meet the facility specifications. Of course, such a detailed site study may not be necessary in cases where vibration levels that are clearly too high or that are very low are observed over a significant period.

As implied in the foregoing paragraph, vibration surveys and the attendant data reduction should not be undertaken blindly, but with facility criteria in mind. Criteria and attenuation possibilities must also be considered, of course, in evaluating sites or selecting one of several alternatives. For example, one generally may more readily isolate equipment against site vibrations that exceed the criteria in some high frequency regions than against others that exceed the criteria at lower frequencies.

Some site vibration reduction may be achievable by controlling external sources. For example, nearby roadways and rail-lines may be smoothed, speed-bumps may be removed, and traffic may be rerouted (or confined to non-operating hours of the day or week) or slowed down.

The most important aspect of a facility design usually consist of providing a suitable structure, particularly for that part of the building that houses the vibration-sensitive equipment. The second most important aspect typically conists of providing a layout that separates the sensitive equipment from vibration sources.

The facility should be configured so as to locate major vibration-producing items (such as pumps, compressors and fans) as far as possible from the critical clean room areas, and careful attention needs to be paid to providing adequate vibration isolation between the sources and the sensitive areas. Some facilities have been designed with all major support equipment housed in a separate building; others have been built with all support equipment located near the sensitive areas, but mounted on entirely separate structural systems. In all cases, the routing and support of the extensive ducting and pipework systems also needs to be considered from the vibration isolation standpoint.

The building structure should be designed so that neither the sensitive areas nor the parts that house vibration-producing equipment have resonance frequencies that match the excitation frequencies associated with the vibration sources. If avoidance of resonances is impossible or uncertain, the use of increased structural damping may be considered; however proven means that provide such damping are not readily available, and one must keep in mind that increased damping broadens the response bandwidth and thus may increase vibrations due to some source components while decreasing those due to others.

Vibration reduction at the source is recommended where possible. This approach may involve the selection of alternatives that inherently produce less vibrations (e.g., using rotating compressors in place of reciprocating pumps; keeping the flow velocities in ducts and pipes low), choosing equipment that is less likely to excite structural resonances or that can be isolated more effectively (e.g., high speed axial flow fans in place of lower speed centrifugal blowers), and specifying better dynamic balancing of equipment.

Primary vibration reduction considerations also involve configurating the entire facility so as to minimize in-plant vehicle and foot traffic near and in the sensitive areas. Where vehicular traffic is unavoidable, care must be taken to avoid surface irregularities, structural joints, and sudden structural stiffness changes along the vehicle paths.

People walking often turn out to constitute a critical source of vibrations about which one can generally do very little that is practical in existing facilities. However, appropriate structural choices can generally be made relatively readily in the process of designing a new facility.

Attention to details is required also not only in the design and specification of isolation systems for all vibrating equipment items so as to obtain adequate performance and to avoid any mechanical short-circuiting, but also in inspecting the final installations. After a facility has been built, measurements may be required to verify that source vibration level and isolation system performance specifications have been met, to determine to what extent the entire facility indeed meets its criteria, and to identify what may need to be done to correct discrepancies.

OPTICAL EQUIPMENT

Typical Configuration

Although many different types of equipment tend to be employed in microcircuit manufacturing, the equipment items that are most sensitive to vibrations fall into the broad class of optical equipment—if one considers this class to include also production and inspection equipment that employs radiation other than light, such as electron beams. For the present discussion, optical equipment thus includes common light microscopes, as well as electron microscopes of all types, in addition to such microcircuit fabrication items as aligners, registration analyzers, pattern generators and wafer steppers.

Although the various specific items of optical equipment may differ considerably in their operational details, they nevertheless share a number of major features from the viewpoint of their structural dynamics. As shown schematically in Fig. 3, a typical equipment item consists of an optical column and an image stage which must be maintained in a precise position relative to each other (at least during an exposure or observation interval). For the present discussion it does not matter whether radiation coming from the optical column is used to expose an item on the image stage or whether an item on the image stage is viewed (by eye or electronically) via the opitcal system.

The "optics support frame" in the figure indicates the structure that is intended to provide the desired aforementioned relative positioning. This structure may be relatively complex in some equipment items; it may, for example, enclose the entire optical system, and it may include electro-mechanical arrangements for adjusting (or stepping or rotating) the stage relative to the optical column.

The entire optics support frame typically is supported on a secondary structure, which is labeled "table" in the figure, and that structure—in turn—rests on a support base. The more sensitive items of optical equipment generally are installed on soft springs (often of the air spring type, in which case the table system often is called a "air table") and may include additional vibration isolation mounts, as also sketched schematically in the figure.

Vibration Criteria

If one knows the amount of image motion that is permissible in a given situation, together with the "transfer function" between the image motion and the floor vibration, one may expect to be able to derive appropriate floor vibration criteria—i.e., limits that the floor vibrations must not exceed if a given desired image quality is to be maintained.

The suppliers and users of optical equipment generally tend to have very precise information on the permissible image displacements, but to know little or nothing about the vibration transfer functions. It should be noted that even for a given machine in a given, fixed configuration, obtaining a transfer function is not easy. Although one generally may count on response linearity for the small amplitudes of concern here (so that one need not consider variations with amplitude) and although one can usually neglect the effects of purely rotational motions, one still needs in general to evaluate the magnitudes of optical column displacements relative to the image stage in each of three orthogonal directions--for each of three orthogonal directions of floor motion--and, of course, all as functions of frequency. Obviously, greater complexity results for machines whose configurations can change appreciably, e.g., due to motion of an image stage.

Although a "transfer function" thus in general may be represented by nine curves that indicate the frequency-variation of the ratio of the x, y and z image displacements to the x, y, and z floor displacements (or accelerations), considerable simplification is possible in many instances. For optical systems that have relatively large depths of focus, for example, relative displacements along the optical column axis tend to be less important than the others. In most facility structures, the horizontal floor vibrations tend to be considerably less significant than the vertical ones and can therefore be omitted from consideration.

Under these simplifying circumstances one may need to deal with only two in-plane image displacements in response to vertical floor vibrations. One may then represent these two remaining transfer function curves conveniently by a single one that corresponds to an envelope or a vector sum, resulting in a simply applied, conservative measure of the maximum image displacement occurring in any in-plane direction due to vertical floor motion.

It appears that the vibration criterion problem for optical equipment has for a long time not been addressed adequately. Many equipment suppliers have provided only a "single number" floor vibration criterion, such as a maximum permissible displacement (or velocity or acceleration) without any frequency information or any hint of how the specified value was to be measured (or how it was obtained). The variations of the permissible acceleration magnitudes with frequency implied by a number of these criteria are indicated in Figs. 4 and 5. It is evident that many of these criteria require unrealistically small motions, particularly in the low frequency region—where these magnitudes are practically impossible to achieve, and where also the equipment items are likely to experience relatively little deflection (and concommitant image dis-

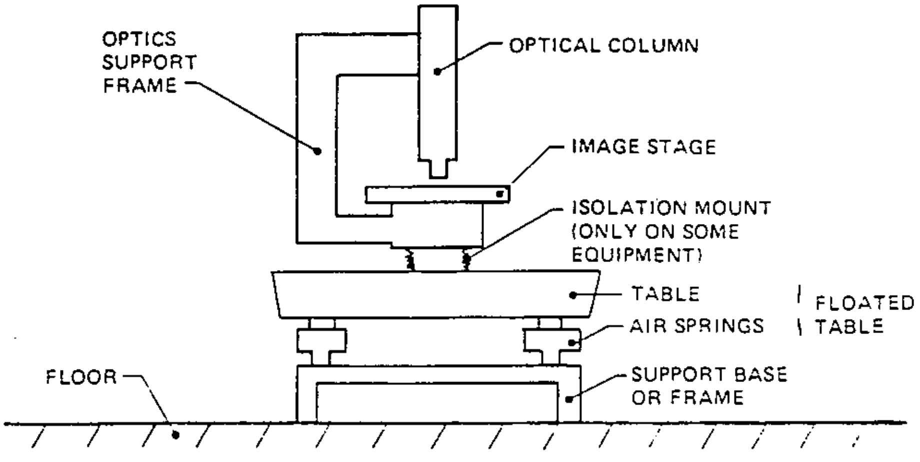

Fig. 3 — Schematic sketch of optical equipment.

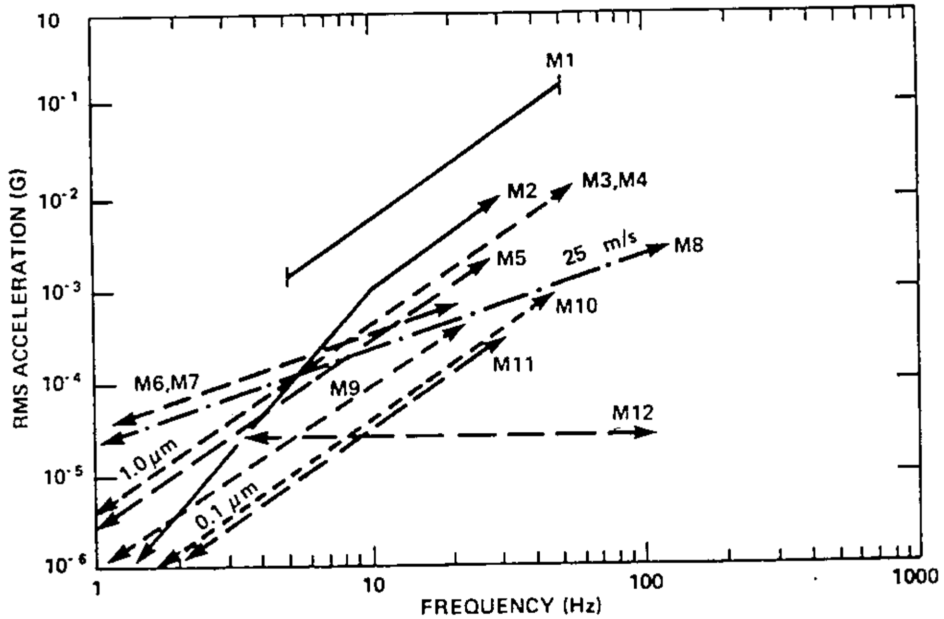

Fig 4 — Suppliers' floor vibration criteria for twelve different electron microscopes. (Slanted lines with μm and μm/s labels are lines of corresponding constant rms displacement or velocity, respectively. Arrows at ends of lines imply that specified criterion is stated without frequency restriction.)

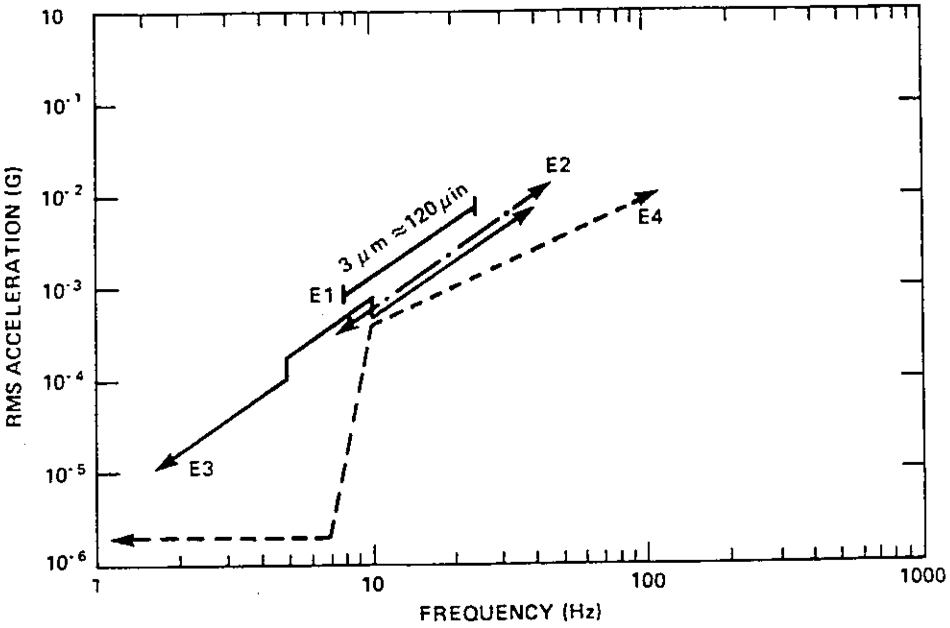

Fig. 5 — Suppliers' floor vibration criteria for four different items of electron-beam microelectronics manufacturing equipment (Same notes apply here as for Fig. 4.)

placement) for a given amount of floor vibration, as has been mentioned.

Several of the equipment criteria that have been put forth, however, are somewhat more realistic and apparently take account of some of the equipments' structural dynamics aspects. For example, as indicated in Fig. 4, some criteria restrict applicability of the stated single-number values to limited frequency regions, others state different values for two or three different frequency regions, and some indicate more complex frequency-dependencies that may have been based on tests or observations. Again, no background documentation appears to be available.

In view of this dearth of useful criterion information, we have taken some steps toward developing defensible realistic criteria, at least for some equipment that is currently in use. We made floor vibration measurements near operating equipment at several facilities, both under normal ambient conditions and in the presence of several different types and levels of disturbing vibrations (e.g., due to nearby traffic or several people walking), and we obtained the corresponding equipment users' evaluation (based on subjective judgements or optical measurements) concerning the acceptability of these vibrations.

Some of the results of this work are illustrated in Fig. 6, which represents the highest observed floor acceleration spectrum peaks (in one-third octave bands) corresponding to conditions under which satisfactory equipment operation was obtained. Two facts should be noted: (1) The magnitudes of some of these peaks were limited by the floor vibrations that could be obtained in these investigations, and not by the onset of unsatisfactory equipment operation. (2) Since all frequency components acted on the equipment simultaneously, one cannot judge which may limit the equipment's performance; considerably higher magnitudes of some components may be acceptable without adverse effects. Thus, the data presented here correspond to conservative criteria--i.e., the equipment is likely to perform satisfactorily even if the floor vibrations exceed the magnitudes represented by the data points, and the equipment will certainly perform satisfactorily if the vibrations do not exceed those corresponding to the data points.

In order to establish well-defined criteria by this approach, a great deal of data collection and analysis is needed. Ideally, data should be obtained for a wide variety of floor vibration conditions that produce both acceptable and unacceptable equipment performance for each item of equipment, and the data should be analyzed in terms of frequency bands that are relevant to the equipment response, as discussed in the previous section. However, some other approaches, based on more concentrated investigations of specific items of equipment, may be preferable.

One such approach involves determination of the transfer functions between floor accelerations and image displacements that were discussed earlier, and then calculating the maximum floor vibrations that result in acceptable image displacements. Evaluation of these tranfer functions is relatively straightforward, but requires extended availability of the optical equipment for testing, as well as provisions for controlled simulation of the floor vibrations and sensitive means for measuring the small image displacements of concern or the corresponding relative displacements between the image stage and the optical columns.

Another approach to developing precise vibration criteria for a specific item of optical equipment makes use of an analytical model of the equipment, developed on the basis of parameter values deduced from a series of measurements made on the equipment item. Once the item is modeled mathematically, the model can readily be used for determining the desired transfer functions—and these, in turn, can be employed to calculate the permissible floor vibrations as mentioned previously.

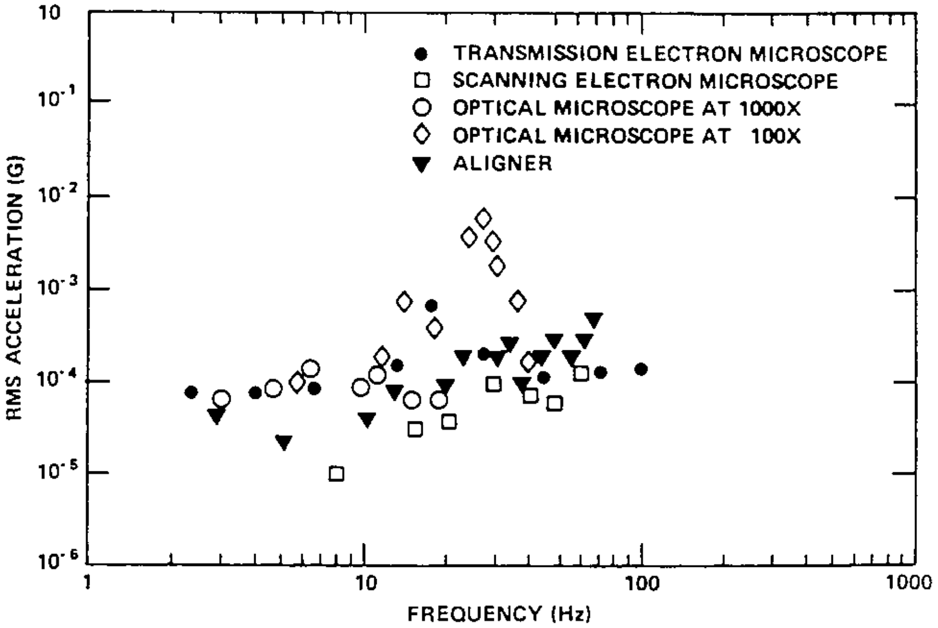

Fig. 6 — Maximum floor vibration spectrum peaks (in one-third octave bands) at which optical equipment items operated satisfactorily.

Because typically only the lowest few modes of each major structural component of a piece of equipment tend to contribute significantly to the dynamic response of the equipment in the low-frequency region of primary concern, the number of parameters needed for the mathematical model generally is not excessive. Often, just a few simple measurements may suffice to evaluate these parameters. For example, observation of the decay of free vibrations produced by an impact or by plucking (deflecting and releasing) a component, with and without disabling the isolation systems, can provide information on the natural frequencies and damping of the structural components and isolation systems. The currently available sophisticated computerized modal analysis systems and system identification (parameter evaluation) codes can, of course, also provide the desired modal and transfer function information.

Figure 7 illustrates criteria for two modern pieces of optical equipment, developed by their manufacturers on the basis of direct transfer function measurements. Also shown is a criterion curve developed by us for one of these same equipment items by use of a two degree of freedom model derived from simple field measurements. One may note that the two corresponding criterion curves agree well with each other, with the differences probably ascribable primarily to the way that the actual information was represented by simple envelope curves.

By comparing Figs. 4, 5 and 7 one may also observe that the more rationally developed criteria of Fig. 7 are less stringent than the older, less defensible, criteria—particularly at the low frequencies. Wider availability of such more rationally derived criteria thus may reduce the severity of the vibration control problems that need to be addressed in the design of microelectronics manufacturing facilities.

CONCLUDING REMARKS

It is apparent that there exists a need for reasonable facilities vibration criteria that neither overstate nor understate the sensitivity of microelectronics manufacturing equipment.

Such facilities criteria can best be developed from corresponding criteria for the equipment. Much of the available equipment criteria information is inadequate; the derivation of realistic specifications from measured transfer functions or analytical models is recommended.

Structural dynamics considerations appear often to have been given inadequate attention in the design of microelectronics manufacturing equipment. Although most sensitive equipment items are furnished with air-spring isolation tables, for many little effort appears to have been made to optimize the isolation systems (e.g., in terms of decoupling of modes and use of two-stage isolation). Many equipment items could also benefit from modifications that increase the dynamic rigidity of the structure interconnecting the optical column and the image stage, that result in greater modal frequency separation, that provide significant increases in structural damping, and that reduce vibrations produced by internal sources such as stepping motors.

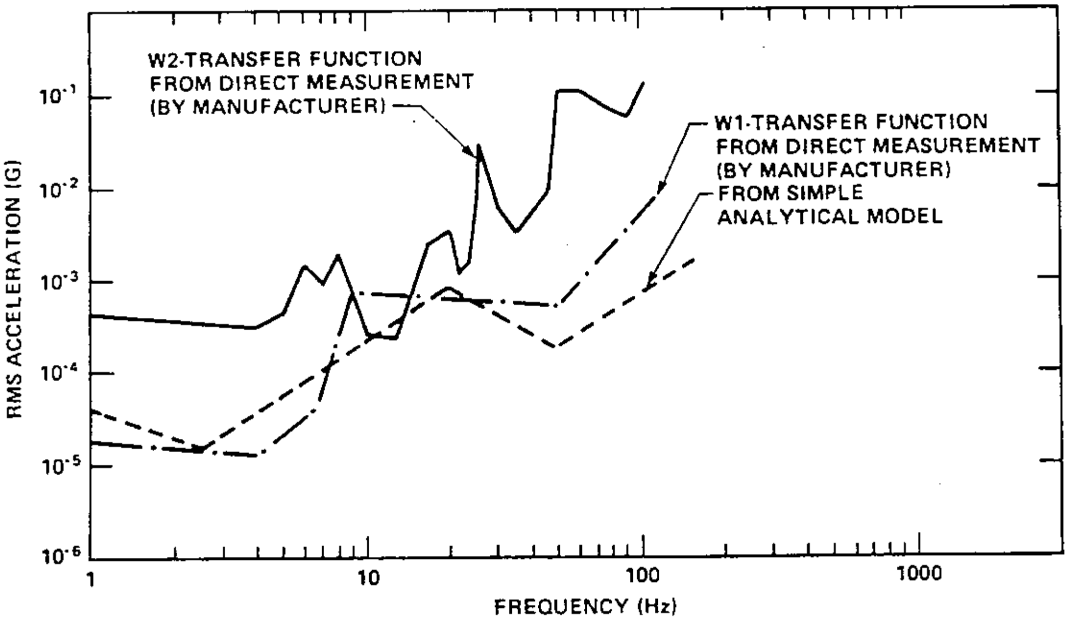

Fig. 7 — Narrow-band vertical floor vibration criteria for 1-μm line width, developed from floor-acceleration–image-displacement transfer functions.