TAMING THE GENERAL-PURPOSE VIBRATION TEST*†

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There is little doubt that the acceleration levels quoted in many of the general-purpose vibration test specifications issued by official agencies are based upon measurements made at vibration antinodes. Where this is so, there is no justification for permitting the acceleration level at any of the attachment points to exceed the level quoted, or for permitting the applied force to exceed a computable value. An extension of the control system results in a more rational test.

THE GENERAL-PURPOSE TEST

Considerable publicity has been given in the course of recent symposia to the difficult task facing the writer of a test specification dealing with vibration environments.[1-6, 8-11] (See References, 216-217.)

The test he evolves will form the basis of a contract (formal or implied) between a supplier and a user, and will result in the acceptance or rejection of a proffered article. Both parties to the contract would like the test to result in the acceptance of only what is service-worthy and the rejection of only what is not, but it is now becoming more widely appreciated that it is beyond our present ability to devise a vibration test which will give a verdict with a confidence level even moderately acceptable to supplier and user alike. In fact, such is the interaction between the dynamic characteristics of an article and those of the hardware with which it will be associated in real life that even a test carefully tailored to relate to a single specific article whose survival in a single environmental circumstance is at issue is likely to be seriously invalid in one or more respects.

Despite this, the specification writer finds himself called upon to tackle the problem of devising a general-purpose vibration test which can be applied by unsophisticated, minimally-equipped, test personnel to broad groupings of widely-diverse articles whose future environmental circumstances can only be guessed at. His protests are unavailing; he has to do the best he can; and in due course the outcome of his labours becomes yet another of the many generalized vibration test specifications issued over the past 15 years by the various official agencies.

We may not like this situation, and we may be further disturbed to note from this year's batch of symposium papers that it is those very writers whose practical experience is most broadly based who have most sympathy with disgruntled suppliers and users when they complain of service-worthy equipment being rejected and inferior equipment being accepted by the application of these tests.[7] But whether we like it or not, the situation will be with us for many years to come, and we would do well to accept and publicise the fact that such tests can be no more than arbitrary barriers to poor design or faulty production, and to do what we can to improve them as such.

TWO POSSIBLE IMPROVEMENTS

The most widely used general-purpose test calls for the article to be attached to a vibrator by its normal points of attachment and subjected to sinusoidal vibration whose frequency is swept backwards and forwards between stated limits.

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The intensity of the vibration is specified in quite simple terms: e.g., 10 g from 20 cps to 2 kc, and the accepted convention is that some form of control system (automatic, or manual) should be employed to maintain this intensity at a single point of the structure (normally one of the points of attachment) throughout the test.

Two aspects of such a test are considered here, each capable of modest improvement. The first is that in maintaining the specified acceleration level at the point of attachment which happens to carry the control accelerometer we may well be generating a much higher level of acceleration at one or other of the remaining points of attachment. This will occur whenever the excitation frequency is such that the control accelerometer finds itself at a local vibration node, as may repeatedly happen at the higher frequencies. The second is that in maintaining the specified acceleration level, regardless of the dynamic reactions of the article under test, we are treating the article as if, in service use, it will be attached to a structure of infinite mechanical impedance, rather than to a structure whose impedance, as the natural outcome of normal engineering practice, will seldom be vastly greater than that of the article itself, and may well be significantly less at certain critical frequencies.

As we shall see, neither practice is consistent with the line of reasoning which, consciously or otherwise, prompted the adoption of the particular acceleration level as being appropriate to the particular specification.

Bearing in mind that we have to be content to make the best of a notably bad job, it is suggested that the test can be improved in two ways: by employing multi-point rather than single-point acceleration control (i.e., insuring that at no point on the normal mounting surface of the article does the acceleration level exceed the specified value), and by setting an appropriate limit to the force we bring to bear on the test article.

THE DATA-REDUCTION PROCESS

To justify these suggestions we must examine, in some detail, the procedure adopted in the derivation of the stipulated test level, because inherent in this process is a factor which appears to have been generally overlooked.

In general, it can be said that these test levels are based upon a somewhat heterogeneous collection of acceleration measurements made over the years at a large number of selected points, on a large number of assorted articles of hardware, situated at a variety of locations, on a large number of vehicles,* and experiencing a variety of service environments.

Depending upon the sophistication of the trials instrumentation and upon the type of data-analysis equipment available to the investigator, each such exercise can be assumed to have yielded either a family of curves of intensity against frequency, or a number of traces of instantaneous acceleration against time, or a number of spot values related to the highest instantaneous value of acceleration encountered during the experience.

Stage by stage, over the years, this unwieldy mass of original data has been processed piecemeal by a variety of individuals employing a variety of data reduction techniques, probably the only commom factor being an understandable wish to err on the safe side.

It is this defensive approach which has lead each individual in his turn to adopt an intensity level high enough to embrace all the maximum values revealed by the data he has been processing, and it is here that the crux of the matter lies.

To take a very simple example let us consider the case of a vital article of navigational equipment which is to be installed in a particular type of jet aircraft. It is envisaged that the user may decide to mount the equipment in any one of three locations on the airframe, and tape records are made of the accelerations at each of the four points of attachment of the article during a particular phase of flight, with the article mounted at each location in turn.

On playback, the investigator may well have been encouraged to note that in terms of rms level of intensity there was little to choose between the dozen records; and had he investigated the spectral distribution of the vibrational energy by employing filters of unusually wide bandwidth (say two octaves wide) there may well have been little to choose between the dozen smooth curves that resulted.

But when he carries out the more normal frequency analysis using filter bandwidths appropriate to the work, and examines the resulting curves of spectral density against frequency,

*The term 'vehicle' is used here in its broadest sense to include a complete missile, a ship, an aircraft, and the like, as well as a land vehicle.

significant differences become apparent. Each curve displays a number of peaks and troughs, and the frequencies at which the major peaks occur differ significantly from curve to curve. If the dozen curves are plotted on a single sheet of paper it becomes clear that the peaks are distributed over quite wide sections of the frequency spectrum, despite the fact that he has so far investigated only three possible locations in a single version of one type of aircraft. In order to err on the safe side, and to cater for the possible use of his navigational equipment in a number of versions of the aircraft, he sees no alternative but to define a test level derived from a smooth curve enveloping not only the peaks whose existence and magnitude he has experimentally established, but also an adequacy of peaks at intermediate frequencies whose level he estimates by visual interpolation between the established peaks.

NODES AND ANTINODES

The implications of this action can best be appreciated by visualizing the behaviour of the complete aircraft structure if it were subjected to single-frequency sinusoidal excitation. For any spot frequency there would be a clearly defined standing-wave pattern distributed three dimensionally over the structure. Some points would be at vibration antinodes, others at vibration nodes. The transfer of a piece of equipment from one area to another would result in a change of pattern, localised or widespread.

If the excitation frequency were altered, a completely new standing-wave pattern would result, and if we confined our attention to a single point on the structure whilst the excitation frequency was being smoothly swept from a low frequency to a high frequency we should observe the acceleration level building up to a peak value as an antinode approached and coincided with our monitoring point, falling away subsequently to a trough as the antinode moved elsewhere and was replaced by a node, only to rise again with the approach of another antinode.

A plot of accleration level against frequency for this point would thus exhibit a number of peaks and troughs, much as did each of the spectral density curves relating to the navigational equipment, and in the main for the same reasons, the presence or absense of vibration antinodes at the measuring point.

Thus we see that in basing his test level upon a line enveloping all the peaks the investigator is in fact postulating the existence of antinodes at all four points of attachment simultaneously, and their continuous existence over a wide range of frequency. He is in fact stating a level of acceleration that will not, in his opinion, be exceeded at any of the points of attachment in any service usage.

MULTIPOINT CONTROL

In the light of this, let us review the vibration test itself.

When the navigational equipment is mounted on a vibrator table for test purposes, the whole assembly (equipment, attachment jig, table, and suspension) becomes a single coherent structure which, when subjected to swept sinusoidal excitation, develops its own ever-changing pattern of nodes and antinodes. If the acceleration level is controlled at only one of the points of attachment, as is normal present-day practice, there will inevitably be frequencies at which this particular point is located at a node whilst one or other of the remaining points of attachment are in antinodal area. In such circumstances the article will suffer unjustified overtest since the excitation at the unmonitored points will greatly exceed the investigator's most pessimistic forecast. If this is to be avoided the control system must be such that the specified acceleration level is exceeded at no point on the attachment surface.

If such a system of control is accepted as necessary in the relatively straightforward example described above where the test level is based upon practical measurements relating to the actual article in a clearly defined usage, then it is suggested that it should be made mandatory where the test is to be a general-purpose one. In such a test the probability is that the test level is already unduly high for the majority of articles which will be subjected to it, since it will have been derived by enveloping a variety of envelopes, some of which will undoubtedly incorporate purely numerical (and unknown) factors of safety, others of which will result from isolated spot-measurements made upon lightly loaded, highly resonant, surfaces such as panels and brackets, and most of which have only marginal relevance to the nature and usage of the article under test.

For the acceleration level applied to articles having two or more points of attachment to be further increased by a factor of 2, or 3, or even 5, (even if this occurs only over parts of the frequency sweep) is quite unjustified and undoubtedly swells the volume of service-worthy stores rejected on test.

THE CRITICAL TROUGH

The second suggested improvement is most easily described in relation to an article constructed with a single clearly-defined point of attachment and liable at the discretion of the user to be mounted at any one of a number of locations in some structure. Again we imagine the input to the structure to consist of a sinusoidal force whose frequency is slowly varying, and we visualize the changing pattern of nodes and antinodes. Again we note that the transfer of the article from one location to another is accompanied by a further change of pattern, widespread or localised.

If, for each location, we prepared a plot of acceleration against frequency for the point of attachment of the article, each curve would have its quota of peaks and troughs and no two curves would be identical, particularly as regards the frequencies at which the peaks occurred. But it might well be noticeable that there was one particular frequency at which all the records revealed a trough, irrespective of the location of the article; and the more nearly the article approximated to a lumped mass supported on a lightly-damped spring the more pronounced would be the trough, and the more noticeably would it be a feature common to all the records.

In short, no matter where it was mounted, the article insured that there was a nodal trough at its point of attachment at this particular frequency. Investigation of the dynamic response of the article itself would show that this was the frequency at which some major internal element came to resonance and experienced an acceleration 5, 10, or 20 times as great as that existing at the point of attachment—clearly a frequency at which the article was very susceptible to damage.

PEAK-TO-TROUGH RATIO

We thus have the situation that the correct test level for this critical frequency would be that indicated by the nodal trough whereas, as we have seen, the test level demanded by the specification will be that decided by the height of the antinodal peaks on each side of the trough. The ratio of the one to the other, the peak-to-trough ratio, is clearly of some importance in that it establishes the degree of overtest which a resonant article will experience at a critical frequency as the result of just one of the many steps in the data reduction process.

Published literature contains little empirical data from which probable values for this peak-to-trough ratio can be evaluated.

Analogue studies based on the response of two single-degree-of-freedom systems mounted one upon the other, each having a Q of 10, with mass-to-mass ratios varying from 0.2 to 5 and resonant-frequency ratios varying from 0.3 to 3, suggest peak-to-trough ratios varying between 20 and 200. Such elementary systems, although they oversimplify the problem, provide useful pointers to the probable behaviour of resonant structures; they indicate the part played by the 'passenger' system (representing our article) in determining the magnitude and the frequency of the adjacent peaks as well as of the trough itself, and they suggest that the transmissibility of the 'passenger' system at the frequency of the adjacent peaks is unlikely to be greater than 1.5, an item of information which comes in handy in the derivation of a force-limited test.

More practical measurements, made on service structures carrying various sub-assemblies, and relating only to those peaks and troughs whose association with a basic resonance of the sub-assembly could be established, suggest peak-to-trough ratios ranging from 4 to 30 for sub-assemblies in which the weight of the resonant section varied between 20 and 80 percent of the total weight of the assembly.

THE IMPEDANCE MISMATCH

Is there any practical way in which a general-purpose test can be modified so as to moderate the degree of overtest which resonant articles experience at these critical frequencies?

It is informative to discuss the problem either in terms of mechanical impedance (the force required to produce unit velocity) or in terms of the closely related 'effective mass' (the force required to produce unit acceleration). Three such values are of interest: the effective mass of the article itself; the impedance of the point on the structure at which it will be mounted in service use; and the impedance of the vibrator table to which it will be attached for test. Each is a function of frequency.

As an example let us assume that half the mass of an article is virtually resonance-free below 200 cps whilst the remainder comes to resonance at 50 cps with a Q of 10. At very low frequencies, below say 20 cps, the effective mass of the article will be constant, a force of say P pounds being required to produce an acceleration of 1 g at any frequency over this range. At 50 cps, however, whilst the non-resonant half is still moving with 1-g acceleration and requiring P/2 pounds of force, the resonant section will be moving with 10 g and requiring an input force of 10 times P/2 pounds to maintain this motion. The total force required to maintain 1-g acceleration at the point of attachment has thus risen from P pounds to around 5P pounds. Its effective mass has risen to around five times its low frequency value; its impedance is around five times as great as that of a non-resonant article of equal weight.

To what extent is this increased force brought to bear on the article, whilst it is undergoing a vibration test, and whilst it is mounted in a structure experiencing a typical service environment?

There is no doubt at all as to the situation whilst it is being tested to a typical general-purpose specification. A control system (manual or automatic) is employed to keep the acceleration at the point of attachment at the specified level, the installation developing whatever force is necessary to maintain this acceleration. No reactional force generated in the article, however great, results in the slightest change in the acceleration of the surface to which it is attached. To all intents and purposes, the article finds itself mounted on a surface of infinite mechanical impedance.

Quite a different state of affairs exists when, in service use, the article finds itself embodied in a practical structure. Practical structures are not of infinite impedance; they are the outcome of normal drawing office practice. Whether evolved by rule of thumb or by careful stress analysis they are no stronger than they need be, since extra strength or rigidity implies extra cost, or extra size, or extra weight. Furthermore, over the range of frequencies of interest, a mounting-point impedance is only marginally determined by the composition of the complete structure; it is predominantly a function of the dynamic characteristics of elements quite local to the mounting point—a section of panel, a bracket, another article closely comparable to the one in which we are interested.

In short, it is suggested that the impedance at a mounting-point on a supporting structure is likely to be of the same order of magnitude as that of the article to be mounted there, and at the critical frequencies with which we are concerned it may well be significantly less. So far from finding itself completely at the mercy of a vibrating structure of infinite impedance, as it does when on test, it experiences an impedance ratio which permits it materially to ameliorate its treatment at critical frequencies, as the existence of specific nodal troughs in acceleration-frequency curves confirms.

Inevitably, there are exceptional cases: small items mounted for convenience upon massive beams or girders designed to support major assemblies; but these are exceptions and must be treated as such: they must not influence the whole test pattern to the grave detriment of the generality of articles.

FORCE LIMITATION

Until such time, then, as we are in a position to define a general-purpose test in terms of a system of forces acting through an appropriate network of impedances, it is desirable to set an upper limit to the force we apply to the article whilst it is undergoing test, thus simulating a non-infinite impedance at the test table and permitting the development of a partial trough in the acceleration level at a frequency to be determined by the article itself.

At this stage it is important to remind ourselves of the many and varied processes of data reduction which led up to the adoption of the specified acceleration level, and to recollect the defensive approach of the successive data manipulators. In determining the maximum force to be applied to an article there is no need for the application of still further "factors of safety"; if anything, the requirement is to be merciful to the test victims. Equally inappropriate would be meticulous accuracy; the accuracy of our raw material does not justify it.

We do not know the magnitude of the force acting upon our article at the frequency of the critical trough when it is embodied in its service structure. We can, however, make an intelligent guess as to how it would compare with the force acting at the frequency of the adjacent peaks. If the twin single-degree-of-freedom analogue discussed above is any guide, the force acting at the trough is materially lower than that acting at the frequency of the adjacent peaks; certainly we shall run little risk of underestimating the former if we equate the two.

The analogue also suggested that the transmissibility of the 'passenger' system was unlikely to exceed 1.5 at the frequencies of the peaks, implying an effective mass at these frequencies of not greater than 1.5 times the 'dead' mass. This figure, of course, relates to a passenger system in which 100-percent of the mass is resiliently mounted; for a more realistic article of which only a portion comes to resonance the figure could be anywhere between 1 and 1.5. We can therefore postulate with reasonable confidence that, in its service usage, the force acting on the article at its critical frequency will not exceed 1.5 times that required to produce the 'adjacent-peak' acceleration in an inert article of equal weight, and is likely to be significantly less.

This is a situation which we can reproduce during the test, by substituting the specified acceleration level for the 'adjacent-peak' acceleration, the former having been derived from the latter, as we have seen. Since we do not know the precise frequency at which the article will come to resonance, any force-limitation we apply must operate over much, if not all, of the specified frequency sweep; we must therefore apply a force at least 1.0 times that required to produce the specified acceleration in an equivalent dead weight. On the other hand, in view of manifold factors of safety inherent in the specified acceleration level and implied in the above argument, a factor of 1.5 appears excessive. An arbitrary figure of 1.2 is therefore suggested.

SUITING THE CIRCUMSTANCE

This factor of 1.2 can be adopted when the force to be controlled is that acting upon the article alone, via its single point of attachment. Where circumstances are such that the only controllable force is that acting upon an attachment-jig carrying the article (so that only a small percentage increase in the effective mass of the driven system is to be expected at the critical frequency) then it is suggested that the factor should be reduced to as near unity as is practicable. Where, again, the article has two, three, or four separate points of attachment and the specification calls for a constant level of acceleration over a frequency range extending down to frequencies at which the article can be relied upon to behave as an inert homogeneous mass, then the force limit appropriate to each point of attachment can be empirically adjusted at the low frequency end of the sweep to the minimum value which will allow the development of the specified acceleration level.

AUTOMATIC TRANSFER OF CONTROL

As the acceleration level, or the force acting, at one or other of the points of attachment rises to and tends to exceed the required level during the frequency sweep, the control function must be passed smoothly backwards and forwards between accelerometer and accelerometer, and between accelerometer and force gauge. This can be achieved quite simply with the aid of biassed semiconductor diodes. The use of relays or other mechanical switching devices is to be deprecated as introducing switching transients and backlash instabilities.

TAILPIECE

Despite its manifold shortcomings, the general-purpose vibration test calling for the application of a specified acceleration level will be with us for many years to come, thanks largely to its deceptive facade of precision, repeatability, and simplicity. It must be recognised for what it is—a crude, but necessary, barrier to poor design and faulty workmanship—and it must be improved where possible.

In its present form the test is unduly prone to result in the rejection of serviceworthy equipment. This tendency can be moderated by an extension of available control techniques.

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