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Advisory Note

Dynamic testing of grandstands and seating decks

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1 Introduction

This Note on the specification and procurement of dynamic testing of grandstand structures is to be read in conjunction with the Interim Guidance[1] on assessment and design of permanent grandstands subject to crowd dynamic action. The Interim Guidance describes the types of grandstand covered by the guidance and gives recommendations to assist in deciding the particular category of use for an existing grandstand.

The Interim Guidance requires the management concerned with the operation of grandstand facilities to know the value of the lowest relevant natural frequency of vertical vibration of any stand or seating deck of a size covered by the Interim Guidance. If the values of natural frequency are not known, the Interim Guidance advises that 'Management should appoint a suitably experienced engineer (consult the IStructE list) to undertake calculations and advise on the appointment of an experienced Test Agency to establish natural frequencies and other relevant parameters'.

This Advisory Note is addressed to both Management and the Engineer concerned with procuring the required testing and using the results.

2 Why dynamic testing?

Dynamic testing is required to provide a check on values of natural frequency obtained by calculation. A check is needed because the calculation of natural frequencies is not a straightforward task if results of sufficient accuracy are to be obtained. In particular, the use of short-cut methods, or rules of thumb, to estimate natural frequencies can give misleading results. The use of testing also provides a check on differences between the structure as designed and the 'as-built' structure with its fixtures and fittings and their added mass and stiffness. As a consequence, testing is recommended for all grandstand structures covered by the Interim Guidance.

[1] IStructE, DTLR, DCMS, (November 2001) *Dynamic performance requirements for permanent grandstands subject to crowd action, Interim guidance on assessment and design.* Institution of Structural Engineers, London, 2001, ISBN 0 901297 17 8

3 What should be tested and what results are needed?

The recommendations of the Interim Guidance are based on values of natural frequency for vertical excitation of an empty stand or seating deck. This should be interpreted as being without people present but otherwise complete with seating and other fixtures.

In order to be able to use the Interim Guidance and for the Engineer to be able to recommend a particular category of use, the minimum natural frequency for vertical vibration that can be excited by crowd movement should be determined. The Engineer will need to specify the type of testing required to provide this information. In addition, and except for the simplest structural arrangements, it will be useful if the testing provides additional information on mode shapes to assist in assessing the significance of any differences between test and calculated results and also the degree to which the mode is likely to be excited by crowd movement.

In some circumstances, the Engineer will require more detailed information than the minimum needed to satisfy the requirements of the Interim Guidance. This could occur if the Management had set particular performance specifications for parts of the structure or if information was needed in the context of upgrading the structure or introducing damping systems to reduce the effects of vibration. Depending on the level of information required, the Engineer would need to decide on the type of testing required. Broadly, two types of test are available corresponding to different levels of information obtained from the tests i.e.:

- **Type 1 Tests** provide basic information concerning natural frequencies that will normally be sufficient to satisfy the needs of the Interim Guidance and so enable the Engineer to recommend a category of use.
- **Type 2 Tests** provide more detailed information than Type 1 tests, in principle leading to a full modal description comprising natural frequencies, mode shapes, modal damping ratios and modal masses for all modes of interest. Tests of this type may be required if the results from analysis and Type 1 testing cannot be reconciled or if additional information is needed to support the design of modifications to the structure.

Type 1 testing will normally be sufficient to meet the requirements of the Interim Guidance. Moreover, if Type 1 testing is conducted in such a way that mode shapes are determined in addition to values of natural frequency, comparisons can be made with the calculated mode shapes as a check that test and calculation are being compared on a like-for-like basis.

Type 2 testing requires more time on site, more specialist equipment and more information processing than Type 1 testing. As a consequence, use of Type 2 testing is likely to cost more than a basic Type 1 test programme. In deciding the form of testing to be used, the additional cost of Type 2 testing needs to be considered in relation to the increased detail and quality of information that can be obtained.

4 Analysis and testing

The Interim Guidance states that natural frequencies '…should be determined by both calculation and testing and adequate agreement obtained between the results'. No measure of agreement is given. This is because it is a matter for the Engineer to decide what significance to give to any difference in results.

The Engineer will be concerned that the value of the lowest natural frequency has been determined with sufficient accuracy to enable a recommendation on a category of use to be made with confidence. In doing this, and bearing in mind the idealisations made in even a sophisticated analysis, it should be realised that exact correspondence between measured and calculated values is extremely unlikely. However, if the difference in results is substantial, the Engineer could be expected to review the results to check *inter alia* that:

- the mode shape corresponding to the lowest natural frequency is the same for the calculated results as that found from physical testing,
- the mass and stiffness of the structure, and all the non-structural elements associated with the grandstand or seating deck, has been properly represented in the dynamic analysis, and,
- the support conditions, including the continuity and fixity of the elements of the structure, are appropriately represented in the dynamic analysis.

Such a review could indicate whether the test programme had missed the mode of vibration corresponding to the minimum natural frequency or whether the analysis should be refined to include some mass or stiffness that had been ignored in an earlier calculation or extended to examine the significance of assumptions made in modelling the structure. Depending on the circumstances, the Engineer might decide that further Type 1 testing is necessary, or that more detailed testing is required and so review the testing specification to provide for some form of Type 2 testing.

It is recommended that an analysis to give an estimate of natural frequencies and mode shapes should be undertaken before testing is commissioned or undertaken. In doing this, it will be important to ascertain that the available drawings properly represent the structure as built with any differences being noted for future reference. Only by having the results of an analysis available can additional tests be requested to find a missing mode within a single programme of testing, so avoiding the Test Agency having to make a second visit to site. Information on the likely mode shape is also helpful in informing the choice of test points to be used in the test programme.

5 Available dynamic testing techniques

The following commonly available dynamic testing techniques can be used on grandstands:

- Ambient vibration survey, AVS.
- Heel-drop testing.
- Measured impact testing.
- Shaker testing of different types and complexity.

Whichever method of testing is used, it is vitally important that the level of excitation available is sufficient to excite all the modes of interest. Also, the instrumentation must be appropriate to record the response of the grandstand with sufficient accuracy to enable meaningful results to be derived.

Different testing procedures may be adopted depending on the type of excitation being used, the availability of instrumentation and the amount of detail required in the results. For instance, testing may be undertaken with accelerometers at a number of fixed locations with the excitation sources being moved, from test point to test point, in order to excite different modes and explore the sensitivity of the structure to vibration. Alternatively, the excitation source can be used in one place and the measuring points changed from test to test. A combination of these two approaches may also be appropriate. Also, if mode shapes are to be determined, testing should be performed across a range of test points that are sufficiently closely spaced that mode shapes are uniquely defined, even when there are neighbouring modes with similar shape.

The shakers used for testing are of two main types. These are:

- Electrical or hydraulic shakers that provide excitation using an inertial mass oscillating in the direction of excitation.
- Rotating mass shakers, usually driven by an electric motor.

In contrast to ambient vibration surveys, heel-drop tests and some forms of measured impact testing, shakers provide a consistent and reproducible source of excitation. This means that, besides providing good quality results for Type 1 testing, shakers can be used for Type 2 testing with the scope, or range of results, being dependent on the experience of the operators and the particular techniques and instrumentation employed. As with all forms of excitation, it is important that the shaker provides sufficient energy to excite the structure at the frequencies of interest.

An overview of the different techniques is given in Table 1. A more detailed assessment of the techniques is given in the Appendix.

TABLE 1

TECHNIQUES FOR DYNAMIC TESTING OF GRANDSTANDS AND SEATING DECKS

Test characteristics			Test outcomes and their relation to Interim Guidance requirements				
			Essential outcome	Desirable outcome	Outcomes not needed to meet requirements of the Interim Guidance but may be specified by the Engineer for detailed design checks requiring data from Type 2 testing		
Test Type	Excitation	Force measurement	Natural frequencies	Mode shapes	Damping ratio	Frequency response function	Modal mass
Type 1	Ambient	Not possible	Yes, but care needed with interpretation. Can combine with other Type 1 techniques to assist interpretation	Yes, if excitation energy is sufficient	Not reliable	No	No
Type 1	Heel-drop	Not normally done	Suitable for simple structures. Difficulties with complex structures or closely separated vibration modes	Provides coarse indication sufficient for simple structural arrangements	Not reliable	No	No
Type 1	Drop-weight or sledge hammer	Measured	Yes	Yes	Better than heel-drop	Possible with further development if excitation energy is adequate	
Type 1 or 2 according to techniques and instrumentation employed	Shaker with variety of possible types and techniques	Measured or inferred depending on technique	Yes and provides more repeatable results than heel-drop, impact or AVS	Yes	Yes	Quality of results dependent on technique and instrumentation. Most reliable results obtained with instrumented shaker giving direct measurement of force time history.	

Note: The table provides an initial guide to the choice of test method. The Appendix to this Note gives more detailed information on the use of the different methods. However, it is important to discuss with a prospective Test Agency the methods that might be appropriate for a particular situation, how these would be implemented and the type and quality of results that the particular Test Agency can provide for a given method and programme of testing.

6 Specification and procurement

The role of the Engineer in preparing the specification, procuring testing and reporting to management is illustrated in Figure 1. Note that the need for Type 2 testing may emerge from the procedures indicated if additional information is considered necessary in order to reach a satisfactory conclusion.

Prior to commissioning a Test Agency to undertake work, the Engineer should decide the extent and types of information required from testing and take a preliminary view of the techniques to be employed. At this stage, it will often be useful to discuss the programme and methods with a possible Test Agency and agree a specification for the work required. The Test Agency should have the necessary experience and capability to undertake the chosen type of testing. Experience of testing structures on site and interpreting the results is particularly important as the equipment required for heel-drop tests or ambient vibration monitoring is quite widely available. The specification should be written as a 'performance' document, based on the agreed types of testing and the properties required from the tests, with the details of the test programme being left to the Test Agency to decide. However, the specification should include:

1. A description of the values and properties required from testing.
2. Confirmation of the agreed type of testing and the form of presentation of results.
3. A requirement for the work to be undertaken to a recognised quality Standard such as BS ISO Standard 14964: 2000, *Mechanical vibration and shock – Vibration of stationary structures – Specific requirements for quality management in measurement and evaluation of vibration*.
4. The time agreed for the delivery of the results and report on the testing.
5. Requirements for reporting, bearing in mind that the Engineer's report to Management should include 'an account of the procedures used and the detailed results'.
6. A requirement for a method statement to meet the requirements of Health and Safety, or CDM Regulations, whichever is applicable.

The Engineer should be available while testing is in progress in order to review results as they are obtained and, if necessary, modify the instructions to the Test Agency.

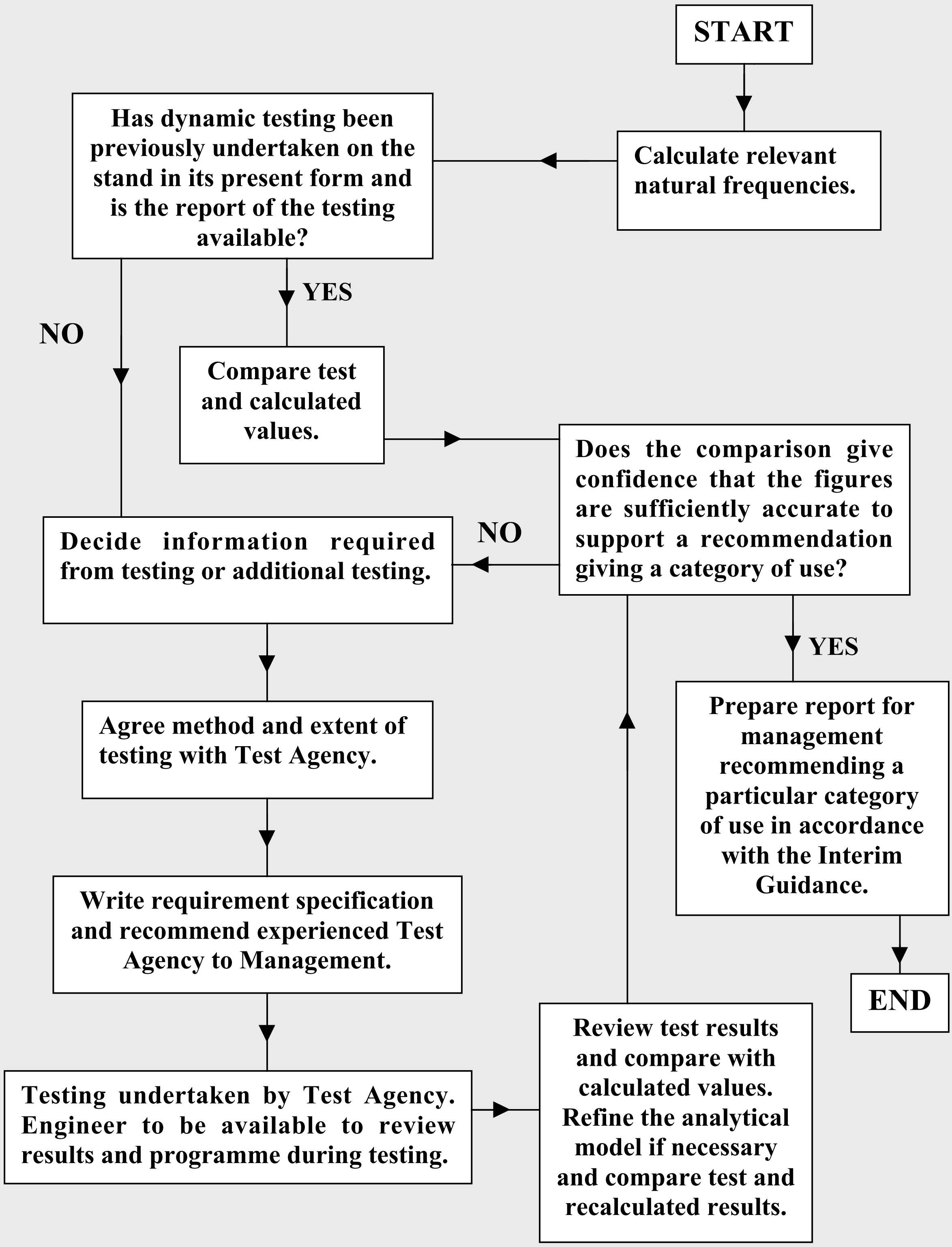

Figure 1. Engineer's role in testing and analysis for assessment of category of use for grandstands under dynamic crowd loading

Appendix: Notes on testing techniques

These notes are provided to supplement Table 1 of this Advisory Note.

A.1 Ambient vibration survey (AVS)

This method relies on ambient excitation – typically wind or passing traffic – to excite the structure. The response is measured and spectra are calculated to yield parameter estimates, either by direct extraction of information from the spectra or by some form of curve fitting. The method can yield useful results for natural frequencies and mode shapes, if the ambient excitation is able to excite the modes of interest adequately, but results for modal damping can be unreliable.

Care is needed in interpreting the results of an ambient vibration survey so that the relevant modes are correctly identified. For example, it is possible to focus on 'roof modes', rather than those that could be excited significantly by crowd loading. Also, care must be taken to avoid misinterpreting peaks in the AVS response spectra that are not primarily due to resonant response but correspond to dominant frequencies in the ambient excitation spectrum such as might occur due to vortex shedding or the influence of adjacent machinery. This is because the method is based upon the excitation spectrum being flat, or at least smooth across the frequency range of interest. Also, as AVS depends on the ability of the ambient excitation to vibrate the empty stand, its application may be limited when measuring vertical modes of seating decks that are protected from the wind.

Bearing these reservations in mind, AVS should be regarded as a Type 1 test. The test can be used in isolation but, because of the potential difficulties of interpretation, it is possibly better used in combination with other techniques.

Beyond the needs of the Interim Guidance, it is useful to recognise that, in the absence of testing using a horizontal shaker of substantial size, an ambient vibration survey may be the only practicable method of detecting the presence of global horizontal modes of grandstand vibration, if these are of interest.

A.2 Heel-drop testing

This method is suitable for Type 1 testing of moderate size, simple structural arrangements. Heel-drops should be performed across a grid of test points making sure that all relevant modes of vibration are excited. The natural frequencies of excited modes of vibration will usually show as peaks in the spectra in the response to the heel drop. As with all dynamic testing, if the modes of vibration are closely spaced, longer data acquisition blocks must be used to provide sufficient frequency resolution to enable close peaks in the spectra to be identified.

It is possible to use one or more heel drop tests to establish mode shapes by measuring the response across a series of test points. However, if results from several heel drops are combined, the results may be too crude to enable useful comparison to be made with results from analysis because of variations in excitation between heel drops. It is unlikely that heel drop testing will excite modes involving significant motion of the whole of a large stand.

A.3 Measured impact testing

Simultaneous measurement of an impact force pulse and the corresponding structural response would enable the full set of modal properties to be determined. The technique is commonly used in laboratory testing but does not appear to have been used on grandstands where the energy required to excite the structure is much greater. It is possible that, for large structures, an instrumented sledge-hammer or a drop weight and force plate could be used. However, as for a heel drop, sledge-hammers may not be sufficiently large to excite the structure sufficiently and drop weight devices may be difficult to install on a grandstand and could damage the seating deck.

Bearing these difficulties in mind, it is considered that measured impact testing should be considered as a Type 1 test being, in effect, an upgraded heel drop test in which the excitation is both measured and more repeatable.

A.4 Shaker testing

There is a wide variety of equipment and techniques available using shakers for dynamic testing. As might be expected, these have been developed furthest in the context of mechanical and aerospace engineering. The latest techniques are now becoming more widely used for site testing structures of significant size so that, from a structural engineering viewpoint, it can be anticipated that the near future will bring greater choice in the type of testing that can be employed and the quality of results that can be obtained.

Up to the present time, most dynamic testing of grandstands using shaker excitation has used rotating mass shakers. Typically, a constant speed of rotation is used to develop sinusoidal excitation at a particular frequency. The tests are normally repeated for a range of increasing speeds, so providing excitation at a range of discrete frequencies, a procedure referred to as stepped sine excitation. The rotating mass shakers that have been used for grandstands are sufficiently large (i.e. the rotating mass produces sufficient force) to excite a cantilever deck for all the modes of interest. The amplitude of the excitation force is easily calculated knowing the rotating mass, its eccentricity and the speed of rotation. Together with measurements of acceleration from locations on the structure, this enables natural frequencies, mode shapes, modal mass and damping values to be estimated for well-separated modes. This capability goes significantly beyond what is needed for Type 1 testing.

As yet, it has not been the practice to instrument the rotating mass shaker so as to record directly the excitation force/time history. However, some Test Agencies have developed procedures to derive the phase difference between the excitation and response and so improve the identification of modes corresponding to closely-spaced natural frequencies. This allows the full range of modal properties to be determined and, in these terms, tests using a non-instrumented rotating mass shaker meet all the requirements for Type 2 testing. However, the processing of the results involves curve fitting to establish the modal parameters. The accuracy of the results of curve fitting depends on the quantity and quality of information available to define the relationships being described. Accordingly, there will be circumstances when the results of Type 2 tests using a non-instrumented shaker can be less accurate than if the force/time history had been obtained by direct measurement and the results used when processing the data to determine modal properties.

Testing with fully instrumented shakers providing a direct measurement of force/time history has been standard practice for some time in mechanical and aerospace engineering and is now being used for structural engineering applications.

Simultaneous measurement of the shaker excitation force and the corresponding response is used when estimating the Frequency Response Function (FRF) between the response and excitation on a test structure. In this case, both modulus and phase information for the FRF is determined directly and used in a curve fitting approach that yields the natural frequency, mode shape, modal damping ratio and modal mass for all the modes of interest. The availability of a complete FRF makes this method the most accurate of all those available, particularly where modes are closely spaced in frequency. However, the increased accuracy might not be needed when only natural frequency values are required as might be the situation in responding to the recommendations of the Interim Guidance. Stepped-sine and slow-sweep sine as well as broadband excitation can be used, depending on the time available for testing, the shaker employed (typically inertial, with acceleration of the mass measured so as to derive the force) and the facilities for information processing. Always providing that the shaker generates sufficient force to excite all the modes of interest, instrumented shakers provide high quality information for both Type 1 and Type 2 testing.

Because of the substantial size of a grandstand seating deck, not all commercial shakers will be suitable for testing grandstands. More particularly, the shaker has to be of sufficient size that the oscillatory or rotating mass develops the force necessary to excite all relevant modes of the structure. More than one shaker can be used to achieve the necessary excitation and it is already common practice to use multiple shakers in other engineering applications. Besides increasing and distributing the energy input, simultaneous use of shakers at more than one location helps to improve the identification of modes with closely spaced natural frequencies and to minimise the possibility of missing a mode of vibration as could occur with a shaker used in a single location. As yet, multiple shakers have not been employed in tests on grandstands. It is a likely option for the future, however.

It will be evident that there are techniques available in other disciplines that, if properly implemented, can enhance the general capability for dynamic testing of grandstand structures. Almost certainly, greater choice of testing techniques for use on grandstands will become available to the Engineer responsible for procuring testing and using the results. In making this choice, the Engineer will need to consult the Test Agency to ascertain its range of expertise and preferred way of working. In a climate of change and new developments, an established track record of dynamic testing of structures of significant size will be a useful recommendation.

A.5 Further information

More information on methods of testing may be obtained from the following sources:

Ewins, D. J. (2000): *Modal testing: Theory and Practice,* Research Studies Press and Wiley

Dynamic Test Agency (DTA), (1993): *Primer on best practice in dynamic testing,* HMSO

Maia, N. M. M., Silva, J. M. M., He, J., Lieven, N. A. J., Lin, R. M., Skingle, G. W., To, W-M. and Urgueira, A. P. V., (1997): *Theoretical and experimental modal analysis,* Research Studies Press Ltd and John Wiley and Sons