Footbridge Pedestrian Vibration Limits

Part 1: Pedestrian Input

Part 2: Human Sensitivity

Part 3: Background to Response Calculation

Chris BARKER
Associate
Flint & Neill Partnership
London, UK

David MACKENZIE
Partner
Flint & Neill Partnership
London, UK

Neil MCFADYEN
Principal Engineer
Flint & Neill Partnership,
London, UK

Simon DeNEUMANN
Engineer
Flint & Neill Partnership
London, UK

Ron KO
Senior Technical Advisor
UK Highways Agency
Dorking, UK

Brian ALLISON
Principal Engineer
UK Highways Agency
Dorking, UK

Summary

The UK Highways Agency has commissioned two companion studies for the review of the dynamic sensitivity of footbridges.

Study 1: To provide information on the dynamic properties of footbridges to enable designers to identify potential vibration susceptibility at the design stage. The project included, a review of the main parameters affecting dynamic performance, the collation of data obtained from the vibration testing of footbridges, and the development of a design strategy. This work was carried out jointly by TRL Limited and Flint & Neill Partnership.

Study 2: To investigate the susceptibility of pedestrians to footbridge vibrations with a view to developing appropriate acceptance criteria. This assignment was carried out by Flint & Neill Partnership.

The results of the overall project have been combined to form the basis for a new and more searching approach to the assessment of the dynamic responses of footbridges. Three papers are being presented at this conference, and these form part of a series of papers being written to report on the progress of the above work.

Part 1: Pedestrian Input

Presents an outline of the calculation design strategy that has been developed for the prediction of discomfort due to vertical responses. It is anticipated that a procedure similar to that described in this paper will be developed for future inclusion in the Highways Agency's Design Manual for Roads and Bridges.

Part 2: Human Sensitivity

Assesses the tolerance of pedestrians to the dynamic motion of footbridges, discusses the variation of sensitivity that seems to occur for different bridge types, and reports on the results of field trials in which surveys were used to quantify user reactions and attitudes to footbridge movement.

Part 3: Background to Response Calculation

This paper presents some useful background to the processes used to estimate vertical responses.

Keywords: Footbridge; dynamic properties; pedestrian-induced vibrations; natural frequency; damping; stochastic analysis; spectral leakage; comfort criteria

1. Part 1:

1.1 Pedestrian Input

1.1.1 Introduction

The current practice in the calculation of footbridge responses, as defined by BD37/01 [1], is to measure the relative liveliness of a bridge by calculating the maximum acceleration that occurs when a standardised pedestrian crosses the bridge with a pace frequency that exactly matches the natural frequency(s) of the bridge. This approach can be shown to have a number of fairly significant shortcomings. In order to deal with the above in a more consistent manner the following main changes are put into place.

1. The magnitude of the applied loading has been revised and special consideration is given to jogging & running.
2. We employ a stochastic model of the loading in order to investigate the likelihood of response, and apply this to a convolution integral approach where time history analyses of all possible cases are considered.
3. The effects of (a)higher harmonics of the applied load and (b) the combination of mode responses, are included
4. We introduce the use of acceleration doses as described in BS6472 [2]. In this approach the fatiguing effect of a smaller but repeatedly occurring level of response has the potential to become more important than the effect of a single large instantaneous peak in the acceleration time history.
5. The frequency dependency of pedestrian response perception has been modelled using ISO 2631 [3]. In this document design curves are presented that allow the calculated responses to be weighted and combined according to their frequency to adjust for this response perception.

1.1.2 Proposed Codification Basis for the Calculation of Pedestrian Response

In general terms the process that needs to be followed in order to estimate the degree of discomfort likely to be experienced during pedestrian usage is as follows.

a) Calculate the reference response due to a hypothetical standard pedestrian crossing the bridge pacing in time with the natural frequency of each contributing mode. For simple cases where the mode shapes can be approximated reasonably well by a half sine wave design curves similar to those of BD37/01 are provided in Figure 1 below.

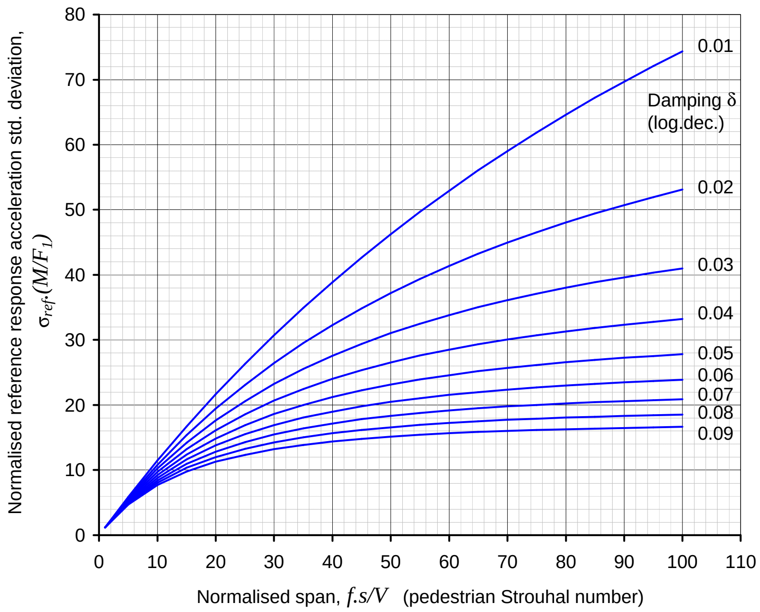


Figure 1: The response of a simple span due to a pedestrian crossing with a pacing at the frequency of the mode

b) Correct values of dynamic response to take into account realistic population parameters and thus allow for the likelihood of response occurring. (The relative discomfort indicated by Figure 2 below is then further modified by the span length but this term is not described in this abstract.)

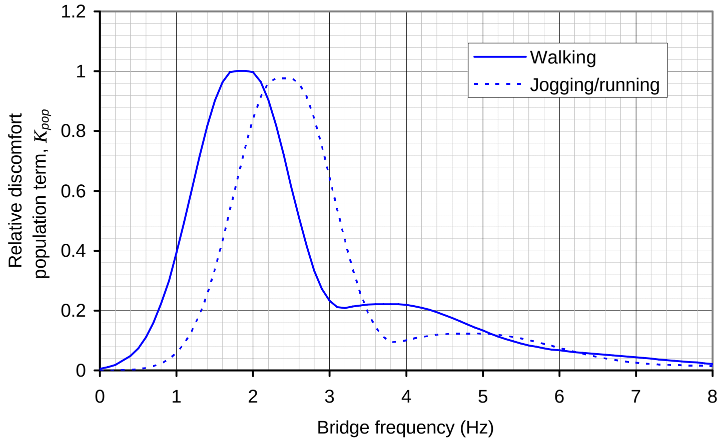


Figure 2: Dependency of relative discomfort on bridge frequency

c) Calculate the quasi-steady (non-resonant) response that occurs. This term deals specifically with the responses that occur when the mode frequency and pedestrian population pace frequency are not very close.

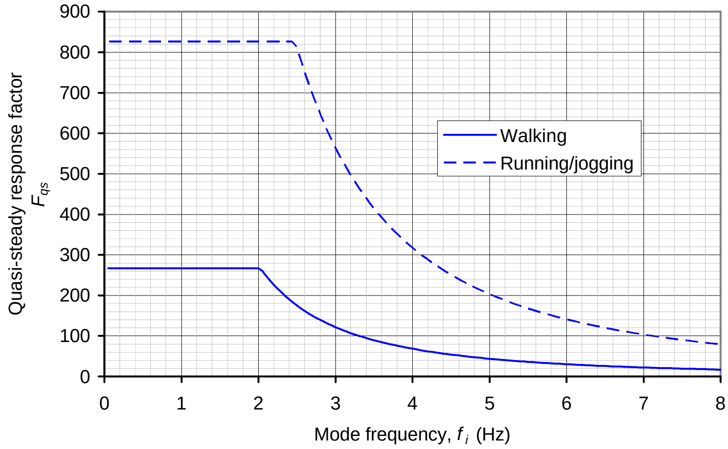


Figure 3: The effective quasi-steady force as a function of mode frequency

d) Combine the factored dynamic response and quasi-steady terms for each mode to determine the net response at each location of interest. Typically the net standard deviation of response is obtained by combining the dynamic and quasi-steady terms using the formula below.

$$s_{eff}(x) = \left[\left(\sum_{i=1}^{n} k_{gi} . s_{qsi}(x) \right)^2 + \sum_{i=1}^{n} (k_{gi} . s_{dyni}(x))^2 \right]^{0.5} \qquad (1)$$

e) Factor the component responses to allow for the number and distribution of the pedestrians being considered. For groups of N pedestrians crossing the span together in a single group, the likely degree of discomfort is increased in proportion to 1.188ÖN. In crowded conditions or when pedestrians are distributed along the length of the span, the approach taken is based on superposition of the responses from single pedestrians.

1.1.3 Conclusion

Although the analysis method proposed within this paper is based on the use of similar simplified analysis techniques as those used within BD37/01, it is able to deliver a much more consistent relative measure of response and discomfort for the wide range of structures that need to be assessed. While retaining much of the simplicity of BD37/01, the suggested approach is now also sufficiently general that it is able to cope with the complex mode patterns that are characteristic of many modern bridges.

2. Part 2:

2.1 Human Sensitivity

2.1.1 Introduction

The brief for this project was quite-wide ranging and required the re-investigation of all aspects of human user tolerance, acceptance and attitude to induced vibration on footbridge decks. The tasks undertaken included the following:

1. Identification of Forms of Vibration
2. Review of Existing Data
3. Cataloguing of Structural Forms and Response
4. Establishment of Human Response Parameters
5. Field Studies

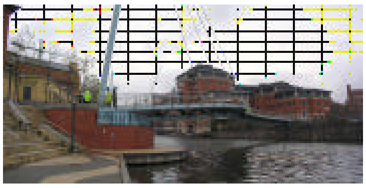
This paper reports on two particular aspects of the project and provides, (a) some results from pedestrian responses to surveys conducted during bridge excitation tests, and (b) proposals for future codification models. Further details of the background to this project are due to be published elsewhere.

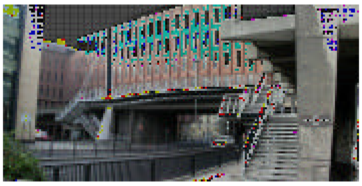
2.1.2 Field Studies

This task was concerned with quantifying users' reactions and attitudes to footbridge movement and, as far as possible, to review the acceptability of the current acceleration-based criteria for design against the findings.

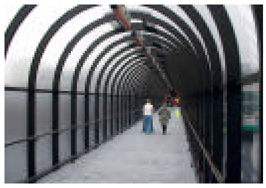
The initial work involved the design of a questionnaire to elicit opinions on a range of bridge design issues, in order to characterise attitudes to bridge movement. The main objective of this project being to determine the degree to which footbridge vibrations give rise to user concerns, and to review the relationship between the vibration limits specified by BD 37/01 and levels at which users experience unease whilst crossing.

Four bridge sites were chosen for testing in the south of England. They were chosen to provide a wide range of structural forms to cover the possible variation in user response issues. The four bridges are shown in Figures 4 to 7. The paper presents details of the questionnaire used and some of the findings of the survey.


Valentine Cable-Stayed Footbridge, Bristol


Trinity Court Footbridge, London, EC4


Royal Victoria Docks Footbridge


Bromley Footbridge

Figures 4 to 7 – Test bridges

2.1.3 Proposals for future codification

It is considered that an approach similar to those outlined in BS 6472 and ISO 2631 is most appropriate for future use.

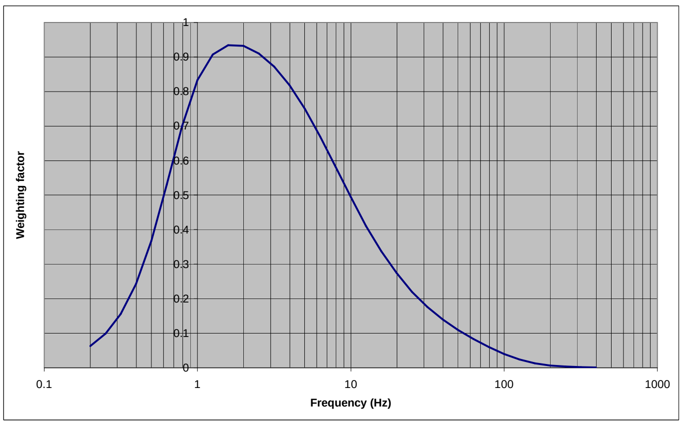


Figure 8: ISO 2631-2 frequency weighting factors

A single motion sensitivity curve will be used that can simply be factored to suit different circumstances and design conditions. This will be presented in the form of frequency weighting (Figure 8) so that responses at varying frequencies can be combined to give a single effective response. (In Part 1 above weighting factors that give an effective response at 2Hz are built into the proposed design curves.)

It is proposed to retain a value similar to the current standard for acceptable vibrations as a base level, and to factor this up and down in recognition of the need to provide the designer and owner the means to modify the response of the bridge for site specific and user sensitivity criteria. Two proposals have been considered.

Proposal One

The first option is to use a single acceleration limit and to modify it by site-specific multipliers, including user sensitivity.

The basic acceleration limit shall be 1.0 m/sec^2. This is slightly higher that the current BD37/01 limit at 2Hz (the significance of the frequency is that it matches that of the 'standard' bridge used to calibration results from Part 1 above). It is also numerically convenient that it is unity, making the acceleration the product of the modifying factors. Thus the limiting acceleration is calculated as follows:

$$a_{limit} = 1.0.k_1.k_2.k_3.k_4 \tag{4}$$

Where

k_1 = site usage factor

k_2 = route redundancy factor

k_3 = height of structure factor

k_4 = exposure design factor

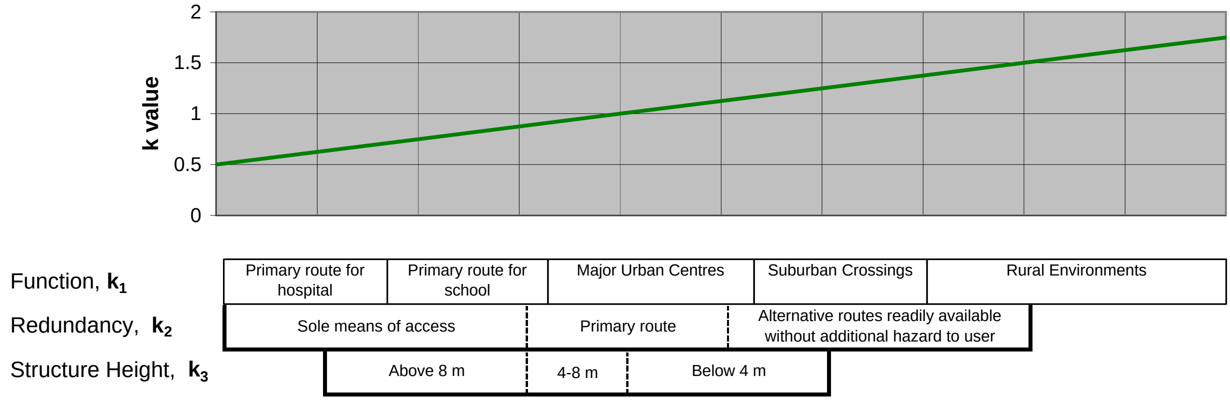


Figure 9 - Proposed response modifiers

Proposal Two

The second proposal is to use a series of acceptance levels that will depend primarily on the nature of user sensitivity for the structure. Note that this is distinct from the number of users of the structure which is taken into account separately within the loading model. This option recognises that the primary function of the bridge should be the dominant criterion and draws this to the fore. The basic levels of response are proposed as follows:

Acceptance Level	**Criteria**	**Upper Limit (ms^{-2})**
Minimum	Routes to essential facilities, such as access to hospitals and schools where users may have impaired mobility	0.5
Median	Standard for bridges in an urban environment	1.0
High	Rural Setting where usage is generally low	2.0

2.1.4 Conclusion

Human tolerance, particularly psychological, aspects are difficult to include within the design process, but a system of modification factors is proposed to cater for this. Aspects of these factors may require further modification in due course as a greater pool of data becomes available, however, the current proposals are considered to provide an appropriate and justifiable starting point. Further thought is needed on the matter of whom to design for.

3. Part 3:

3.1 Background to Response Calculation

The content of this paper deals with 3 specific issues:-

- A detailed description of the development of factors to cater for the relative effect of pedestrian groups. This section also extends the existing methods to look at the relative nuisance value of groups using the 'root-root-4th power mean' as its measure of the acceleration signal.
- A discussion is given on some particular problems that occur in the prediction of vertical bridge responses due to crowd loading using spectral analytical methods. Specifically addressed is the effect that spectral leakage can have on the accuracy of response predictions.

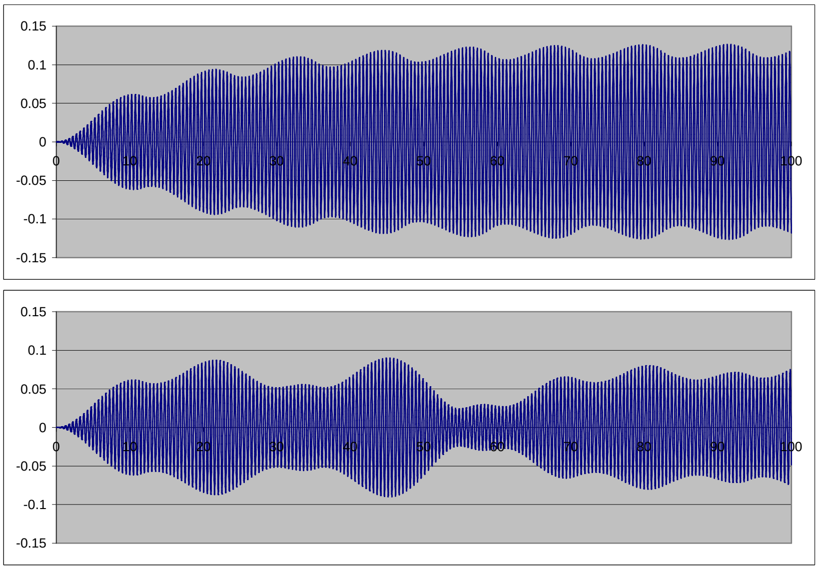


Figure 10 Response due to a recycling pedestrian at resonance, (a) for continuous pacing (b) resetting starting phase

- A simple but precise method for the calculation of dynamic responses at resonance is supplied. The routine provided only requires the solution of a single simple recursion formula (easily able to be implemented in a spreadsheet) in order to achieve an accurate prediction of footbridge modal responses due to pedestrian excitation. In many cases, a slightly modified version of the same routine could enable engineers to calculate pedestrian dynamic responses at their desk without the need to use large and often unwieldy dynamic FE packages that are more commonly employed to perform such time history analyses.

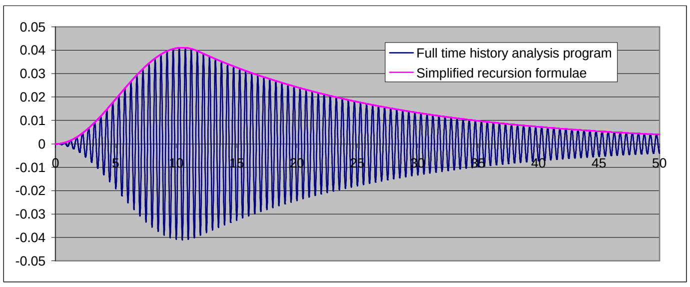


Figure 11: Comparison of full dynamic analysis with simple recursion formula

4. References

[1] *"Design Manual for Roads and Bridges: Volume 1: Approval Procedures and General Design: Section 3: General Design: Part 14: BD 37/01: Loads for Highway Bridges"*, UK Highways Agency, 2001

[2] *"British Standard BS 6472: 1992 Guide to Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)"*, British Standards Institute 1992

[3] "*International Standard ISO 2631-1:1997, Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole Body Vibration - Part 1: General Requirements*"