Journal of Sound and Vibration 414 (2018) 318–337

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Extension of roughness noise to bluff bodies using the boundary element method

Antoni Alomar [a,*], David Angland [a,**], Xin Zhang [b]

[a] Faculty of Engineering and the Environment, University of Southampton, Southampton, Hampshire, SO16 7QF, UK
[b] Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Clear Water Bar, Kowloon, Hong Kong Special Administrative Region

ARTICLE INFO

Article history:
Received 27 September 2016
Revised 15 September 2017
Accepted 18 September 2017
Available online XXX

Keywords:
Roughness noise
Boundary element method
Bluff body
Aeroacoustics

ABSTRACT

A prediction model of roughness noise generated by bluff body flow at high Reynolds numbers is proposed. Howe's roughness noise theory extended by Liu and Dowling is used, and the boundary layer inputs to the theory have been modified for a bluff body. The scattering due to the bluff body has been accounted for by the boundary element method. The procedure to couple the roughness noise sources to the tailored Green's function is detailed for the case where the boundary element method mesh is orthogonal and aligned with the boundary layer outer velocity. The proposed method has been implemented and compared to experimental results for the particular case of a circular cylinder with large roughness. Two different estimations of the skin friction, which is an input to the roughness noise theory, are considered. One is a zero-pressure gradient model, and the second is based on published experimental data of the skin friction on a rough circular cylinder, but with smaller roughness than was used in the experiments. The zero-pressure gradient skin friction estimate leads to a better prediction of the effect of changes in the area covered by roughness elements. The success of the zero-pressure gradient skin friction estimate is encouraging as the only modifications that need to be made to the boundary layer model to account for a bluff body are the boundary layer outer velocity distribution and the location of separation.

1. Introduction

There is a growing global effort to reduce noise pollution due to aircraft. The aeroacoustics of aircraft has been the subject of intense research over several decades. New aircraft must meet certification levels for noise. Therefore, noise prediction tools are increasingly important in the design phase.

Most aircraft contain surface irregularities in the form of small components laying on the surface, e.g. protrusions, joints, ridges, etc. These small components contribute significantly to the high frequency noise. The first prediction schemes for landing gear noise did not consider the small components, which resulted in Equivalent Perceived Noise Level underprediction of up to 8 dB [1]. It was postulated that the underprediction was due to an inadequate description of high-frequency noise, as well as neglecting the small components. Subsequent prediction models included more accurate descriptions of the high frequency noise, such as the statistical model of Guo [2]. In this model, the far field spectrum was derived in terms of the surface pressure spectrum assuming uncorrelated noise sources. A later model by the same author [3] accounted explicitly for the small elements,

---

[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: tonignasi@gmail.com (A. Alomar), d.angland@soton.ac.uk (D. Angland), aexzhang@ust.hk (X. Zhang).

http://dx.doi.org/10.1016/j.jsv.2017.09.021

but through empirical laws with limited predictive power.

A simplified view of the effect of small components or roughness elements on noise generation is as follows. On the upstream face of a component, a boundary layer grows until separation, and the small components on the surface are immersed in it. The noise generated through the interaction of the turbulent field with the surface elements is described by roughness noise theory. For this description to be valid, it is required that the bluff body surface is approximately flat over distances of the order of the roughness size, and that the small components are fully immersed in a turbulent boundary layer.

The main advantage of this approach is that roughness noise theory provides a physical description of the noise generation mechanism. Also, the approach should be better at higher Reynolds numbers, where transition occurs further upstream and more small components will be immersed in a fully developed turbulent boundary layer. The main weakness is the simplification of real geometries to generic distributed roughness elements. It is clear that the resulting model will be at most an approximation. However, it will potentially have greater predictive power than a purely empirical approach.

A previous experimental study [4] showed that roughness noise was dominant over a wide frequency range for both a flat plate and a circular cylinder with large distributed roughness (by large roughness it is meant, not only that the turbulent boundary layer is in the fully rough regime, but also that the roughness height is comparable to the boundary layer thickness). The discrepancies between the experiments and Howe's theory were mostly attributed to roughness edge effects. It was argued that two main issues need to be addressed in order to apply roughness noise theory to bluff bodies. Firstly, the rough wall boundary layer model must be adapted for a bluff body. Secondly, the scattering of roughness noise by the bluff body needs to be accounted for.

For the sake of generality, the boundary element method (BEM) has been used to account for the scattering on the bluff body. For the two-dimensional case as well as the three-dimensional axisymmetric case, analytical solutions exist [5,6]. However, the proposed prediction model is capable of dealing with arbitrary bluff body shapes and represents a general approach. In addition, a novel procedure to couple the BEM solution to the roughness noise sources has been proposed, based on combining the surface monopoles into surface dipoles to model the roughness noise sources.

The proposed model has been implemented and compared against experimental results for the case of a circular cylinder. The reason is twofold. Firstly, it is a representative geometry of landing gear components, and secondly, there is more experimental and computational data in the literature than for other bluff bodies. The calculation of the boundary layer evolution and the determination of the roughness noise dipole sources are particularly simple in this case, where the natural surface mesh is orthogonal and aligned with the boundary layer outer velocity. However, the methodology proposed is applicable to arbitrary bluff body geometries.

The structure of the paper is as follows. Firstly, the literature on roughness noise and on rough wall boundary layers subject to a favourable pressure gradient are revised. Secondly, the rough wall boundary layer model for the case of a circular cylinder is detailed. Thirdly, the validation of BEM applied to a three-dimensional circular cylinder is presented. The coupling of the roughness noise model with the tailored Green's function obtained from BEM is also presented. Lastly, the outputs from the resulting prediction model are compared to experimental data, and a parametric study of the far field noise dependence on roughness size and surface density is presented.

2. Background

2.1. Roughness noise

Roughness noise constitutes an important source of sound in many engineering applications. Owing to the high Reynolds number nature of the problem, it has mainly been studied experimentally [4,7–11]. The roughness elements act as compact dipole sources with streamwise and spanwise components. Several numerical studies have also been performed [12,13], focusing on the flow features in the vicinity of the roughness elements and their relationship to the far field noise.

Based on experimental evidence and the theory of rough wall boundary layers, several theoretical approaches have been developed [14–16]. Howe's approach [14] assumes that roughness consists of hemispherical bosses, which scatter the quadrupole noise sources within the boundary layer. It is assumed that quadrupole noise sources contained within the interstitial flow are negligible compared to the ones above the roughness elements. This approximation, together with Townsend's similarity hypothesis [17–20], implies that a smooth wall pressure spectrum, appropriately scaled to account for roughness, can be used. Liu and Dowling [21] extended the theory of Howe, substituting the asymptotic approximation of the integral over wavenumber space, with an exact numerical integration. Liu et al. [9] determined the streamwise and spanwise dipole strengths of a single roughness element, for given properties of the boundary layer. Liu and Dowling's scheme has been shown to accurately predict the roughness noise peak level and frequency for large hemispherical roughness [4]. The theoretical approach of Glegg and Devenport [15] uses an asymptotic expansion of the roughness height, retaining only the first order term. However, the asymptotic expansion is strictly valid for low frequencies where the hydrodynamic pressure is constant on the roughness elements, and for roughness elements without vertical slope [22]. Despite the limitation of the asymptotic expansion, agreement was found with experiments up to relatively high frequencies [23]. Howe's theory is deemed the most suitable for the particular case under investigation in this paper. In this case there are a relatively low number of large roughness elements with vertical sides. Liu and Dowling's extension of Howe's theory is used, and is summarised in Appendix A.