MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Recommendation for selection of input force locations to improve blocked force determination on curved shells

Chen, Keyu[1]
Herrin, David[2]
University of Kentucky
Lexington KY 40506

ABSTRACT

Blocked force determination is increasingly being used as an alternative to the long-established approach of using transfer path analysis to determine inverse forces. In practice, the main difference between the two approaches is that the source does not need to be detached from the machine or receiver structure if blocked forces are determined. Moreover, blocked forces remain the same even if the receiver structure is modified. In this research, blocked forces are determined on curved shell structures along an interface which has been selected for measurement ease. Guidelines for numbers and placement of blocked forces are developed based on the bending wavelength using a simulation example. A measurement example follows where a small compressor is placed on a cylindrical drum structure and blocked forces are determined along an interface offset from the cylinder edge. Results are assessed by comparing the predicted and measured responses at a position which was not used for determining the blocked forces.

Keywords: blocked force method, transfer path analysis, plates and shells

1. INTRODUCTION

Noise control specialists regularly use finite element analysis to investigate modifications to structureborne noise paths. While finite element analysis is useful for understanding the effect of design changes on noise levels, simulations are less successful at predicting actual sound pressure levels. This is partly because analysts in most instances estimate damping, and connections between components like bolts or fasteners are oversimplified. Even more significantly, models of sources are normally less accurate than models of paths, and solutions are CPU intensive because they are in the time rather than frequency domain.

Consequently, industry often uses measurement approaches to quantify the input forces. The most common approach for doing so is transfer path analysis [1-2]. Responses are measured with the machine operating, and transfer functions are measured between inputs and response locations with the sources not operating. Usually there are 2 to 3 times more response positions than input forces, so the problem is overdetermined. Using least squares approaches, input forces can be determined. The analytically determined forces are not unique [3], but they are useful as an input to simulation models.

[1] keyu.chen@uky.edu
[2] david.herrin@uky.edu

In conventional TPA, sources are disconnected from the receiving structure when measuring transfer functions. This was generally recommended up until recently when Moorhouse et al. [4,5] showed that blocked forces could be calculated with source and receiver structures connected. Blocked forces are defined as the forces acting at the interface between source and receiver structures that provide the same interface vibration as the operating source free-free. Moorhouse et al. [4,5] showed that the blocked forces are independent of the receiving structure. Hence, modifications can be made to the receiving structure and the blocked forces should not change whereas inverse forces are likely to change if conventional TPA is used. Lennström et al. [6] determined blocked forces for an automotive application and Gibbs et al. [7] applied the approach to predict structure-borne sound in buildings.

There is one important proviso in the theoretical development by Moorhouse et al. [4,5]. Namely, blocked forces should be determined at the interface between the source and receiver structures, and there should be no important structureborne paths except between the source and receiver. The greatest real-world difficulty of the method is selection of this interface and whether the interface can be instrumented. Certainly, the interface is well-defined in the case of engine mounts, but that is not always the case.

In recent work on plate structures [8], the authors selected blocked force locations on an interface which was offset from the more natural interface. This offset interface had the advantage of being easier to instrument. Guidelines for selecting the number of blocked forces required on an offset interface were developed as well.

Janssens and Verheij [9] and Janssens et al. [10] studied a variation of the blocked force method where force locations were user-selected and not along a source-receiver interface. The determined forces were called pseudo-forces. However, there is no guarantee that the number of forces will be sufficient a priori to measurement.

The current work aims to answer the question of how many blocked force positions are necessary along a continuous interface for shells. This question has already been investigated for flat plates in Ref. [8]. Guidelines for selecting the number and positioning of blocked forces developed based on a simulation example and the method is then applied to a measurement case.

2. BLOCKED FORCE DETERMINATION THEORY

The theoretical framework for blocked forces [4] is briefly reviewed. Consider two subsystems A and B, and the assembly of subsystems is denoted C as shown in Fig. 1. Subsystem A is the active component with input forces while subsystem B is the passive component. The interface between subsystems is c, and a and b are response locations of subsystems A and B respectively.

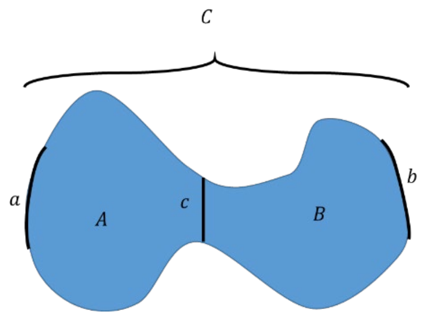


Fig. 1 – Assembled system C, comprising source subsystem A and receiver subsystem B

In the case of TPA, the inverse forces at the interface f_c are obtained by inverting the expression

$$v_b = Y_{B,bc} f_c \tag{1}$$

where $Y_{B,bc}$ is the mobility of substructure B, excited at c, with response at b. v_b is measured with source running and $Y_{B,bc}$ with source isolated from the assembled system. The operational forces f_c can be determined but will change if the receiver structure (i.e., $Y_{B,bc}$) changes. Therefore, the calculated operational force f_c cannot be used when the receiver subsystem has changed.

In the case of blocked forces (f_{bl}), Moorhouse et al [4] showed that

$$v_b = Y_{C,bc} f_{bl} \tag{2}$$

where $Y_{C,bc}$ is the mobility of combined system C, excited at b, with response at c. The left-hand side of the equation is the operational velocity measured at locations on subsystem B. These locations may be the same as those used for TPA. Since transfer functions are measured on the combined system, there is no need to isolate the source during measurement and calculated blocked forces are independent of the receiving subsystem.

An inverse problem must be solved at each frequency, and such calculations are prone to ill conditioning. In some of the more notable work. Thite and Thompson [11,12] summarized strategies like singular value rejection and Tikhonov regularization to improve the ill conditioning problem. Although singular value rejection and regularization methods may improve the accuracy of reconstructed forces, they do not provide guidelines on how to determine the number of input forces that are required in advance.

In prior work [8], the authors investigated how many blocked forces are needed along a continuous interface for a plate structure. The structural bending wavelength (λ_B) for a plate can be expressed as

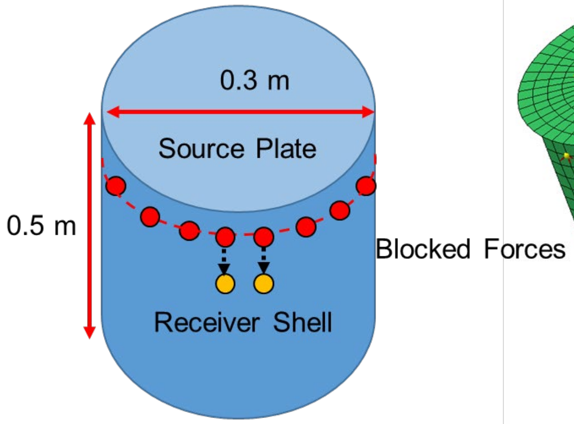
$$\lambda_B = \frac{2\pi}{k_B}, \qquad k_B = \left[\frac{12\rho(1-v^2)\omega^2}{Eh^2}\right]^{\frac{1}{4}} \tag{3}$$

where ρ is the mass density, E is the elastic modulus, v is Poisson's ratio, and ω is the angular frequency. Finite element simulation was used to develop the guideline that the distance between blocked forces should not exceed $0.5\lambda_B$ at the maximum frequency of interest.

3. BLOCKED FORCE DETERMINATION ON SHELL STRUCTURES

The placement of blocked forces on shells was investigated using the example shown in Fig. 2a. A circular thin flat plate is connected to a semi-cylinder; both component structures are 2 mm thick steel (mass density of 7800 kg/m^3 and elastic modulus of 210 MPa). The circular plate is the source structure with a radius of 0.15 m and the semi-cylinder is the receiver structure with height of 0.5 m. If the plate and semi-cylinder were welded at right angles to one another as shown in Fig. 2a, the most natural interface is at the weld line. However, that connection is very stiff, and it is unclear which directions should be chosen for the blocked forces. An offset distance of

2 cm is instead selected. Since the system is continuous along this line, the analyst should select a finite number of locations for blocked forces.



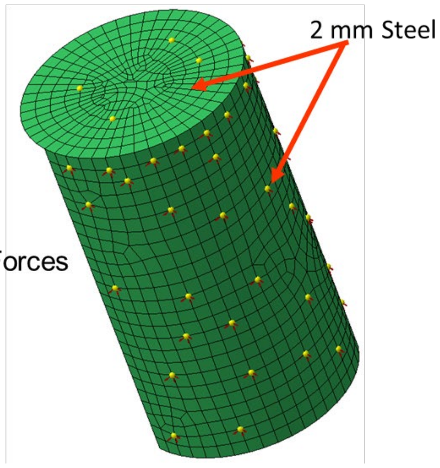


Fig. 2a – Simulation Case 1 *Fig. 2b – FEM model*

The simulation model is shown in Fig. 2b. The model was prepared in ANSYS [13] and then imported into Siemens Virtual.Lab [14] for blocked force calculations. A set of 4 input forces was applied to the source plate and 8 blocked forces were identified on the offset interface of the semi-cylinder as shown in Fig. 2a. The distance between each blocked force is 6 cm. These force locations are indicated in red and are 2 cm from the edge. To calculate blocked forces 24 indicator positions were spaced equally on the cylinder shell and 2 target positions were selected to check the accuracy of the calculated blocked forces. All input forces are assumed to be perpendicular to the plate and responses were likewise determined normal to the cylindrical surface. The model was used to determine the operational responses on the semi-cylinder, and transfer functions between response locations and blocked forces. The blocked forces were calculated using Eqn. (2). Fig. 3 compares the exact and predicted results at one of the target locations.

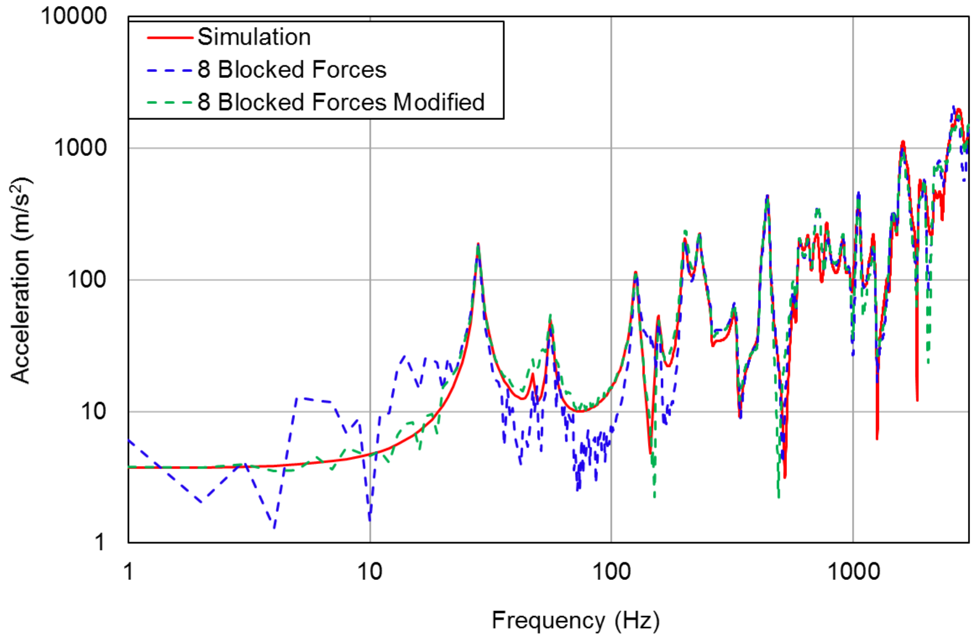


Fig. 3 – Simulation Case 1 Target Response Comparison.

Agreement is good up to 3000 Hz for blocked forces except for discrepancies below 100 Hz. After looking at deformation results at these frequencies, it was hypothesized that the offset interface coincided with a node line on the structure. The blocked forces were then modified by translating two positions (shown in yellow in Fig. 2a) to 6 cm from the edge. The analysis process was repeated, and the predicted results are shown in Fig. 3 and labeled *8 Blocked Forces Modified*. It can be observed that the agreement is now much improved below 100 Hz.

It is desirable to select a set of blocked forces before measurement and minimize that number. Hence, an investigation was performed to develop a rule of thumb for selecting the number of blocked force locations. For plate structures, a spacing of 0.5 λ_B was recommended in Ref. [8].

Flexural waves propagating in a uniform cylindrical shell may be characterized by axial and circumferential wavenumbers k_z and k_s, as shown in Fig. 4. It seems reasonable to select a spacing based on the circumferential wavelength if an interface completes an angular sweep around the semi-cylinder. In [15], by neglecting the axial wavenumber k_z as a simplification, the non-dimensional frequency Ω can be expressed as

$$\Omega^2 = \beta^2 (k_s a)^4 \left[1 + \frac{1}{2}\left(\frac{1}{1-\nu}\right)\left(\frac{4-\nu}{(k_s a)^2} - \frac{2+\nu}{(k_s a)^4}\right)\right] \tag{4}$$

where β is a non-dimensional thickness parameter defined as $\beta = h/\sqrt{12}a$, h is the thickness and a the mean radius of the cylinder. The non-dimensional frequency can be expressed as $\Omega = \omega a / c_l'$ where c_l' is longitudinal wave speed. ν is Poisson's ratio and ω is angular frequency. Eqn. (4) can be solved for k_s and then the circumferential wavelength is equal to $\lambda_s = 2\pi/k_s$. This expression was checked using the finite element model at selected frequencies and wavelengths were similar.

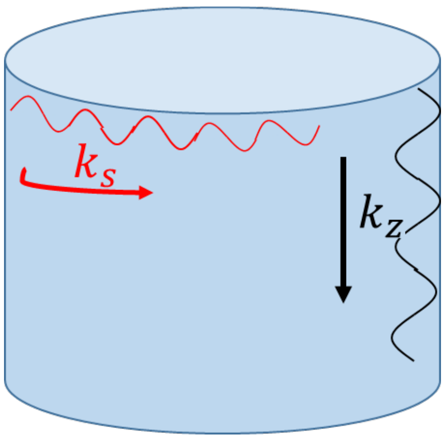


Fig. 4 – Flexural waves of cylinder shell.

The error in dB for the predictions was plotted versus the ratio of the spacing to circumferential wavelength for both blocked forces along a single sweep and for two forces offset. There are large errors at low spacing per wavelength ratios which correspond to very low frequencies if the blocked forces are located along a single path, but these errors are significantly reduced if a few positions are offset. There are a few additional regions of high error which correspond to troughs in the response for ratios between 0.2 and 0.5, but these errors are less important. Errors become more important at ratios exceeding 0.5. Therefore, it is recommended that ratio of spacing between blocked forces to bending wavelength should not exceed $0.5\lambda_s$.

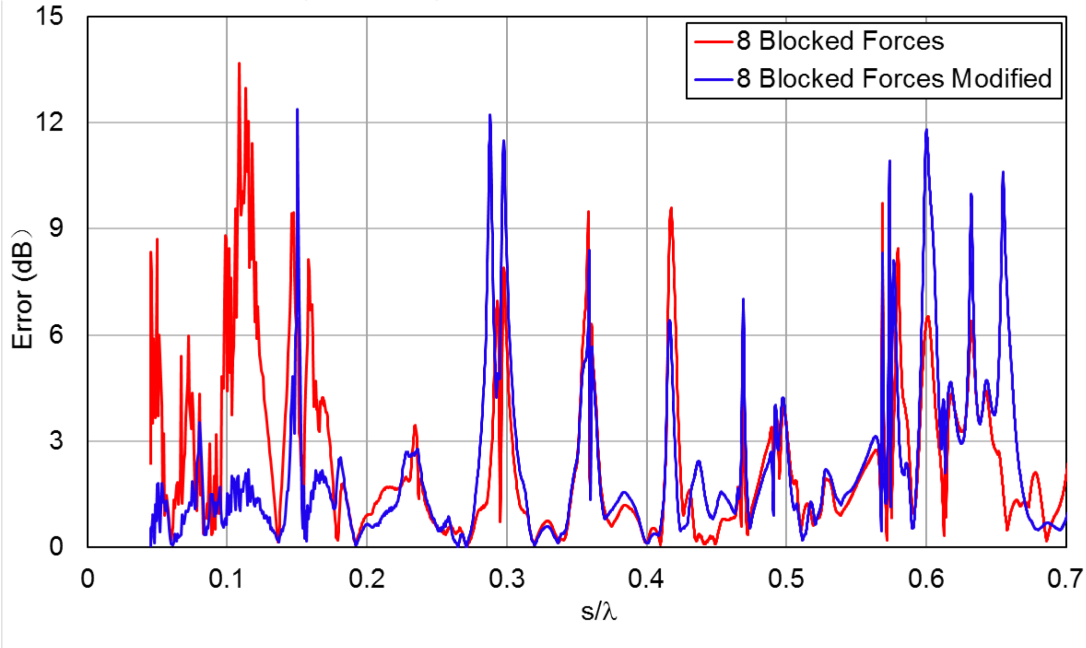


Fig. 5 – Error in dB plotted as a function of spacing between blocked forces per wavelength.

4. COMPRESSOR OPERATING ON CYLINDRICAL DRUM

The process was then validated using a measurement example. An air compressor (Thomas Model No. 2660CE37) with maximum dimensions of 20.5 cm × 9 cm × 18 cm and mass of 8.62 kg was bolted to the top of the steel cylinder shown in Fig. 6. The thickness of both the top plate and cylinder is 1.6 mm. The radius of the cylinder is 0.14 m with height of 0.3 m. The air compressor and top plate are considered as the source and the cylinder is considered as the receiver structure.

Fig. 6 – Test Case Setup

Blocked forces were determined along an offset interface 2 cm away from the welded edge. 8 blocked force positions were evenly spaced at 1.1 cm apart. There were 19 measurement locations distributed evenly on the cylinder and 1 target location. During the test, the assembled system was placed on foam to simulate a free-free boundary condition. All measurements were exclusively in the normal direction since other directions on the shell are very stiff. With $s = 0.5\lambda_s$, 8 blocked forces on the virtual interface should provide good accuracy up to 280 Hz. Direct measurement is compared to blocked force prediction in Fig. 7, and agreement is good up to 300 Hz. Above 300 Hz, there are larger errors at the troughs but results are still acceptable for engineering purposes.

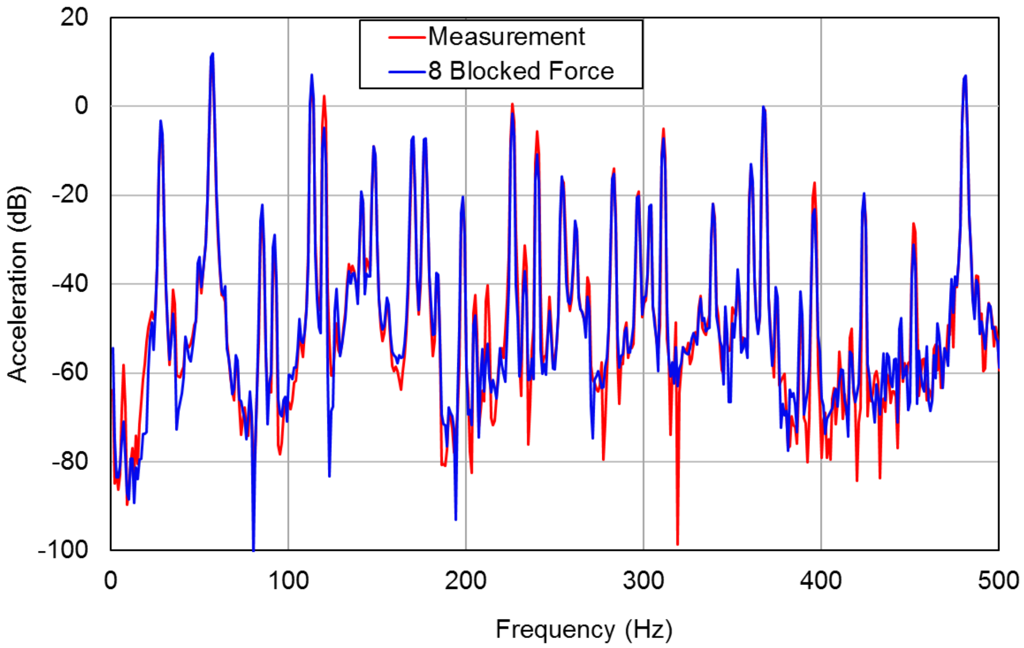


Fig. 7 – Test Case Target Comparison

5. CONCLUSIONS

Blocked forces are advantageous because the receiver does not need to be isolated from the source structure, and blocked forces remain constant even if the receiver structure is modified. It has been demonstrated that a limited number of discrete blocked forces can be selected along an offset interface for both plate and shell structures. As a conservative guideline, it is recommended that the spacing between discrete blocked forces be below $0.5\lambda_s$ where λ_s is the shell circumferential wavelength.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from the Vibro-Acoustics Consortium.

7. REFERENCES

1. M. J. Crocker, "*Chapter 55 noise and vibration source identification,*" Edited by M. J. Crocker, Handbook of noise and vibration control, 678-680 ,2007.
2. H. van der Auweraer, P. Mas, S. Dom, A. Vecchio, K. Janssens, and P. van de Ponseele, "*Transfer path analysis in the critical path of vehicle refinement: the role*

of fast, hybrid and operational path analysis," SAE Technical Paper, 01, 2352, 2007.
3. S. E. S. Karlsson, "*Identification of external structural loads from measured harmonic responses,*" Journal of Sound and Vibration, 196(1), 59-74 (1996).
4. A.T. Moorhouse, A.S. Elliot and T.A. Evans, "*In situ measurement of the blocked force of structure-borne sound sources,*" Journal of Sound and Vibration, 325, 679-685, 2009.
5. A.T. Moorhouse, T.A. Evans and A.S. Elliot, "*Some relationships for coupled structures and their application to measurement of structural dynamic properties in situ,*" Mechanical Systems and Signal Processing, 25, 1574-1584, 2011.
6. D. Lennström, M. Olsson, F. Wullens and A. Nykänen, "*Validation of the blocked force method for various boundary conditions for automotive source characterization,*" Applied Acoustics, 102, 108-119, 2016.
7. B.M. Gibbs, N. Qi, and A.T. Moorhouse, "*A practical characterization for vibro-acoustic sources in buildings,*" Acta Acustica united with Acustica, 93(1), 84-93, 2007.
8. K. Chen and D. W. Herrin, "*Selection of input force locations when determining blocked forces,*" INTER-NOISE Conference Proceedings (2018).
9. M.H.A. Janssens, and J.W. Verheij, "*A pseudo-forces methodology to be used in characterization of structure-borne sound sources,*" Applied Acoustics, 61, 285-308, 2000.
10. M.H.A. Janssens, J.W. Verheij and T. Loyau, "*Experimental example of the pseudo-forces method used in characterization of a structure-borne sound source,*" Applied Acoustics, 63, 9-34, 2002.
11. A.N. Thite and D.J. Thompson, "*The quantification of structure-borne transmission paths by inverse methods. Part 1: Improved singular value rejection methods,*" Journal of Sound and Vibration, 264, 411-431, 2003.
12. A.N. Thite and D.J. Thompson, "*The quantification of structure-borne transmission paths by inverse methods. Part 2: Use of regularization techniques,*" *Journal of Sound and Vibration,* 264, 433-451, 2003.
13. ANSYS Online Help 2016.
14. Siemens, LMS Virtual.Lab Online Help 2016.
15. F. Fahy, "*Chapter 4 Transmission of Sound through Partitions,*" Sound and Structural Vibration Radiation, Transmission and Response, 200-204, 1985.