Automated updating of simplified component models for exhaust system dynamics simulations

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Abstract: - To facilitate overall lay-out optimisation simplified component models for dynamics simulations of automobile exhaust systems are desired. Such optimisation could otherwise be computationally expensive, especially when non-linear analyses are necessary. Suggestions of simplified models of the mufflers and the catalyst are given. To account for the flexibility at the connections between those components and the pipes short beam elements with individual properties are introduced at these locations. An automated updating procedure is developed to determine the properties of these beam elements. Results from an experimental modal analysis are used as the reference. The theoretical model of the exhaust system is built in the finite element software ABAQUS. The updating procedure uses the sequential quadratic programming algorithm included in the Optimization Toolbox of the software MATLAB to minimise the sum of the differences between experimentally and theoretically obtained natural frequencies. Constraints are used on the correlation between the experimentally and theoretically obtained mode shapes by considering the MAC-matrix. Communication between the two software packages is established by an in-house MATLAB script. The correlation between results from the updated theoretical model and the experimental results is very good, which indicates that the updating procedure works well.

Key-Words: - Correlation; Dynamic; Exhaust system; Modal analysis; Optimisation; Updating

1 Introduction

Demands on shortened time to market, higher product performance and greater product complexity in combination with the fast development of computers have resulted in more simulations for prediction and evaluation of product performance. Simplified modelling and inexpensive simulation procedures are often desired early in the product development process to study certain product characteristics and for overall introductory systems optimisation. The models and simulations should reflect the interesting characteristics of the real system accurately enough to support relevant design decisions. To gain confidence of this some kind of experimental verification is often necessary. If the correlation is not good enough the models need to be updated. Doing this manually is usually a time consuming and difficult task, especially if there are many parameters to be updated in the theoretical models.

Procedures for more automated updating have therefore attained interest within the analysis community. See for example the works by Langenhove et al. [1] and Deweer et al. [2] regarding updating of dynamic systems. Avitabile [3] discusses different updating criteria and points out the importance of the choice of parameters in the updating procedure. Chen and Ewins [4] describe the effect of discretisation errors when updating finite element models.

This study is a part of a co-operation project between the Department of Mechanical Engineering at the Blekinge Institute of Technology, Karlskrona, Sweden and Faurecia Exhaust Systems, Inc., Torsås, Sweden. The overall aim of the project is to find a procedure for effectively modelling and simulating the dynamics of customer-proposed exhaust system lay-outs at an early stage in the product development process, to support the dialogue with the costumer and for overall lay-out optimisation. An accompanying paper is that of Englund et al. [5], which focuses on simplified and experimentally verified modelling of a typical automobile exhaust system. The updating of the simplified models of the components within that system is performed according to the procedure described in the present paper. The MATLAB Optimization Toolbox [6] is used for the updating procedure and ABAQUS [7] is used to solve for the natural frequencies and mode shapes. Communication between the two different software packages is established by an in-house MATLAB script to obtain automated updating.

2 Exhaust system design

The studied automobile exhaust system is shown in figure 1. The mass of the system is about 22 kg and it has a length of approximately 3.3 m.

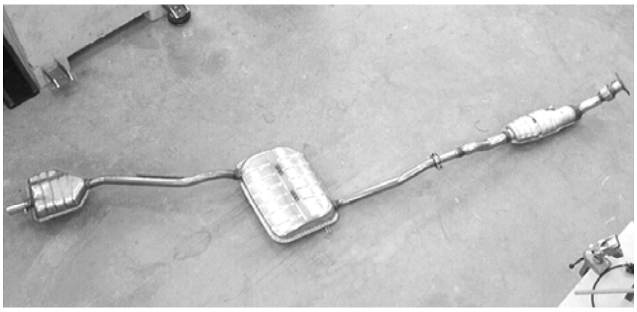

Fig. 1. The studied exhaust system.

The system consists of a front assembly and a rear assembly connected with a sleeve joint. Both are welded structures of stainless steel. The front part is attached to the manifold by a connection flange. The engine and manifold are not included in the study.

Between the manifold and the catalyst there is a flexible joint. This joint is significantly non-linear due to internal friction. More information on this type of joint is given by, for example, Broman et al. [8] and Cunningham et al. [9].

The front assembly consists of this joint, the catalyst and pipes. The rear assembly consists of pipes, an intermediate muffler and a rear muffler. Perforated pipes pass through the mufflers. The mufflers are filled with sound silencing material.

Besides the connection to the manifold the exhaust system is attached to the chassis of the car by rubber hangers. Two hanger attachments are placed at the intermediate muffler and a third is placed just downstream the rear muffler, see figure 1.

3 Theoretical and experimental analysis

A theoretical model of the exhaust system is built in ABAQUS [7]. The pipes are modelled using quadratic beam elements and the mufflers and the catalyst are modelled using lumped mass and mass moment of inertia elements. Such simplified modelling is valid in the frequency interval of interest [5]. These elements are connected to the beam elements representing the pipes by rigid elements. The properties of the lumped mass and mass moment of inertia elements are obtained from a finite element (FE) model where these parts are modelled with shell finite elements [5]. If more suitable in a general case these properties can also be obtained directly from the CAD-model or experimentally.

To simulate the flexibility of the connections between the pipes and mufflers/catalyst, short beam elements with individual properties are used. These elements are located at the true connection locations, that is, with reference to the real system. Thus, they are placed between the rigid elements that are connected to the lumped mass and mass moment of inertia elements and the beam elements representing the pipes.

Lumped mass elements are used to model the connection flange attached to the flexible joint, attachments for the hangers and the heat shield. Free-free boundary conditions are used and the natural frequencies and mode shapes are solved for by the Lanczos method. More information about the theoretical model can be found in [5].

The results from the theoretical model are compared with natural frequencies and mode shapes obtained experimentally. The theoretical mode shapes are calculated without consideration of damping and are therefore real-valued. To be able to compare these modes with the modes obtained experimentally, which are complex due to damping, the experimental modes are converted into real-valued modes.

The experimental modal analysis (EMA) is performed using free-free boundary conditions. To exclude the influence of the non-linearity of the flexible joint it is assured that it does not have any internal deformations. Thus it will move as a rigid body in the present analysis. More about the EMA can be found in [5].

The frequency interval of interest is 0 – 200 Hz but actually no significant modes occur above 150 Hz for this particular exhaust system [5].

4 Updating

The experimentally obtained natural frequencies and mode shapes are used to update the theoretical model. If, in a general case, a full physical prototype does not exist results from a detailed finite element model can be used as the reference.

The selection of parameters to be included in the updating procedure is important. This is true whether the updating is based on frequency differences, mode shape differences or frequency responses [3]. Except for the connections between the mufflers/catalyst and the pipes the theoretical model of the exhaust system is straightforward. Properties influencing the flexibility (stiffness) of these connections are used when updating the theoretical model. There are six connections marked in figure 2 and 3. Each of them includes the following three stiffness related properties; the two area moments of inertias and the polar area moment of inertia of the short beam elements representing the connections. All connections have individual properties. Altogether this gives 18 independent parameters to consider when updating the theoretical model.

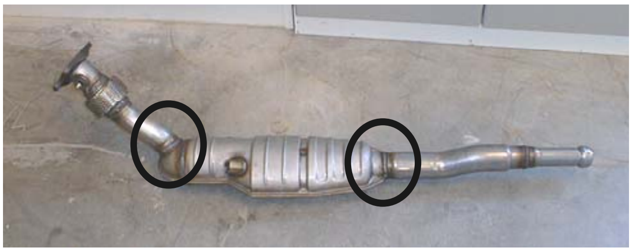

Fig. 2. Front assembly.

Fig. 3. Rear assembly.

To sort out the important ones, a simple parameter study is performed. The parameters are modified by a factor ten, one at a time, and the natural frequencies are calculated. It can then roughly be concluded which parameters that are important to consider when updating the theoretical model of the exhaust system. Ten parameters are found to be significantly more important than the others. Using this approach the possibility to detect interaction between parameters is lost. Considering also these effects can be very time consuming. The procedure used in this work is a compromise between accuracy and time consumption. The aim is not necessarily to find the global optimum, but rather a solution that is good enough. Since many parameters are still involved an automated updating procedure using the Optimization Toolbox in MATLAB is developed. A constrained optimisation is performed using a sequential quadratic programming (SQP) algorithm [6]. The optimisation algorithm is supplied with start-values, bounds, constraints and optimisation criterion. The optimisation criterion chosen, which is to be minimised, is the sum of the differences in natural frequency within each correlated mode pair. Constraints are used on the correlation between theoretical and experimental mode shapes using the diagonal values of the MAC-matrix. The modal assurance criterion (MAC) is a technique to quantify the correlation between two sets of mode shapes. This constraint is important since it forces the algorithm to use correlated mode pairs when calculating the optimisation criterion. Good agreement is sought for both natural frequencies and mode shapes. Using constraints and bounds limits the search space, which usually reduces the number of function evaluations, that is, the problem converges faster [6].

Since natural frequencies and mode shapes must be solved for many times during the updating procedure ABAQUS and MATLAB interact with each other. An in-house MATLAB script, taking advantage of MATLAB's ability of reading and writing ASCII-files, is used to transfer data between the two different software packages. The optimisation procedure is schematically shown in figure 4.

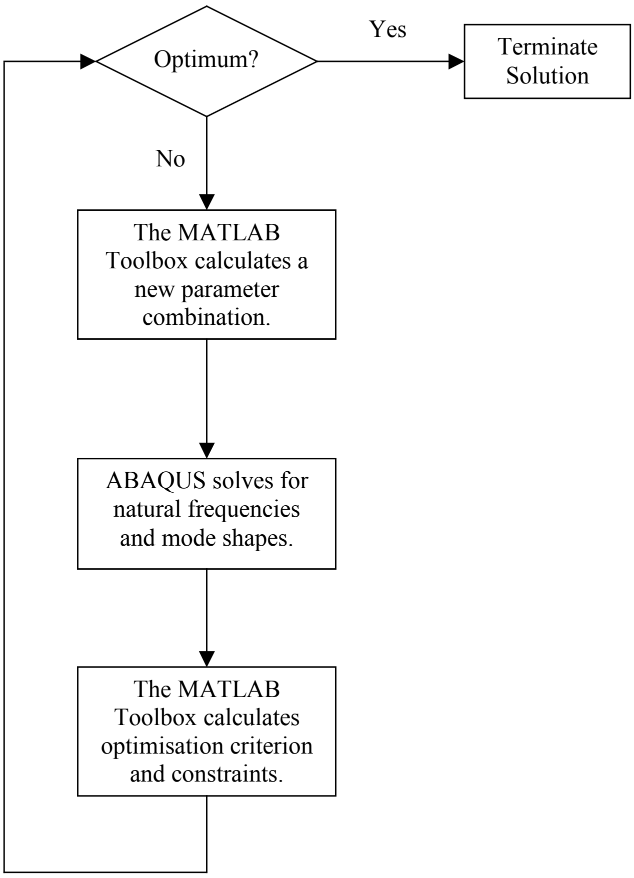

Fig. 4. Automated updating procedure.

Setting appropriate tolerances for the search algorithm in the Optimization Toolbox is not a trivial task. It usually has to be tuned for specific problems. Setting the tolerances to tight forces the algorithm to make a large number of function evaluations without finding a much better solution. On the other hand setting them to loosely the search algorithm might not find the correct optimum. To be able to set the tolerances for the optimisation algorithm in a straightforward way all the ten parameters are scaled to be between zero and unity.

An important aspect to consider is that SQP is a gradient-based optimisation routine. This means that it only finds local optima, that is, different optima can be found depending on the start-values. Some kind of multi-start procedure can be used to reduce this problem. Another way is to use some kind of derivate-free optimisation method. In this work the start-values for the short beam element properties are taken from the beam elements representing the pipes at the connections in the theoretical model. If the start-values are good, that is, are near an optimum, the search algorithm finds this optimum faster.

5 Results and discussion

A comparison between the results from an initial theoretical model, that is, a model without the short beam elements accounting for the flexibility at the connections between the mufflers/catalyst and the pipes, and the experimental results shows that this model is far too stiff. Some of the theoretical natural frequencies are more than fifty per cent higher than the corresponding natural frequencies obtained experimentally.

In a first step to achieve a theoretical model that correlates better with the experimental results Young's modulus, of the fictive material of the short beam elements representing the connections, is updated. The same value of this parameter is used for all connections. The comparison between results from this roughly updated model, and the experimental results are summarised in table 1. The correlation is still not considered good enough.

As seen in table 1 mode six and seven is not correlating. This is due to a mode switch between these modes, see figure 5. Furthermore, it can be seen in the figure that some of the off-diagonal values are high. This also indicates bad correlation.

Table 1. Results after the first update.

Mode	Experimental Frequency (Hz)	Theoretical Frequency (Hz)	Correlation[a] (%)	MAC
1	10.9	10.6	-2.4	0.95
2	12.9	13.1	1.2	0.93
3	34.9	35.9	2.8	0.58
4	36.4	42.1	16	0.67
5	59.1	50.0	-15	0.84
6	67.1	74.6	11	
7	80.8	82.9	2.6	
8	101	86.2	-14	0.91
9	127	116.5	-7.9	0.72
10	139	141.2	1.5	0.70

[a] The correlations are calculated before rounding off.

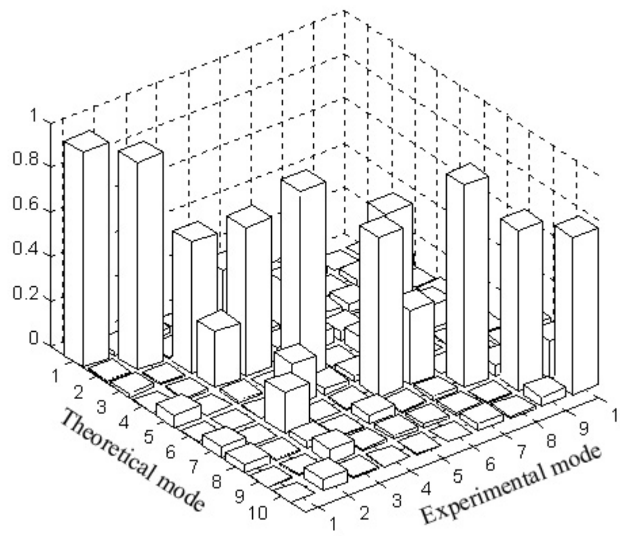

Fig. 5. The MAC-matrix after the first update.

In a final step the ten independent parameters are included in the automated updating procedure. The correlation between modes of this theoretical model and the experimental modes are calculated using the MAC-matrix, see table 2 and figure 6.

The correlation is very good. All diagonal MAC values are above 0.85 except for mode nine and ten. Furthermore all the off-diagonal terms in the MAC-matrix are below 0.2. As also seen all differences in natural frequencies are below four per cent.

Table 2. Results after the final update.

Mode	Experimental Frequency (Hz)	Theoretical Frequency (Hz)	Correlation[a] (%)	MAC
1	10.9	10.9	0.24	0.95
2	12.9	12.8	-1.0	0.93
3	34.9	35.8	2.6	0.88
4	36.4	36.9	1.3	0.85
5	59.1	57.3	-3.0	0.93
6	67.1	69.7	3.9	0.85
7	80.8	83.7	3.6	0.91
8	101	101	0.30	0.96
9	127	126	-0.60	0.64
10	139	135	-2.9	0.60

[a] The correlations are calculated before rounding off.

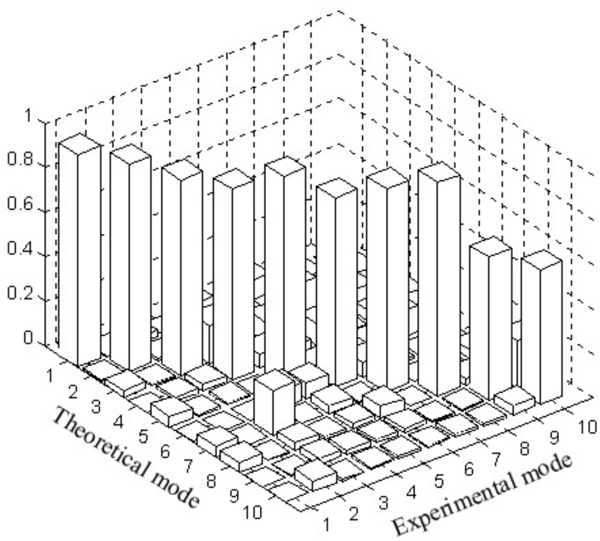

Fig. 6. The MAC-matrix after the final update.

6 Conclusions

Updating of simplified component models for simulation of the dynamic behaviour of an automobile exhaust system is the subject of this paper. Results obtained from an experimental modal analysis are used as the reference. If, in a general case, a full physical prototype does not exist results from a detailed finite element model can be used as the reference.

The simplified component models can be used for, otherwise computationally expensive, overall lay-out optimisation and they can also be re-used when the same or similar components are to be included in other exhaust system assemblies.

An automated updating procedure is developed. The sequential quadratic programming algorithm in MATLAB's Optimization Toolbox is used to minimise the difference between theoretical and experimental natural frequencies. Constraints are used on the correlation between the theoretical and experimental mode shapes using the MAC-matrix. The natural frequencies and mode shapes are solved for by ABAQUS. Communication between the two software packages is established by an in-house MATLAB script.

The very good correlation between the updated theoretical model and the experimental results shows that the updating procedure works well.

7 Acknowledgements

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References:

[1] Van Langenhove, T., Fredö, C. and Brunner, O., FE model correlation & code shape updating using qualification test data. A case study on the Olympus satellite, *Proceedings of Nafems World Congress*, Como, Italy, 2001.

[2] Deweer, J., Van Langenhove, T. and Grinker, S., Identification of the best modal parameters and strategies for FE model updating, *SAE Noise & Vibration Conference & Exposition*, Grand Traverse, USA, 2001.

[3] Avitabile, P., Model updating – endless possibilities, *Sound and Vibration*, September, 2000.

[4] Chen, G. and Ewins, D. J., Perspective on modal updating performance, *Proceedings of the international Modal Analysis Conference – IMAC*, San Antonio, USA, 2000.

[5] Englund, T., Wall, J., Ahlin, K. and Broman, G., Significance of non-linearity and component-internal vibrations in an exhaust system, *2nd WSEAS International Conference on simulation, modelling and optimization*, Skiathos Island, Greece, 2002.

[6] MATLAB, The MathWorks, Inc., http://www.mathworks.com.

[7] ABAQUS, HKS, http://www.abaqus.com.

[8] Broman, G., Jönsson, A. and Hermann, M., Determining dynamic characteristics of bellows by manipulated beam finite elements of commercial software, *Int. J. of Pressure Vessels and Piping*, vol. 77, Issue 8, 2000.

[9] Cunningham, J., Sampers, W. and van Schalkwijk, R., Design of flexible tubes for automotive exhaust systems, *ABAQUS Users' Conference*, 2001.

[10] Belingardi, G. and Leonti, S., Modal analysis in the design of an automotive exhaust pipe, *Int. J. of Vehicle Design*, vol. 8, no. 4/5/6, 1987.

[11] Verboven, P., Valgaeren, R., Van Overmeire, M. and Guillaume, P., Some comments on modal analysis applied to an automotive exhaust system, *Proceedings of the international Modal Analysis Conference – IMAC*, Santa Barbara, USA, 1998.