

Embedded MEMS accelerometers for the in-situ measurement of blocked forces in coupled structures

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Introduction

Transfer Path Analysis (TPA) is a widely used tool in automotive industry to develop products of high noise, vibration and harshness (NVH) quality and to efficiently trouble shoot potential NVH issues in the vehicle or on component level. A TPA, such as classical [1] or in-situ TPA (iTPA) [2], aims to determine the contribution of a source to a target quantity. This is achieved by propagating the measured target quantity back to the dynamic forces of the source using measured frequency response functions (FRF).

A major step within TPA is therefore to identify dynamic forces acting between the vibrational source and connected passive receiver structures. Amongst the potentially available force characterisation methods the in-situ blocked force method by Moorhouse and Elliott [3],[4],[5] is a valuable tool since the loads are characterised independent from the receiver. For a successful conduction of the method it is important to determine accurate FRFs from degrees of freedom (DOF) at the contact interface between source and receiver to arbitrary locations on the receiver. For some products this poses a challenge since the DOFs at the contact zone are often not satisfactorily accessible for excitation or the measurement of acceleration.

This paper introduces a method to determine the FRFs for the calculation of in-situ blocked forces if the interface is not accessible with surface mounted accelerometers. Micro electro mechanical system (MEMS) accelerometers embedded within the contact zone between source and receiver are used to reciprocally measure FRFs in a non-reactive way. The FRFs measured in-situ, i.e. when source and receiver are connected, then can be used for indirect identification of blocked forces as required for iTPA, for instance. To prove the feasibility of the presented method a case study is carried out in which the in-situ blocked forces of an electric motor (EM) are determined and subsequently validated with an on-board validation approach.

In-situ blocked force method

Blocked forces are the forces that are necessary to constrain the movement of a source in such a way that the motion of the source at its connection points is zero. In theory blocked forces can be measured directly using force transducers. However, in theory the boundary conditions of the measurement require an infinitely rigid receiver structure which makes direct measurement impractical and difficult to achieve. Therefore the in-situ blocked force method is used.

To determine in-situ blocked forces a two stage measurement has to be conducted. During the first stage of the measurement the source is passive and a FRF matrix $Y_{C,cb}$ of the coupled structure indicated by the first index C containing the mobilities between all DOFs at interface c and arbitrary locations on the receiver side b is determined (see Figure 1). For that reason the coupled structure C is excited at the receiver-DOFs b and the resulting velocities at interface c are determined. The location of excitation for the determination of a FRF matrix is denoted by the third index (e.g. b) while the second index denotes the location of the response measurement (e.g. c).

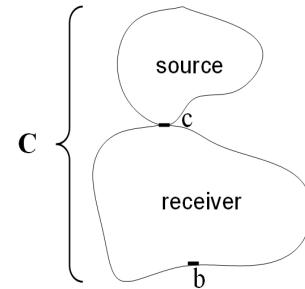


Figure 1: Vibrational source coupled to a passive receiver.

The second stage comprises the measurement of velocities $v_{op,b}$ at the receiver-DOFs b which result from the source in operation denoted by the index op. In the following variables that are written in small letters represent vectors and variables written in capital represent matrices.

The in-situ blocked force vector f_{bl} is calculated using an inverse force identification approach as follows

$$f_{bl} = (Y_{C,cb}^T)^+ v_{op,b} \quad [N] \quad (1)$$

For the calculation of the blocked forces an inversion of the transposed mobility matrix $Y_{C,cb}^T$ is necessary which is known to be error-prone [6]. Therefore the stability of the solution to equation (1) can be improved through over determination of the system by adding additional entries to the operational velocity vector $v_{op,b}$. Since the mobility matrix $Y_{C,cb}$ of the over determined system is rectangular the Moore-Penrose pseudo inverse approach denoted by + is used to solve equation (1).

To ensure that the calculation of the in-situ blocked forces according to equation (1) is correct it is important to validate the forces. For that purpose on-board validation is used [7]. To conduct on-board validation the in-situ blocked forces are

used to predict a velocity $v_{val,b}$ on the receiver side b by multiplying the obtained blocked force vector f_{bl} with the corresponding transposed mobility matrix $Y_{val,cb}$ as follows

$$v_{val,b} = Y_{val,cb}^T f_{bl} \quad [\text{m/s}] \quad (2)$$

The predicted velocity $v_{val,b}$ according to equation (2) is then compared to a measured velocity $v_{meas,b}$ at the same location on receiver side b to yield a criteria for the quality of the calculated in-situ blocked forces (see Figure 2). This approach also works for the prediction of other kinematic quantities such as acceleration if acceleration rather than mobility is used, for instance.

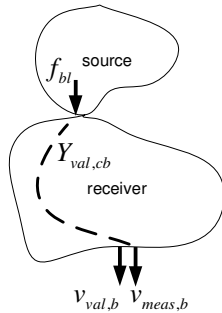


Figure 2: On-board validation approach.

Method using MEMS accelerometers

For a meaningful calculation of in-situ blocked forces it is crucial to determine accurate FRFs between interface c and locations on the receiver side b (see Figure 1). For many products this is in fact possible since the interfaces can be treated as point connections and therefore are accessible for surface mounted accelerometers. However, for some cases such as an EM mounted against any kind of housing the interface is not sufficiently accessible with surface mounted accelerometers. This inaccessibility poses a challenge for the conduction of blocked forces in-situ. However, if small MEMS accelerometers are embedded at the sensitive contact interface the in-situ blocked force method can be conducted. In the following an application of MEMS accelerometers for the conduction of the in-situ blocked force method will be presented.

The suitability of MEMS accelerometers for the measurement of vibration was shown by Béliveau et al. [8] and Albarbar et al. [9],[10]. Albarbar proposed a test setup to compare MEMS accelerometers against a reference accelerometer. The test setup consists of a cantilever beam that is equipped with a MEMS accelerometer on top and an integrated electronics piezoelectric (IEPE) accelerometer on bottom which is used as reference (see Figure 3). Excitation is applied at one end of the beam and the responses at the other end are measured to determine a FRF (accelerance). The FRFs are then compared against each other.

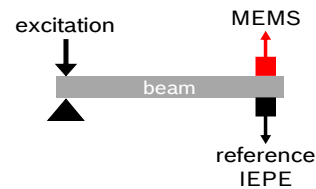


Figure 3: Test setup for the comparison of MEMS and reference IEPE accelerometers.

Figure 4 shows the comparison between the determined FRFs. It can be observed that in the frequency range below 1 kHz the agreement between the MEMS and the reference accelerometer is very good. Above 1 kHz calibration of the MEMS accelerometers is needed. Badri proposed a calibration approach which was shown to be suitable for that purpose where the ratio between MEMS and reference accelerometer is used as calibration factor [11].

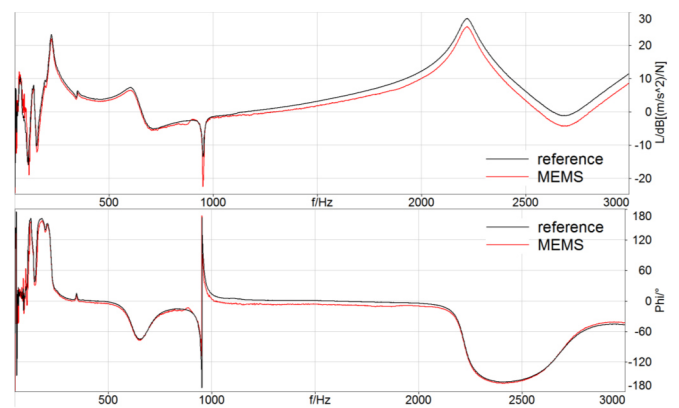


Figure 4: Comparison of FRFs of a cantilever beam measured with a MEMS and a reference accelerometer.

The small size of MEMS accelerometers allows embedding them with introducing only minor modifications to the very sensitive contact interface. Consequently, FRFs measured with MEMS, directly embedded in the flux of forces, are assumed to contain more meaningful information than FRFs measured with surface mounted accelerometers close to the contact zone. In order to embed the sensors the interface has to be prepared with e.g. additional grooves. The accelerometers are placed in the grooves and the cavities are filled with a two component adhesive. Figure 5 shows part of an interface prepared with two additional milled grooves close to one of the thread holes which is used to mount the source and an embedded MEMS accelerometer.

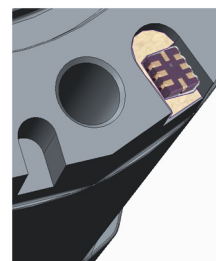


Figure 5: Interface prepared with milled grooves and an embedded MEMS accelerometer.

The in-situ blocked forces are calculated according to equation (1). The only difference is the fact that the accelerometers which are necessary for the determination of the mobility matrix $Y_{C,cb}$ are embedded at the interface and not surface mounted close to the interface.

Case study: electric motor

To prove the feasibility of the presented application of MEMS accelerometers for the conduction of the in-situ blocked force method a case study of an EM is carried out. Figure 6 shows the test setup which is used to determine the in-situ blocked forces of the EM. The EM (red coloured) is mounted against a receiver plate (blue coloured) with three bolts indicated by dotted orange lines. On the back of the receiver plate (opposite of the EM) 24 accelerometers are placed arbitrarily that measure in out-of-plane direction. One of the accelerometers which is placed at the bottom left corner of the plate is used for on-board validation.

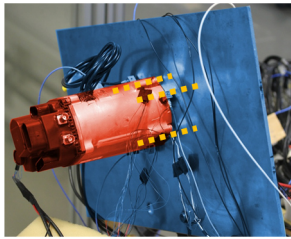


Figure 6: Test setup to determine in-situ blocked forces of an EM.

The in-situ blocked forces of the EM are determined close to the three bolts since the assumption is made that most of the vibrational energy generated by the EM is transferred via these paths. Every location near the bolts is therefore characterised by three perpendicular forces. Consequently 9 blocked forces are calculated in total. For the calculation of the blocked forces the EM was operated with a constant rotatory speed of 2600 rpm and no load was applied.

The interface and the locations of the MEMS accelerometers embedded with adhesive in grooves in the motor housing next to the bolts are illustrated in Figure 7. The reason for the use of two MEMS accelerometers close to each bolt is the fact that this type of accelerometers only measures two perpendicular directions. Therefore it is necessary to embed two MEMS accelerometers, rotated to each other close to each bolt. Since the interface is circular the MEMS accelerometers are embedded according to the three directions of a cylindrical coordinate system (axial, radial and tangential).

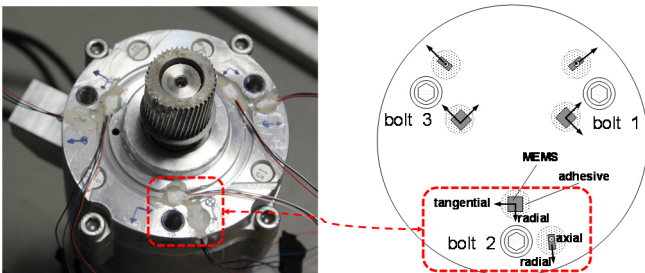


Figure 7: Prepared interface between an EM and a receiver plate for the determination of in-situ blocked forces.

The shaft of the EM that was used to carry out the case study shows a significant imbalance which results in a distinct first order. Since the EM was operated with a constant speed n it is easy to calculate the frequency ω that represent a distinct order o as follows

$$\omega = on . \quad [\text{Hz}] \quad (3)$$

The first order and its harmonics can be observed in the spectrum of the acceleration at the validation point on the plate shown by Figure 8. Both the measured and the predicted acceleration show the same behaviour of the first order (first peak of the spectrum) superposing the unique orders of the EM. For the prediction of the acceleration at the validation point according to equation (2) 9 in-situ blocked forces are used at the same time. One axial, one radial and one tangential DOF near each bolt is used for the characterisation of the EM with in-situ blocked forces.

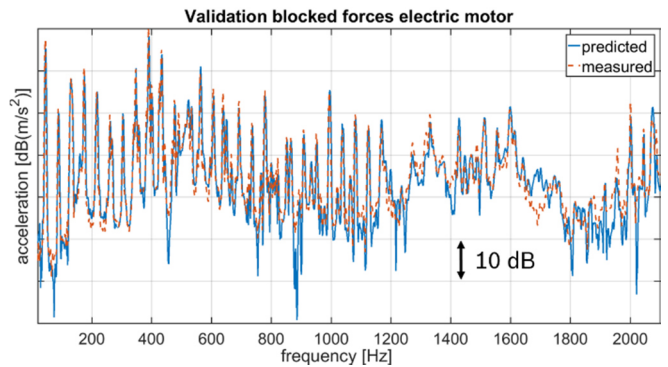


Figure 8: Acceleration at the validation point for a constant rotatory speed of an EM of 2600 rpm.

Since it is shown that above 1 kHz the used MEMS accelerometers need to be calibrated and because of the fact that it can be observed from Figure 8 that the order pattern of the EM is only clearly observable until 1,2 kHz the further discussion of the results is focussed on that frequency range.

At this point it should be mentioned that the results are achieved with a twofold over determination of the system. This means that out of the 24 accelerometers 18 accelerometers according to signal noise ratio were chosen to calculate 9 in-situ blocked forces. Furthermore no regularization of the solution to equation (1) was applied.

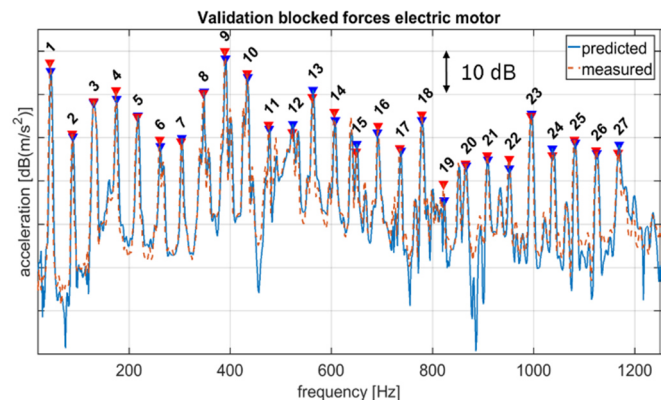


Figure 9: Acceleration at the validation point for a constant rotatory speed of an EM of 2600 rpm with marked orders.

Figure 9 shows a successful on-board validation of the determined in-situ blocked forces and hence a successful calculation of the forces. It clearly can be observed that the difference between the acceleration that is predicted based on the determined in-situ blocked forces and the measured acceleration at the validation point is very small. The deviation between the measured and predicted acceleration at the frequencies that represent the orders of the EM (27 marked peaks in the spectrum) can be seen in Figure 10. Except from the 12th and 19th order the agreement between the predicted and measured acceleration is always below 3 dB (indicated by green colour) which is a very good agreement between measurement and prediction.

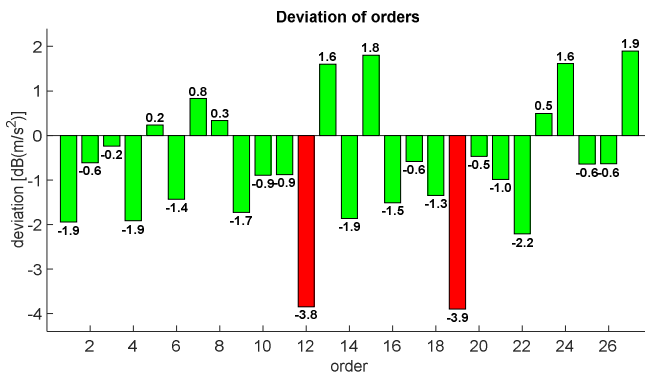


Figure 10: Deviation between predicted and measured acceleration at validation point on the receiver plate for distinct orders.

Concluding remarks

It was shown that it is possible to measure vibration with MEMS accelerometers at the same quality as with commonly used IEPE accelerometers. This is of great benefit since MEMS accelerometers are of low cost and small size. Especially in the frequency range below 1 kHz the agreement between IEPE and MEMS accelerometers is very good. This makes MEMS accelerometers a reliable choice for the measurement of vibration of coupled systems. However above 1 kHz a calibration is necessary to measure the same vibration signals as IEPE accelerometers.

A method using embedded MEMS accelerometers to determine meaningful FRFs from locations at a sensitive contact interface between a vibrational source and a passive receiver structure to locations on the receiver side was presented. This method is especially helpful for the determination of in-situ blocked forces if the interface is inaccessible with surface mounted accelerometers. With the help of a case study of an EM it was shown that accurate and meaningful in-situ blocked forces can be calculated using FRFs that are determined with embedded MEMS accelerometers at the sensitive contact interface. Furthermore it was shown that 9 blocked forces (axial, radial and tangential DOFs) are necessary to characterise the vibrational behaviour of an EM sufficiently accurate if the EM is mounted against a receiver plate with three bolts.

Since it was shown that it is possible to determine in-situ blocked forces of an EM using embedded MEMS accelerometers it is also suitable to use MEMS accelerometers

for any other inverse force identification approach. The determined forces can then be used for TPA approaches such as classical and iTPA, for instance.

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