Improvement of the Blocked Force method by considering the cross & moment mobilities

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Introduction & motivation

Nowadays few acceptable methods for proper characterization of the dynamic system and it's constituent parts are known. By ZF, most common way is to use Transfer Path Analysis (TPA) technique. TPA is ordinarily test-based procedure, which provides us with information about vibro-acoustic energy flow from a source of vibration to the chosen receiver structure.
As an improvement and upgrade to the TPA, a relatively new In-situ Blocked Force method was described by Andrew Elliott in [1]. Blocked force is an independent source property, therefore it remains the same, for one kind of source structure at certain load case, even if we change the receiver structure. The main advantage of this method is that during measurement source and receiver remain attached as in real operation, no dismantling is needed and there is also no need to establish free-free or fixed boundary conditions.
During our research through FE simulations and simple experiments it was observed, that inclusion of rotational degrees of freedom could have an important role when obtaining blocked forces and using them to predict the receiver response, especially in the case of rigid coupling elements. The reason for that could be the transfer of the moments caused by forces acting on a connection surface and lever from the middle point (where blocked forces are obtained) to the point of force application.
To prove our assumptions and for the better understanding of a problem we decided to do a basic research with finite element simulations.
The main idea was to solve a simple 2D problem with two main beam structures and one coupling structure between, where we could clearly see the difference in calculated blocked force for the case where only 1 DOF (out of plane translational velocity) and 2 DOFs (out of plane translational velocity and in plane rotational velocity - around axis perpendicular to the longer rectangle side) were taken into account. Furthermore effect of a connection area size, source and receiver bending stiffness, coupling element stiffness and distance between the source remote and "real" connection point on the accuracy of calculated blocked forces was analysed and will be shown in this article.

Theoretical background

Blocked force

The blocked force F_{bl} is the force required to counter the operational velocity of the source to zero [1]:

$$F_{bl} = -F_s|_{v_s=0} \tag{1}$$

and is related to the free velocity v_{sf} by:

$$F_{bl} = \frac{v_{sf}}{Y_s} \tag{2}$$

where Y_s denotes source point mobility.
Theoretically equation 1 requires an infinite rigid receiver structure, which is almost impossible to achieve in practice, therefore we will focus our interests on a in-situ blocked force method.

In-situ blocked force with receiver remote points

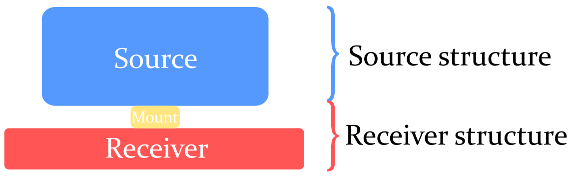

Figure 1: Sub-structuring for in-situ blocked force method.

If we assume that we have rigid contact between source and receiver (despite the fact that there is also resilient mount in between - it is part of receiver as shown in figure 1) the blocked forces in every contact point can be obtained from in-situ measurement. To do so and to avoid measurements in contact points we have to introduce receiver remote points. These are the points located on a receiver structure with good access possibilities as the hammer excitation will be required there to obtain transfer mobilities between contact and receiver remote points. In the next measurement step operational velocity will be measured at the same points. Than the blocked forces can be calculated with the following equation:

$$\{v_{Ar}\} = [Y_{Acr}]^T \{F_{bl}\} \tag{3}$$

where subscription c denotes coupling point, r receiver remote point and T matrix transpose.
Equation 3 allows us to obtain the blocked forces from in-situ measured transfer mobility and operational velocity. The main advantage of this formulation is that no force or moment excitation is required at the source-receiver connection point, where the access is limited. Instead of

this, remote points on receiver structure are excited using force and the response in form of linear and angular velocities is measured at the (remote) contact points as shown in figure 2. Remote contact points (described in next chapter) are introduced for the purpose of finite difference method and will be used to calculate the actions in a “real”contact point, which is not accessible (point 0 in figure 3).

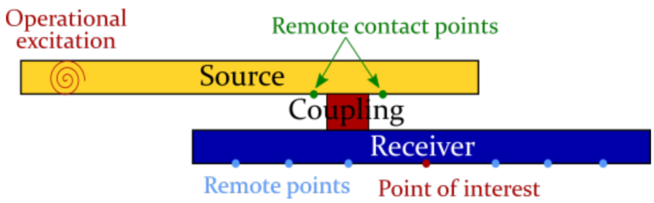

Figure 2: Important points for the in-situ blocked force measurement.

Finite difference method

In paper [1] finite difference method was derived from basic principles:

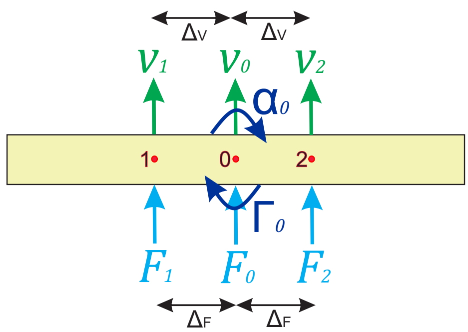

Figure 3: Measuring force and moment mobilities.

Figure 3 shows a beam with three red points. Point 0 is our contact point or reference point and points 1 and 2 are measurement points. There are four quantities describing actions in the reference point - force F_0, moment Γ_0, velocity v_0 and angular velocity α_0. Our goal is to define force and moment mobilities in a contact point (0) so we can write them as:

$$Y_{v_0 F_0} = \frac{v_0}{F_0} \tag{4}$$

$$Y_{\alpha_0 F_0} = \frac{\alpha_0}{F_0} \tag{5}$$

$$Y_{v_0 \Gamma_0} = \frac{v_0}{\Gamma_0} \tag{6}$$

$$Y_{\alpha_0 \Gamma_0} = \frac{\alpha_0}{\Gamma_0} \tag{7}$$

Equations 4 and 5 describe force and moment point mobilities, equations 6 and 7 describe cross mobilities, which are equal by the reciprocity.

With the aim to avoid measuring moments and rotational velocities in point 0, which would be quite problematic (from the measurement and access point of view) it was shown that force, cross and moment mobilities can be calculated with the approximation by the forces and velocities at closely spaced points (1 and 2). This can be done with the following equations:

$$Y_{v_0 F_0} = \frac{v_0}{F_0} \approx \frac{Y_{v_1 F_1} + Y_{v_2 F_1} + Y_{v_1 F_2} + Y_{v_2 F_2}}{4} \tag{8}$$

$$Y_{\alpha_0 F_0} = \frac{\alpha_0}{F_0} \approx \frac{-Y_{v_1 F_1} + Y_{v_2 F_1} - Y_{v_1 F_2} + Y_{v_2 F_2}}{4\Delta_v} \tag{9}$$

$$Y_{v_0 \Gamma_0} = \frac{v_0}{\Gamma_0} \approx \frac{-Y_{v_1 F_1} - Y_{v_2 F_1} + Y_{v_1 F_2} + Y_{v_2 F_2}}{4\Delta_F} \tag{10}$$

$$Y_{\alpha_0 \Gamma_0} = \frac{\alpha_0}{\Gamma_0} \approx \frac{Y_{v_1 F_1} - Y_{v_2 F_1} - Y_{v_1 F_2} + Y_{v_2 F_2}}{4\Delta_v \Delta_F} \tag{11}$$

where sign $\approx$ denotes approximation by finite difference. As we can see, all of the mobilities are of the velocity-force type and there is no moment excitation required.

Results

For the colour figures and better resolution it is recommended to read the article in electronic version.

Force, cross and moment mobility

The purpose of the first test is to calculate force, cross and moment mobilities on a simple beam structure and to show the effect of the distance Δ (see figure 3) used for the final difference method calculation.

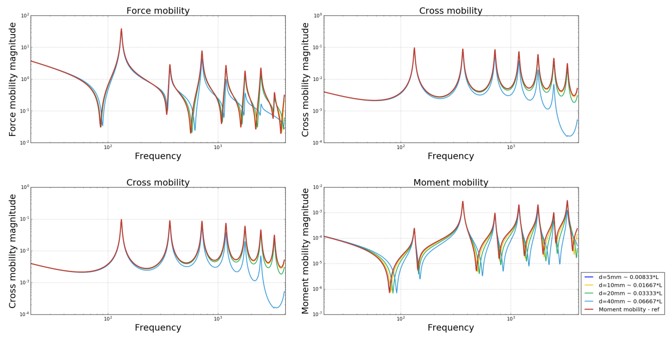

Figure 4: Force, cross and moment mobilities.

As expected the distance between remote contact and theoretical contact point has an important role when obtaining mobilities. As clearly seen, with the distance rising, also the deviation between the reference and measured curve is increasing. Mobilities obtained with the distance smaller than 0.33% of the beam length are relatively good in comparison to the reference (directly measured - eq. 2) mobility, while the deviation for 40mm distance is already much bigger and increasing faster with the frequency.

Distance between remote and theoretical connection point

In this section the effect of the distance between remote and theoretical contact point on the accuracy of the calculated blocked force and predicted receiver operational velocity will be shown.

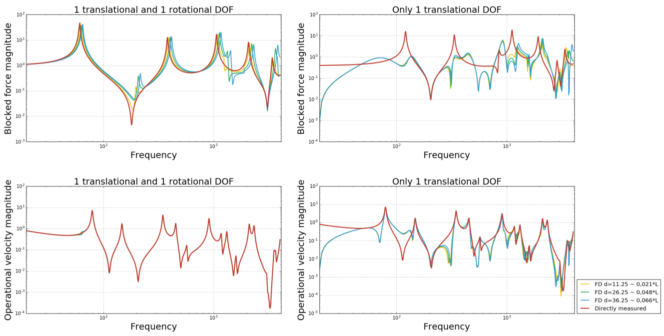

Figure 5: Blocked force and velocity prediction in dependency to the remote point distance.

Based on the results seen in the upper figure two important conclusions can be made. First, it is definitely recommended to measure the accelerations (velocities) as close as possible to the connection point when obtaining transfer mobilities. Second, even more important as the distance is the inclusion of the rotational degrees of freedom. The match between blocked forces when calculation them with 2 DOF is good, there is some deviation due to the distance, but in the case of receiver velocity prediction, where the distance is shortened in the equation, the match between curves is almost perfect and no deviation can be seen.
In the case of 1 DOF the match between calculated and reference blocked force is much worse, same can be said for the receiver velocity prediction, which is still acceptable with quite good matching in the resonance areas, but due to the poor blocked force calculation, the modified on board validation - velocity prediction with the different receiver structure would not give us satisfying results.

Connection area

In this section effect of an connection area on the accuracy of the calculated blocked force and predicted receiver operational velocity will be shown.
With changing the section of the coupling bar element, also the Young modulus was changed to prevent our result from being affected by the change in element stiffness.
As we can see in figure 6 the result for calculated blocked force and predicted receiver velocity is better when using 2 DOF. On the other hand, if we take a closer look to the velocity prediction results for 1 DOF we can see, that there is no big difference in deviation between the $900mm^2$ and $150mm^2$ area. That was not the outcome we expected at first, but there could be a plausible explanation for it.
First reason could be the fact, that we are calculating the response in the point 0 (figure 3) and if the points 1 and 2 stay on the same distance no matter if the connection area is changing the result for the middle point should be of the same "quality".
Another explanation is concerning so called "wave length at the modal shape". At higher frequencies when the wave length is shorter, the connecting area could have bigger effect, as the area could be split into two or more waves and therefore the outcome of the finite difference method worse. Poor blocked force calculation and velocity prediction would surely be a consequence.

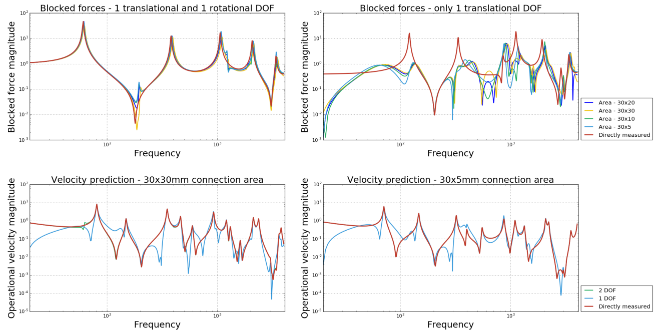

Figure 6: Blocked force and velocity prediction in dependency to the connection area.

Coupling element stiffness

Effect of the coupling element stiffness was one of the most interesting investigations for us. During the first simulations and real measurements concerning blocked forces we realized, that blocked forces obtained and predicted receiver velocity using only 1 DOF were much more accurate in the case where rubber coupling element was between source and receiver. That can be nicely seen in figure 7.

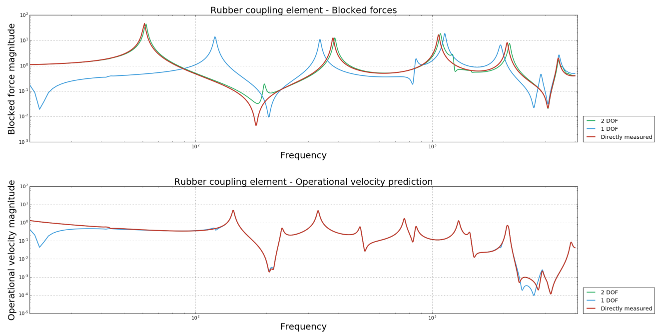

Figure 7: Blocked force and velocity prediction in dependency to the coupling stiffness.

In case where rigid (steel) coupling element was connecting source and receiver the result for predicted receiver velocity was much poorer as shown in figure 8.
At this point an important question appeared - why the change of coupling elements causes such a deviation of result even though it should give us the same outcome, as blocked forces are source independent property and should always be the same, regardless if we change the receiver structure.

It was found out, that due to the stiffer connection and operational forces acting on some distance from the middle point - causing "operational" moments, rotational degrees of freedom have an important role and provide us with additional information about the structure response and should therefore be also taken into calculation.

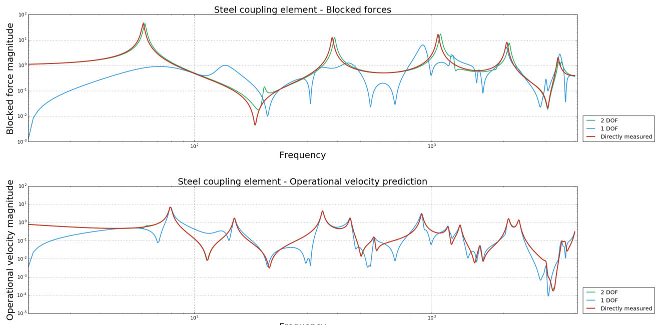

Figure 8: Blocked force and velocity prediction in dependency to the coupling stiffness.

Modified on-board validation

The following section is of great importance for proper validation of obtained blocked forces. The results shown in upper sections were made as a part of on-board validation. That means that the point of velocity prediction was somewhere on the same receiver structure which was used for the blocked force calculation. In this section blocked forces were used to predict the velocity with another (different) receiver structure - the so called modified on-board validation was done (MOBV).

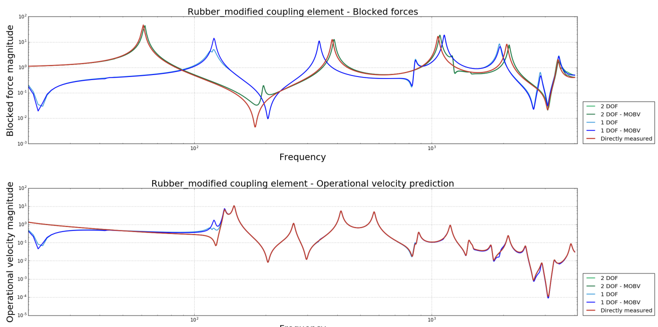

Figure 9: Blocked force and modified on-board validation for a system with rubber mount.

As we can see in figure 9, the MOBV for the rubber mount works well also for only 1 DOF taken into account. As already mentioned in section above, we assume that most of the credit goes to soft mounting structure, which "absorbs" a part of vibro-acoustic energy transferred from source to the receiver. Therefore moments acting on a connection surface are smaller and have a less noticeable effect. The opposite situation is visible for the case of steel mounts (figure 10). The use of only 1 DOF results in poor blocked force calculation and poor MOBV. It is obvious that inclusion of rotational degree of freedom is necessary for a sufficient accuracy of result in form of blocked forces and also velocity prediction.

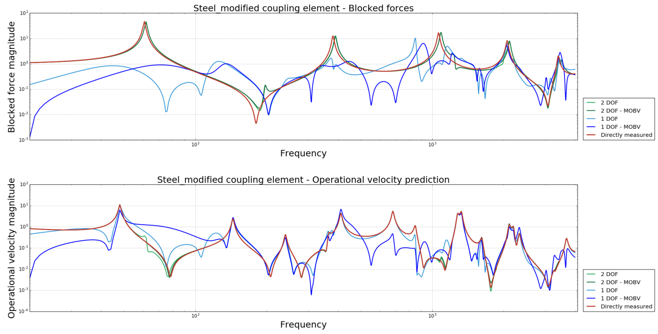

Figure 10: Blocked force and modified on-board validation for a system with steel mount.

Conclusions

During this research we gained knowledge how inclusion of rotational degrees of freedom effects our final result in terms of calculated blocked force and predicted receiver operational velocity for different experimental cases. Especially important for us is to know, that a good velocity prediction (MOBV), in case where rigid mount is placed between source and receiver structure, the rotational degrees of freedom have to be taken into account. Same can be said for OBV, nevertheless the velocity prediction is slightly better.
Another conclusion was done concerning the connecting area. As long as connection area is small enough not to interfere with more than one modal-shape-wave in our frequency range of interest, its effect on the final result is small, almost negligible. Another investigation evaluated with both, OBV and MOBV should be done for the case, where the source is connected to the receiver structure through the whole surface and bolt connections. In this case, connection area should be of higher importance, especially for MOBV. It would also be interesting to see the application and limitations of this method for a 3D problem. In this case at least 3 (preferably 4) sensors per contact point would be needed, meaning much more effort in case of bigger system.
Another disquieting and still unsolved issue by this methods (also TPA) is related to the transfer FRF measurement. Our grain of doubt is load dependency of measured transfer functions. This method requires measuring operational velocities at receiver remote points (system is active) and measuring transfer functions between contact points and receiver remote points when the system is passive. Since blocked force is the independent source property and it is valid for a certain operational load case also transfer mobility should be measured at the same load case. We think this issue has to be taken into account and at the same time this offers many chances for further research and consequently improvement of the accuracy of the calculation of blocked forces.

References

[1] Andrew Elliott: *Characterisation of structure borne sound sources in-situ: Ph.D. Thesis*, University of Salford, 2009.