Indirect in-situ determination of blocked forces

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Vision

ZF Lenksysteme GmbH (ZFLS) is a major manufacturer and innovation leader of steering systems. To enhance the good market position, ZFLS takes care about the NVH performance of steering systems in vehicles. The need for reasonable development costs favours the use of test bench approaches for product development and testing. This implies that steering systems are to be developed mainly on test rigs, independent from vehicles. In order to achieve this aim, it is necessary to obtain test rig data that can be transferred to vehicles for prediction of the interior sound pressure level. Blocked forces satisfy these requirements and can serve as a quantity of independent characterisation for steering systems. An application of the novel in-situ blocked force method is presented in this paper, along with the validation, and extended to mathematical optimised forces.

Force calculation approaches

The classical treatment of mechanical acoustic assemblies separates into source and receiver structures, which are connected in various ways. On each point like mounting location 3 translational forces and 3 moments transmit acoustical power. In the following the moment contributions are neglected and the focus is on translational force transmission. The appropriateness of this approach is documented in the predictions at the end of this paper. All of the subsequent variables are transformed in the frequency domain.

Contact forces

At the connection points of an operating source and a passive receiver contact forces act. The force vector $\{f_c\}$ often cannot be measured without altering the mounting properties, but can be calculated indirectly using the inverse of the receiver mobility matrix $[Y_r]^{-1}$ and the velocities at the contact points $\{v_c\}$ during operation [1].

$$\{f_c\} = [Y_r]^{-1}\{v_c\} \tag{1}$$

This relationship is usually used in TPA approaches to separate the source contribution from the transfer properties of the vehicle. The major disadvantage of this method is the fact, that the operational forces are just valid for an individual source-receiver assembly and hence not an independent source characterisation. To circumvent this shortcoming, the blocked forces can be used.

The in-situ blocked force method

Recently, Moorhouse et al. [1] published an opportunity to calculate the blocked forces $\{f_{bl}\}$ through measurements done in-situ, i.e. source and receiver are assembled.

$$\{f_{bl}\} = [Y_c]^{-1}\{v_c\} \tag{2}$$

The resulting practical advantages in determining the coupled mobility matrix $[Y_c]$ are shown to yield promising results. This approach is also referred to as 'in-situ TPA'.

It is well known that matrix inversions are error-prone [2] and hence indirect calculations can yield inaccurate results. Therefore over determination of the linear equation system, equation (2) is used to optimise the calculations in Figures 2 and 3.

Tikhonov regularised blocked forces

In literature, Tikhonov regularisation is shown to improve the calculation by taking errors of the measured coupled mobility matrix, as well as errors from the velocity measurements into account [2]. This regularisation procedure is applied in a real setup and yields very promising results. To determine the amount of regularisation the ordinary cross validation is used [3].

Validation approach

The in-situ calculated blocked forces cannot be validated by comparison with measured ones because of the practical difficulties in measurement of forces [4]. Therefore velocity predictions are performed on a 'validation structure' $\{v_{pre}\}$ and verified with velocity measurements $\{v_{mea}\}$.

$$\{v_{mea}\} \stackrel{?}{=} \{v_{pre}\} = [H_{c,vs}]\{f_{bl,ts}\} \neq [H_{vs}]\{f_{c,ts}\} \tag{3}$$

$[H_{vs}]$ denotes the transfer mobility matrix of the 'validation structure' decoupled of the source and $[H_{c,vs}]$ is the transfer mobility of the coupled assembly. The needed blocked forces $\{f_{bl,ts}\}$ are calculated according to equation (2) using data from a test bench called 'test structure' with different dynamic properties than the 'validation structure'. The right hand side of equation 3 is included to emphasise that the contact forces obtained on the test structure cannot be transferred to the validation structure.

It is important to note that all regularisation and cross validation work is done on the 'test structure' solely, so that the independence and invariance of the blocked forces concerning the dynamic structural properties are conserved and the comparison between measured and predicted velocities on the second structure can serve as validation.

Experimental results

The following results in Figures 1 and 2 are to approve the experimental in-situ approach and therefore use a simplified source with forces acting in 6 degrees-of-freedom. The excitations of the source is performed using an instrumented hammer, so that all of the following velocities are normalized to a known force, having the physical unit of [(m/s)/N].

Predictions with a simplified source

Figure 1 compares the measured velocity on the validation structure with that predicted from the right hand side of equation 3, i.e. from the contact forces obtained from the test structure (via equation 1). Ranges with more than 20 dB deviation can be seen which confirms, as expected, that significant errors result from erroneously transferring contact forces.

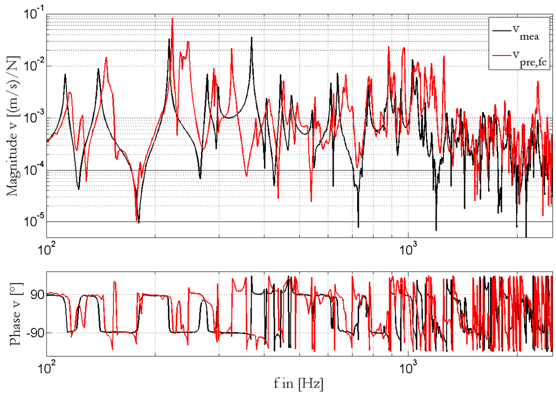

Figure 1: Measured (black) and predicted (red) velocities at a remote position, using operational contact forces.

Therefore it is not possible to transfer contact forces, determined from test benches, directly to vehicles. In contrast to the contact force application the in-situ blocked force method with a three times over determined mobility matrix is shown in Figure 2.

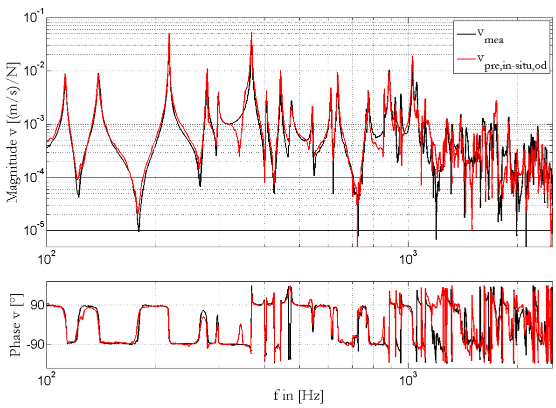

Figure 2: Measured (black) and predicted (red) velocities at a remote position, using the in-situ blocked force method with a three times over determined matrix.

The prediction is very promising and approves the approach experimentally. Besides some limited frequency ranges the magnitude and phase of the prediction maps the measurement very well. This confirms that blocked forces, measured in-situ, can be used to characterise structure-borne sound sources independently of the passive receiver structures.

Prediction with steering system as source

With this motivation a steering system is characterised on the 'test structure'. Besides the over determination, Tikhonov regularisation is employed in the inversion process for this more challenging application. The result is shown in Figure 3.

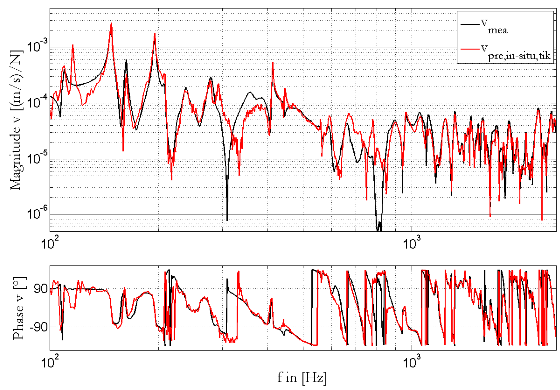

Figure 3: Measured (black) and predicted (red) velocities at a remote position, using the in-situ blocked force method and Tikhonov regularisation.

Except for some limited frequency ranges a very good agreement can be achieved.

We conclude that the blocked forces can be used to characterise structure-borne sound sources independent from the attached structures. Furthermore it is possible to determine these forces from measurements, done in-situ. For real application setups mathematical optimisations may be required.

Literature

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