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OPERATIONAL STRUCTURAL TRANSFER PATH ANALYSIS

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Abstract

A lot of mechanical systems are composed of different subsystems that are coupled by several links. The Transfer Path Analysis aims to identify the operational forces and the most important propagation paths of the vibrations. In this contribution a new technique will be presented which can be used in operational conditions. The proposed technique has several advantages. First of all the disassembling of the system is not necessary anymore which reduces the overall testing time. Secondly, the real boundary conditions are present. In this contribution the theory will be tackled and the procedure will be validated by some simulations.

1. INTRODUCTION

If a mechanical system consists of several subsystems, it is interesting to know how the vibrations of one subsystem propagate to other subsystems [1, 2, 3]. This can be useful to optimise the noise and vibration characteristics of vibro-acoustic systems. During the last 15 years a lot of research has been done concerning the experimental transfer path analysis [4]. One of the main disadvantages of experimental transfer path analysis is that most of the proposed procedures can not cope with operational forces during the identification of the transfer paths. The proposed procedure will combine known and operational forces. When the operational forces are uncorrelated with the applied forces - which normally is the case - , it is possible to eliminate the effects introduced by the linked subsystems. We will show this using a 2 DOF mechanical system with 1 link. In the following part we will discuss the results of a simple 6 DOF mechanical system with 2 links. At the end we will tackle a more realistic problem which uses the responses that were calculated using a Finite Element Model.

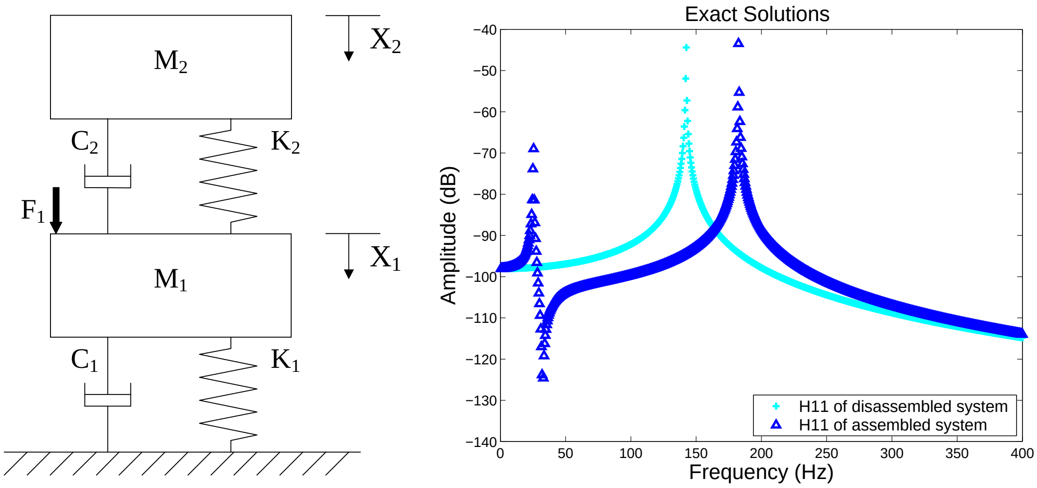
2. THEORETICAL ASPECTS

2.1. A mechanical system with 2 degrees of freedom

For simplicity we will focus on a simple mechanical system. In Figure 1(a) a mechanical system with 2 degrees of freedom is shown. Assuming the initial velocity and position to be zero, the system equations in the Laplace domain are:

$$\left(s^2\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} + s\begin{bmatrix} C_1+C_2 & -C2 \\ -C_2 & C2 \end{bmatrix} + \begin{bmatrix} K_1+K_2 & -K2 \\ -K_2 & K2 \end{bmatrix}\right)\begin{Bmatrix} X_1(s) \\ X_2(s) \end{Bmatrix} = \begin{Bmatrix} F_1(s) \\ 0 \end{Bmatrix} \tag{1}$$

Suppose we are interested in the Frequency Response Function (FRF) between a force on mass 1 and the response of mass 1. In this case M_1, C_1 and K_1 form the disassembled system which we are interested in. C_2 and K_2 form the link and M_2 is the linked subsystem. Figure 1(b) shows that the exact Frequency Response Function (FRF) of the assembled system (which has 2 peaks) does not resemble the exact Frequency Response Function of the disassembled system (which has only one peak). Currently, if one wants to know the FRF of the disassembled system one has to disassemble the system and measure it. This is what happens during a traditional transfer path analysis. But in fact it is possible to estimate the FRF of the disassembled system without doing this.



(a) system (b) Frequency Response Functions

Figure 1. Mechanical system with 2 degrees of freedom

When we define $H_{11}(s) = (s^2M_1 + s\,C_1 + K_1)^{-1}$ the displacement X_1 equals to:

$$\begin{aligned} X_1(s) &= (s^2M_1 + s\,C_1 + K_1)^{-1}\big(F_1(s) + (s\,C_2 + K_2)(X_2(s) - X_1(s))\big) \\ &= H_{11}(s)F_1(s) + H_{11}(s)(s\,C_2 + K_2)(X_2(s) - X_1(s)) \end{aligned} \tag{2}$$

If there exists an (unknown) operational force which acts on M_2 and this force is uncorrelated with the known force $F_1(s)$, the known force $F_1(s)$ and the relative displacement $(X_2(s) - X_1(s))$ are uncorrelated. In this case it is possible to estimate $H_{11}(s)$ using an H_1

estimator with $F_1(s)$ and $(X_2(s) - X_1(s))$ as the references:

$$X_1(s) = H_{11}(s)F_1(s) + G_{11}(s)(X_2(s) - X_1(s)) \tag{3}$$

Note that we have to measure a signal that has to be correlated with $(X_2(s) - X_1(s))$. This can be done by using strain gages. Note also that these strain gages do not have to be calibrated.

2.2. Mechanical system with 6 degrees of freedom and 2 links

The same formulas can be used for more complex systems. If we take for example the 6 degrees of freedom system that is shown in Figure 2 one can prove that:

$$X_1(s) = H_{12}(s)F_2(s) + H_{12}(s)K_{24}(X_4(s) - X_2(s)) + H_{13}(s)F_3(s) + H_{13}(s)K_{35}(X_5(s) - X_3(s)) \tag{4}$$

Suppose that we are interested in subsystem 1 and more specific in the transfer path $H_{12}(s)$ between M_2 and M_1. Then we apply a known force $F_2(s)$ at M_2. If there are at least 2 uncorrelated operational forces, $(X_4(s) - X_2(s))$ and $(X_5(s) - X_3(s))$ will be uncorrelated with $F_2(s)$ and it will be possible to estimate $H_{12}(s)$. In this situation we can apply the H_1 estimator with $F_2(s)$, $(X_4(s) - X_2(s))$ and $(X_5(s) - X_3(s))$ as references:

$$X_1(s) = H_{12}(s)F_2(s) + G_{12}(s)(X_4(s) - X_2(s)) + G_{13}(s)(X_5(s) - X_3(s)) \tag{5}$$

One can conclude that for every additional link one needs to have an additional uncorrelated operational source. Note that it is not necessary to know these operational forces.

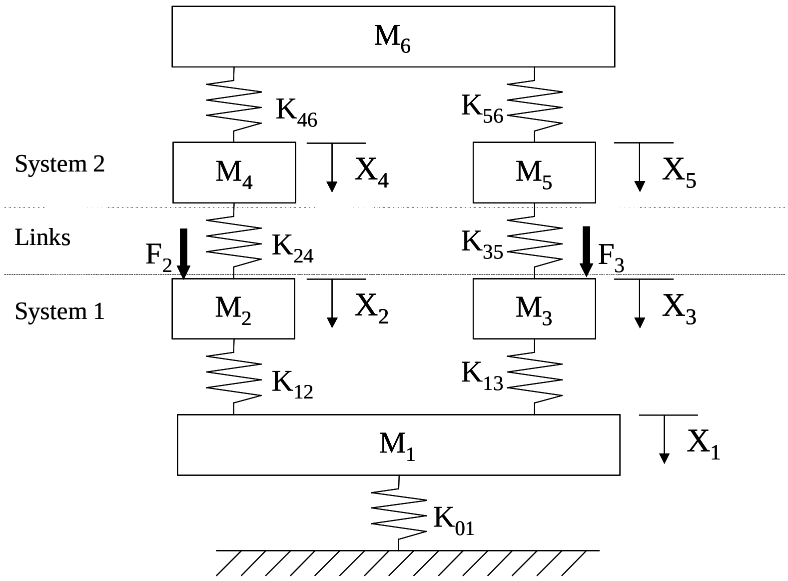


Figure 2. Mechanical system with 6 degrees of freedom

In Figure 3(a) the FRF of the transfer path H_{12} where we are interested in - the FRF of the disassembled system - is plotted together with the FRF that we measure when the system is assembled. It is obvious that there is a big difference. In this case there are no operational forces applied and this results in a wrong estimate (see Figure 3(b)).

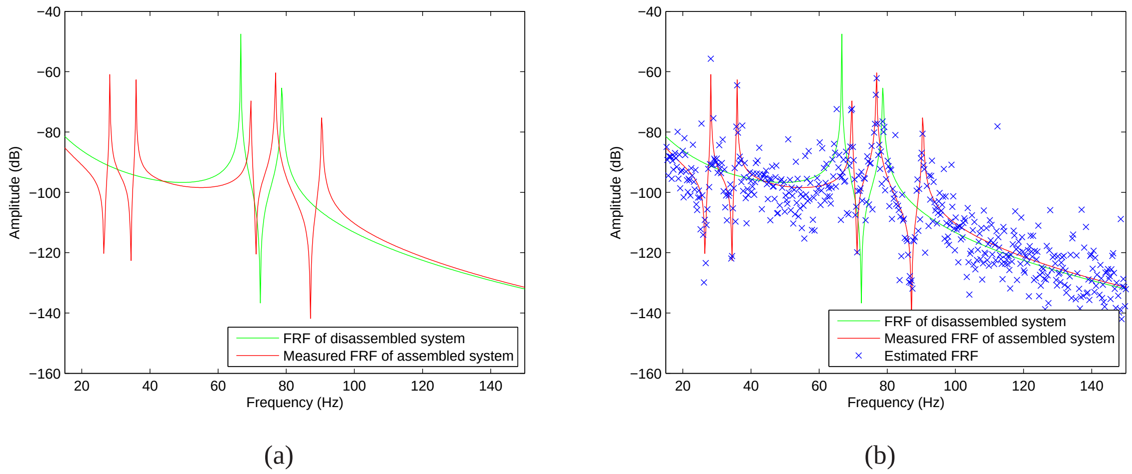


Figure 3. H_{12} of 6 DOF system without operational forces

Now we apply 2 uncorrelated operational noise sources. In Figure 4(a) we see that the FRF that we measure even gets worse. But in this case the estimate is perfect (see Figure 4(b)).

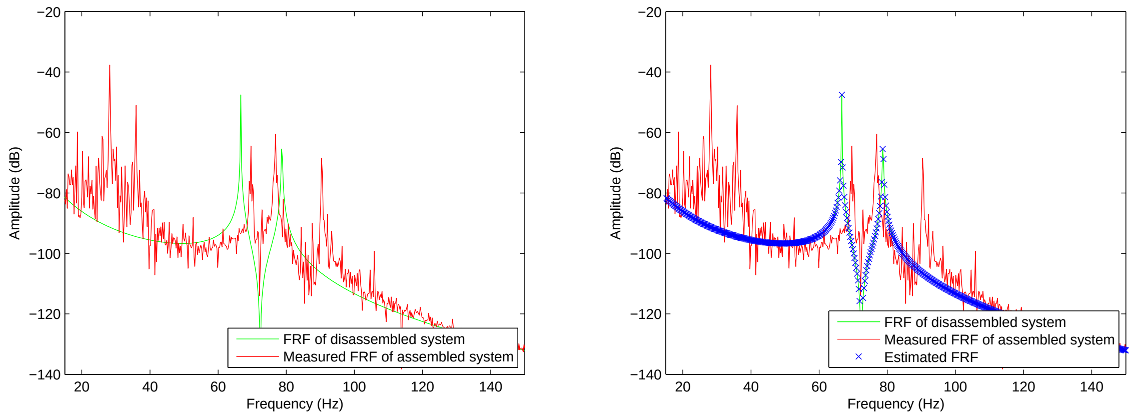


Figure 4. H_{12} of 6 DOF system with 2 uncorrelated operational forces

Note that it is important to have enough uncorrelated operational sources. When we have 2 links, we need 2 uncorrelated operational sources. If one only applies 1 operational source (or 2 correlated sources) the estimate is wrong. This is illustrated in Figure 5.

Note also that one needs enough data blocks. In this situation we have 3 references. Thus we also need 3 data blocks. In Figure 6 the estimate is shown when one uses only 2 blocks which results in a wrong estimate.

3. FINITE ELEMENT SIMULATION

3.1. Set-up

In Figure 7 the subsystem we are interested in is visualised. In this case it is a clamped beam. One wants to know the FRF between the force F applied to the midpoint of the beam (where another subsystem will be linked to the beam) and the point X on the beam.

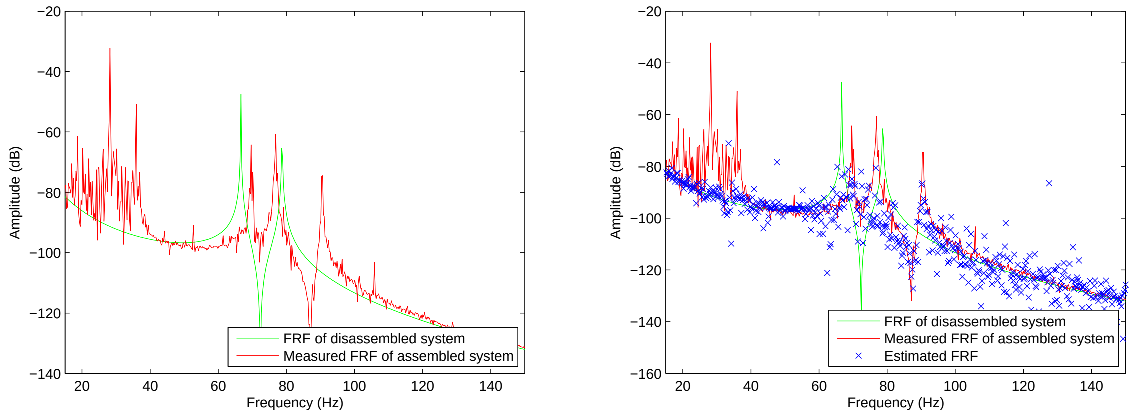


Figure 5. H_{12} of 6 DOF system with 1 uncorrelated operational force

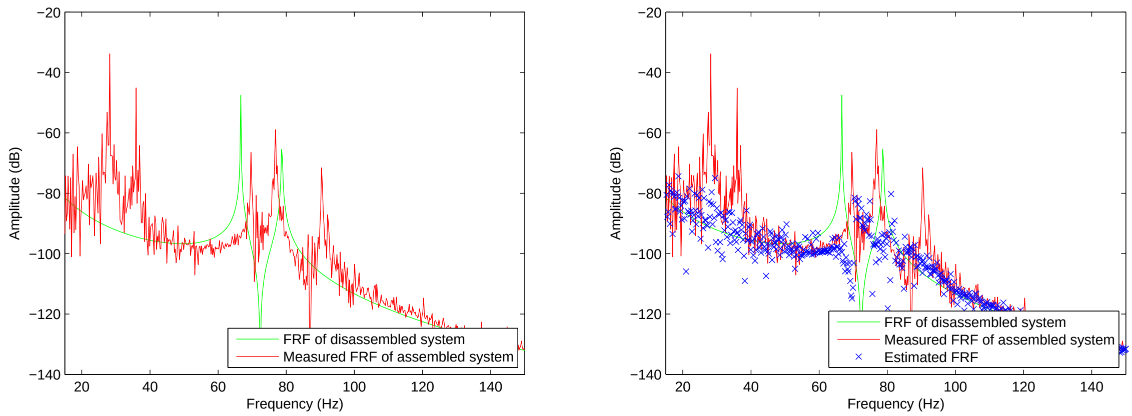


Figure 6. H_{12} of 6 DOF system with 2 uncorrelated operational forces (2 blocks)

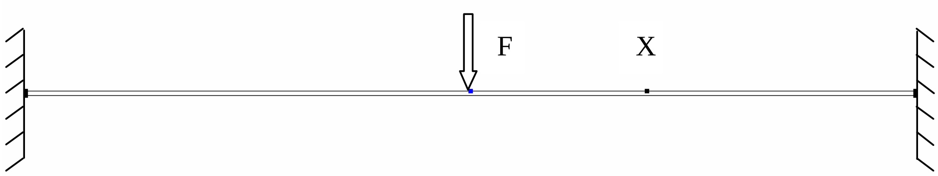


Figure 7. Mechanical subsystem which we are interested in

In Figure 8 the assembled system is shown. In this case the other part of the system is a vertical beam. As we know from before we have to apply a known force at the link. In this case it is the force F. We also have to measure the displacements or strains at the link. Here we assumed that in reality it would be possible to place a strain gage $0.5\,cm$ below the horizontal beam. The simulated strains were used in the estimate. Because of the fact that we only have one link, we now only need 1 operational force. The unknown operational force N is located at the bottom of the vertical beam.

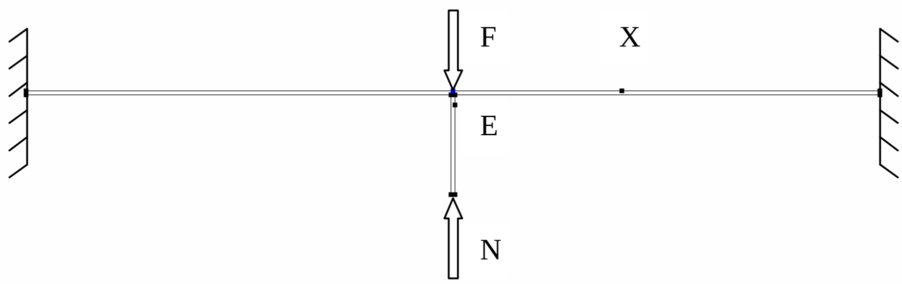


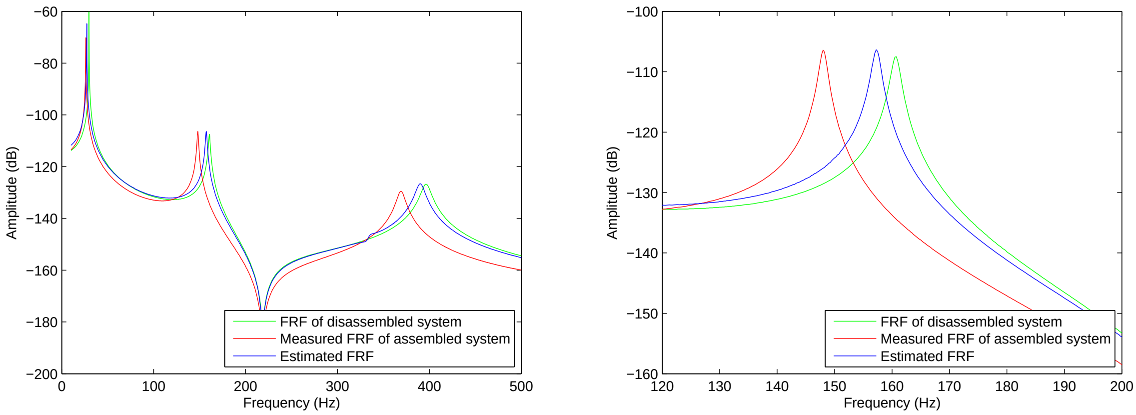
Figure 8. Mechanical subsystem with link

3.2. Simulation results

The response of X due to the superposition of the operational force N and the known force F was calculated with a Finite Element Model. Also the strain E due to these forces was calculated. Then we used an H_1 estimator to calculate the FRF of the disassembled system. Here we used the force F and the strain E as references. In Figure 9 the FRF of the disassembled system, the measured FRF of the assembled system and the estimate of the FRF of the disassembled system are plotted. One sees that in this case the estimate is not perfect. This is due to the fact that we measured the strains $0.5\,cm$ below the point where the vertical beam is attached to the horizontal beam which seems realistic in a possible set-up for a real system. From these results one can conclude that one has to glue the strain gage as close as possible to the horizontal beam. One can also conclude that even for real mechanical situations the procedure results in good estimates.

4. CONCLUSIONS

In this contribution we showed that it is possible to estimate the FRF of a subsystem without disassembling the whole system. To have good estimates one needs an uncorrelated force for each link. Operational forces can be used because one does not need to know these forces. This makes this procedure very interesting for Operational Transfer Path Analysis. It has the advantage that no disassembling is needed and that operational forces do not have to be eliminated. The procedure has been validated using a Finite Element Model of a simple mechanical system.



(a) (b)

Figure 9. Estimate of a transfer path H of a disassembled system

5. ACKNOWLEDGEMENTS

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