Coupling a compliant structure with a Hand – arm system using FBS

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ABSTRACT

The vibrational behavior of a lightweight compliant structure with low damping is strongly influenced by contact with parts of the human body. In this work, a close look is taken at the influence of the hand-arm system in the context of cycling sports. Force transmitted to the hand, along with hand-arm vibration, generates discomfort and sometimes results in injury. Designing structural changes in a given road bike component with the goal of reducing discomfort requires a clear understanding, in this case, of the interaction mechanisms between the hand-arm system and the handlebar (the coupled structure).

This paper describes an experimental investigation of this type of interaction between the hands and a handlebar using an FRF Based Substructuring method (FBS) to calculate the resulting dynamic behavior of the coupled structure. The equations supporting the FBS method for this particular application are presented. The compliant structure and the hand-arm system are individually characterized by mechanical mobility Frequency Response Functions (FRF) in the frequency range of 20-400 Hz. Hand mobility is obtained by using the FBS method in a reverse manner. The influence of the hands and the upper body position on hand-arm mechanical mobility is considered. The merits and limitations of using FBS are discussed.

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INTRODUCTION

In a recent trend, the cycling sports market has witnessed the emergence of rider comfort as the most desirable characteristic in a bike along with performance. Rider comfort is a subjective human experience, and although traditional evaluations have been carried out by expert panels, most notably in the automotive industry, no similar studies have been done in the cycling field. As a consequence, objective evaluation indicators and universal design guidelines have not yet been developed. Quantification of human sensitivity in evaluating rider comfort using measured physical values thus emerges as an interesting avenue for research [1]. Recent evaluation methods focusing on vibration sensitivity characteristics and human vibration characteristics have attracted intense scrutiny. For future developments and designs, there is a need to establish a clear understanding of the dynamic involved, and a method to evaluate rider comfort that focuses on the improvement of specific bike components.

In the context of functioning as a system in tandem with the human body, the dynamic behavior of a lightweight structure changes radically from its original uncoupled condition. The dynamic behavior of the human body has to be taken into account in order to evaluate how the system is modified and to evaluate the response in terms of transmitted force or measured velocity at the interface points. Furthermore, vibrations transmitted to the human body through the structure generate discomfort, can also reduce performance or even cause injury.

The purpose of this study is to establish the basic mechanical knowledge of the coupling between a structure and a unit or dynamic system of the human body. Rider comfort would thus take into account human sensitivity as well as the dynamic behavior of an entire system composed of various units.

In this work, the FBS technique (Frequency Response Function Based Substructuring) is used in an investigational manner to couple a structure assembled from both mechanical components and human body parts. This technique was chosen because it enables us to couple various components from an overall structure using their individual dynamic behaviors. It also allows us to classify these elements in terms of vibration isolation capacity. An original element in this paper is that this technique has been used with the human hand-arm system, which is known to be nonlinear. Moreover, this method can be used when only mobility data at the connecting points are known, which is the case with the human body where only the interface points are of interest. Since this approach is an investigational one, the merits and limitations of using the technique with human involvement will be discussed.

There are only three contact points between the cyclist and the bike: hand-transmitted vibration is thus one of the major concerns for road bike comfort. In this paper, the coupling between the cyclist and the bike at the points of the handlebar has been examined. Road excitation is predominant along the vertical Z–axis, therefore the excitation considered in this paper will be limited to this direction.

Hand position and direction, along with other factors, have a strong influence on the dynamic behavior of the hand-arm system [2; 3]. For the sake of accuracy when using the FBS method, hand mobility data that represent real operating conditions must be used. However, this data does not exist in the literature. A technique employing the FBS method in a reverse manner has therefore been selected to obtain hand-arm input mechanical mobility.

A bike's dynamic behavior is also strongly influenced by the cyclist's position and posture [4]. A typical cycling position was used and posture was controlled for by measuring the cyclist's leaning vertical DC force applied to the stem.

The merits and limitations of this approach will be examined by comparing experimental values obtained with the assembled structure to the data calculated using the FBS method. Results show solid agreement which confirms that this method is promising.

COUPLING METHODOLOGY USING THE FBS INTERFACE EQUATIONS

To obtain the dynamic behavior of a complete structure using the dynamic contribution of its components, a generalized frequency domain substructure synthesis was used. This well known technique, also referred to as FBS (Frequency Based Substructuring), combines the response FRF data of each component to analyze the dynamics of an assembled structure. The dynamic behavior of the assembled structure can be synthesized through the method presented here. This method is based on an implicit statement of the force and velocity continuity considerations at the connection nodes and enables substructures to be coupled by considering interface characteristics only [5; 6]. The two substructures involved in this paper (the hands and the handlebar) can be effectively characterized separately by measuring their respective input mobilities. The methodology is thus ideally suited to the analysis of hands-on-handlebar coupling.

Let's consider two substructures as shown in Fig. 1.

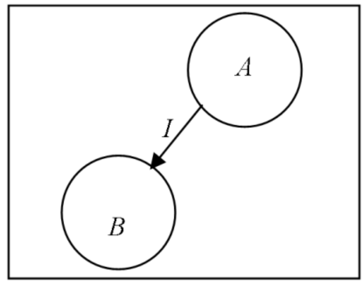

Figure 1. Diagram of two coupled substructures A and B with interface coupling interface I

The known mathematical expression of the mobility FRF coupling method is:

$$\begin{bmatrix} Y^{ab}_{AA} & Y^{ab}_{AI} & Y^{ab}_{AB} \\ Y^{ab}_{IA} & Y^{ab}_{II} & Y^{ab}_{IB} \\ Y^{ab}_{BA} & Y^{ab}_{BI} & Y^{ab}_{BB} \end{bmatrix} = \begin{bmatrix} Y^{a}_{AA} & Y^{a}_{AI} & 0 \\ Y^{a}_{IA} & Y^{a}_{II} & 0 \\ 0 & 0 & Y^{b}_{BB} \end{bmatrix} - \begin{Bmatrix} Y^{a}_{AI} \\ Y^{a}_{II} \\ -Y^{b}_{BI} \end{Bmatrix} \left[Y^{a}_{II} + Y^{b}_{II} \right]^{-1} \begin{Bmatrix} Y^{a}_{IA} \\ Y^{a}_{II} \\ -Y^{b}_{IB} \end{Bmatrix}^{T} \tag{1}$$

where superscripts a and b identify the two substructures involved.. For the subscripts:
A is the set of internal degrees of freedom of structure a,
I is the set of interface contact points degrees of freedom between the substructures a and b and
B is the set of internal degrees of freedom in structure b.

In this paper, substructure a represents a handlebar connected to a stem which is clamped to a rigid steel table. The stem handlebar end is identified as point $A1$. This point will be used to apply an external force and is part of the internal set of the degrees of freedom A of structure a. Substructure b is the hand-arm system. The contact points between the two structures (hands and handlebar) are designated $I1$ and $I2$. They represent the set of interface contact point degrees of freedom I, as illustrated in Fig. 2.

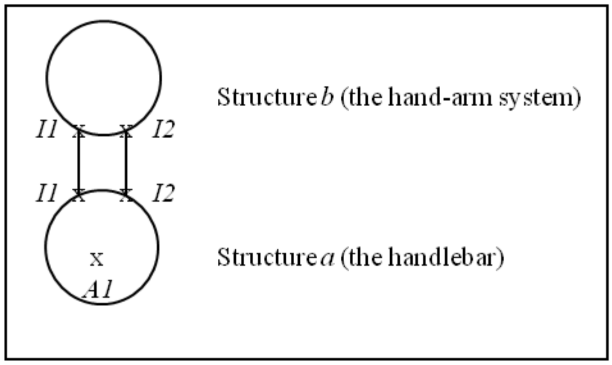

Figure 2. Symbolic coupling of the two substructures with the points of interest

The context of this study is the transmission of vibration to the cyclist. Only the contact points between the hand and the handlebar are of interest and consequently only one specific term from Eq. (1) is relevant:

$$Y_{IA}^{ab} = Y_{IA}^{a} - Y_{II}^{a}\left[Y_{II}^{a} + Y_{II}^{a}\right]^{-1} Y_{IA}^{a} \quad (2)$$

where Y_{IA}^{ab} corresponds to an excitation force applied in A and a velocity response in I for the assembled structure *ab*. Considering that set A contains point $A1$, and set I points $I1$ and $I2$, Eq. 2 becomes:

$$\begin{bmatrix} Y_{I1A1}^{ab} \\ Y_{I2A1}^{ab} \end{bmatrix} = \begin{bmatrix} Y_{I1A1}^{a} \\ Y_{I2A1}^{a} \end{bmatrix} - \begin{bmatrix} Y_{I1I1}^{a} & Y_{I1I2}^{a} \\ Y_{I2I1}^{a} & Y_{I2I2}^{a} \end{bmatrix} \left[\begin{bmatrix} Y_{I1I1}^{a} & Y_{I1I2}^{a} \\ Y_{I2I1}^{a} & Y_{I2I2}^{a} \end{bmatrix} + \begin{bmatrix} Y_{I1I1}^{b} & Y_{I1I2}^{b} \\ Y_{I2I1}^{b} & Y_{I2I2}^{b} \end{bmatrix} \right]^{-1} \begin{bmatrix} Y_{I1A1}^{a} \\ Y_{I2A1}^{a} \end{bmatrix} \quad (3)$$

Assumptions

- Hands are uncoupled ($Y_{I1I2}^{b} = 0$; $Y_{I2I1}^{b} = 0$).
- Only vertical axis Z is considered for the excitations or the responses
- There are no couplings between the three directional axes (X, Y, and Z) for each substructure. All measurements are along the vertical Z axis.
- Left and right hand measurements are identical because $Y_{I1zI1z}^{b} = Y_{I2zI2z}^{b}$.

Formulation

Using the assumptions, the following expression is obtained:

$$\begin{bmatrix} Y^{ab}_{I1zA1z} \\ Y^{ab}_{I2zA1z} \end{bmatrix} = \begin{bmatrix} Y^{a}_{I1zA1z} \\ Y^{a}_{I2zA1z} \end{bmatrix} - \begin{bmatrix} Y^{a}_{I1zI1z} & Y^{a}_{I1zI2z} \\ Y^{a}_{I2zI1z} & Y^{a}_{I2zI2z} \end{bmatrix} \left[\begin{bmatrix} Y^{a}_{I1zI1z} & Y^{a}_{I1zI2z} \\ Y^{a}_{I2zI1z} & Y^{a}_{I2zI2z} \end{bmatrix} + \begin{bmatrix} Y^{b}_{I1zI1z} & 0 \\ 0 & Y^{b}_{I1zI1z} \end{bmatrix} \right]^{-1} \begin{bmatrix} Y^{a}_{I1zA1z} \\ Y^{a}_{I2zA1z} \end{bmatrix} \quad (4)$$

Specific method to obtain the dynamic characteristics of the hands

In Eq. 4, the only term related to the hands is Y^{b}_{I1zI1z}. In practice, this term cannot be measured directly [7]. Hand mobility is influenced by several factors such as the direction the hands are facing, grip, and the push forces. A specific technique to evaluate this term was developed so that measurements using a typical and realistic posture could be taken. Using the same setup as described previously, the handlebar was replaced by a stiff, short hollow tube long enough for the placement of both hands. This new structure, a short tube connected to a stem clamped to a stiff table, is called structure *c*. This structure does not have any mode in the frequency range of interest. Using Eq. 4 and replacing structure *a* by structure *c,* Eq. 5 can be obtained.

$$\begin{bmatrix} Y^{b}_{I1zI1z} & 0 \\ 0 & Y^{b}_{I1zI1z} \end{bmatrix} \left[\begin{bmatrix} Y^{c}_{I1zI1z} & Y^{c}_{I1zI2z} \\ Y^{c}_{I2zI1z} & Y^{c}_{I2zI2z} \end{bmatrix} \right]^{-1} \left[\begin{bmatrix} Y^{c}_{I1zC1z} \\ Y^{c}_{I2zC1z} \end{bmatrix} - \begin{bmatrix} Y^{cb}_{I1zC1z} \\ Y^{cb}_{I2zC1z} \end{bmatrix} \right] = \begin{bmatrix} Y^{cb}_{I1zC1z} \\ Y^{cb}_{I2zC1z} \end{bmatrix} \quad (5)$$

All the terms from this equation can be measured and Y^{b}_{I1zI1z} can be computed. This is a sort of reverse way of using the FBS method. Instead of using the dynamic behavior of two substructures *b* and *c* to calculate the dynamic behavior of the assembled structure *cb*, measurements from structures *cb* and *c* are used to calculate the dynamic behavior of substructure *b*.

EXPERIMENTATION

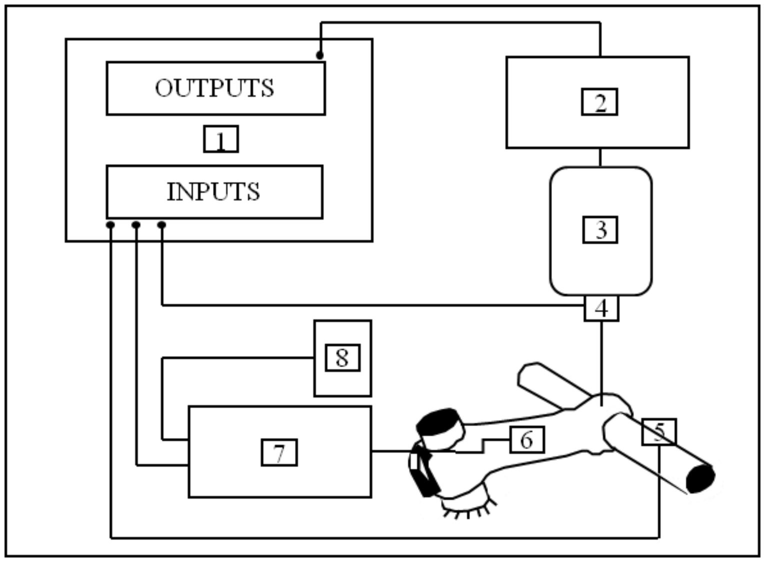

Figure 3. Diagram of the measurement system

1) LMS Test.Lab software Rev 10A (Spectral Testing, Random Excitation, Hanning Windowing, 0.5 Hz resolution)
2) Power amplifier type 2706 from Brüel & Kjaer for the shaker
3) Vibration exciter type 4809 from Brüel & Kjaer (shaker)
4) Force sensor 208C03 type ICP from PCB Piezotronics
5) Accelerometer 356B11 type ICP from PCB Piezotronics
6) Instrumented stem with strain gauges to obtain the static vertical push force from the hands
7) Signal conditioning amplifier type 2310 from Vishay for the stem
8) Fluke 112 True RMS multimeter to allow the subject to control his posture

Dynamic characterization of the hands

This section of the paper describes the materials and the procedure used to get the term Y^{b}_{I1zI1z} which represents the dynamic characteristic of the hand (structure *b*).

The intrinsic dynamic characteristics of the hands were obtained using the measurement system. The handlebar was replaced by a hollow aluminum tube long enough for both hands. The tube has a circular section with a diameter of 2.54 cm; it is 20 cm long with a wall thickness of 3.18 mm.

Figure 4 shows the diagram of the measurement showing the stiff hollow tube and the measurement location *C*1, *I*1 and *I*2. The accelerometer was placed under the tube but it was assumed that the acceleration levels at the top and bottom of the tube are the same.

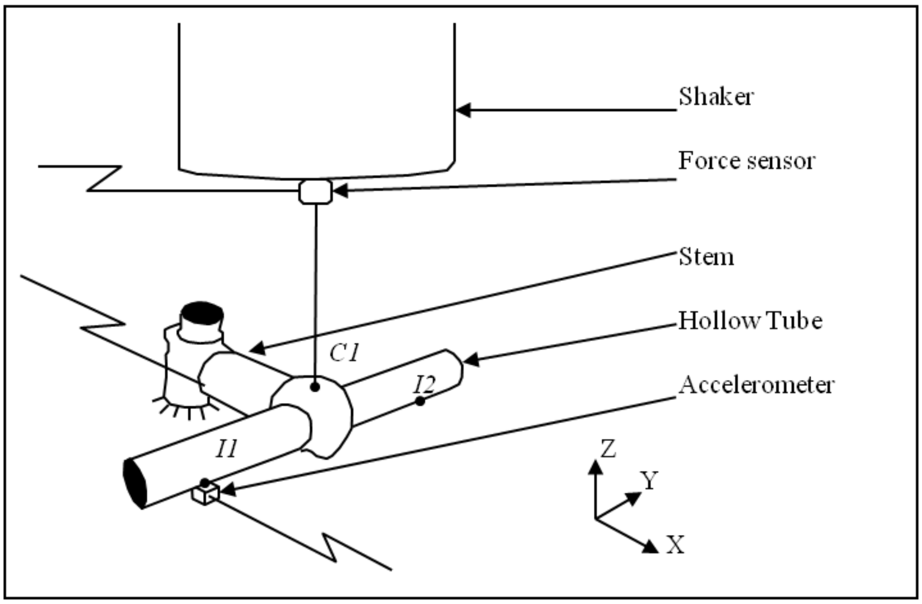

Figure 4. Experimental setup to measure the dynamic behavior of the hands Y^{b}_{I1zI1z}

Typical cyclist position was used and the posture was controlled by measuring the cyclist's leaning vertical DC force applied to the instrumented stem. Looking at the monitored DC force value, the cyclist was asked to keep the force constant at a level of 110 N. The data was obtained in 2 steps with 2 configurations:

- Tests on structure c , meaning that no hands are touching the tube to measure Y^{c}_{I1zC1z}, Y^{c}_{I2zC1z}, Y^{c}_{I1zI1z}, Y^{c}_{I1zI2z}, Y^{c}_{I2zI1z}, Y^{c}_{I2zI2z}
- Tests with the hands on the tube, corresponding to structure cb to get Y^{cb}_{I1zC1z}, Y^{cb}_{I2zC1z}

Dynamic characterization of structure *a* and measurement on structure *ab*

The objective of this paper is to investigate the FBS method (Eq. 4) to determine if it can provide accurate results when a compliant low damped mechanical structure and a human body segment are involved.
This section presents the method used to obtain the dynamic characteristics of the other structure (structure *a* stem-handlebar) and to obtain this measurement when both structures are coupled (*a* and *b*).
For the sake of simplicity in this investigational work, a simple homemade handlebar was manufactured. As shown in Figure 5, we used a hollow aluminum tube with a circular section of 2.54 cm in diameter, a wall thickness of 1.59 mm and a total length of 55 cm. The modal behavior of a real road handlebar was tested to measure its first natural frequency. This information was used to select the mass (0.68 kg) of two steel cylinders fixed at both ends of the tube. The objective was to obtain a similar first natural frequency for the custom-made handlebar. The same measuring system is used and an input force is applied on *A*1. Fig. 5 shows the custom-made handlebar along with the measurement points *A*1, *I*1, *I*2.

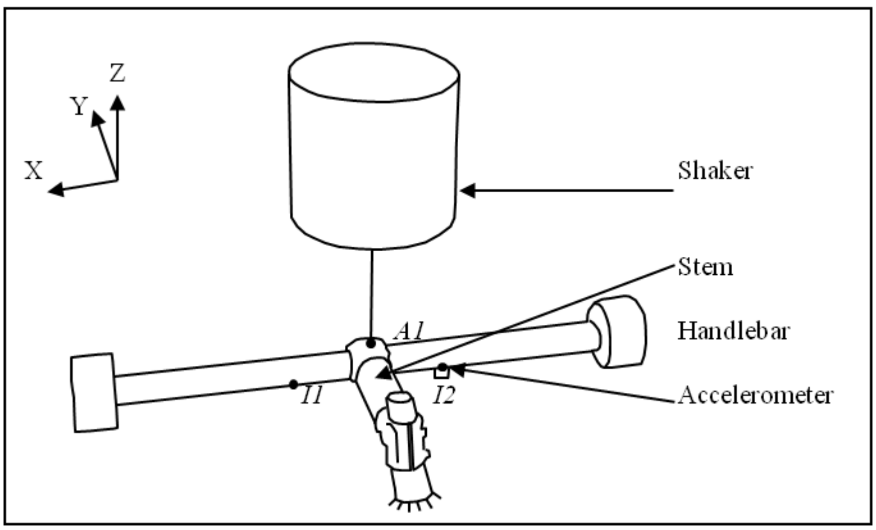

Figure 5. Experimental setup for measurement on structure *a* (handlebar- clamped stem)

Two sets of measurements were also done using the structure shown in Fig.5

- Tests on structure *a* to measure $Y^{a}_{I1zA1z}, Y^{a}_{I2zA1z}, Y^{a}_{I1zI1z}, Y^{a}_{I1zI2z}, Y^{a}_{I2zI1z}, Y^{a}_{I2zI2z}$
- Tests on the structure shown in Fig.5 with the hands on the handlebar which corresponds to structure *ab* to get $(Y^{ab}_{I1zA1z}, Y^{ab}_{I2zA1z})$

The same position and posture as described previously were used in this test.

RESULTS

- Dynamic characterization of the hands

The Fig. 6 shows the mobility obtained at point *I1* for the structure b (the hands) using the FBS technique in a reverse way. Results show various damped peaks mainly in the frequency range of 50 - 200 Hz. They reveal the dynamic behavior of the hand-arm system for a specific cyclist position and push force. There is no data available for comparison in the published scientific literature.

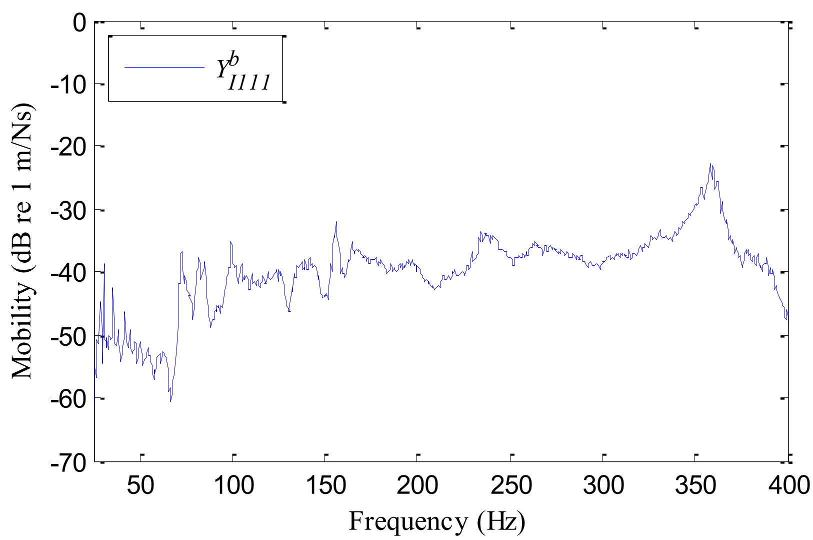

Fig. 6. Mobility of Y^{b}_{I1zI1z}

- Dynamic characterization of structure *a*

The Fig. 7 shows the mobility between points $A1$ and $I1$ which was measured on structure a (handlebar-clamped stem). This result along all the other measured mobilities Y^a_{I1zA1z}, Y^a_{I2zA1z}, Y^a_{I1zI1z}, Y^a_{I1zI2z}, Y^a_{I2zI1z}, Y^a_{I2zI2z} provide the intrinsic dynamic characteristic of structure a. This undamped structure has 2 modes as shown in Fig.7 by the two peaks at 56 Hz and 280 Hz. On Fig. 7, the mobility Y^{ab}_{I1zA1z} measured with the hands in contact to handlebar is provided. This shows the influence of the hands on the structure a. The hands essentially add damping to the 2 modes.

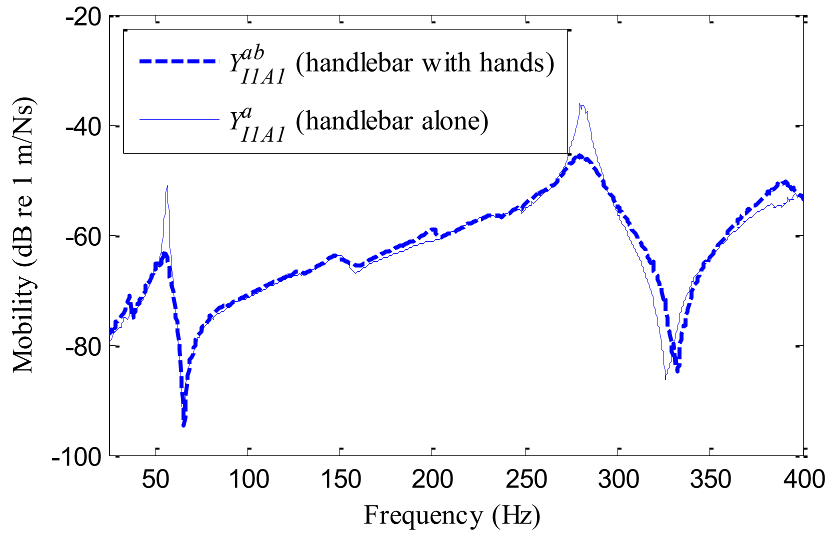

Fig. 7. Mobility measured between point *A1* and *I1*.
Solid line: structure *a* (handlebar-clamped stem)
Dashed line: structure *ab*: hands grip the handlebar

- Measured and calculated results

The Figs. 8 and 9 show results in relation to the main objective of this paper. Two mobility curves are presented. The solid line represents the calculated results for the assembled structure *ab* obtained by using the intrinsic characteristics of both structures *a* and *b* using Eq. 4. The dashed line represents the measured curve when the hands were grasping the handlebar. The agreement between the curves is satisfactory at this stage of development in the ongoing project.

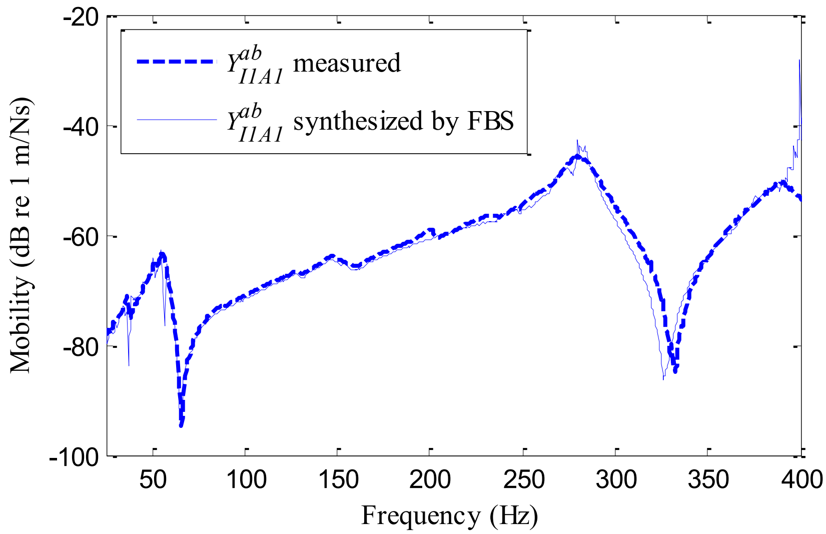

Fig. 8. Mobility measured between points *A1* and *I1* on structure *ab*.
Solid line: calculated results; Dashed line: measure where hands are on the handlebar

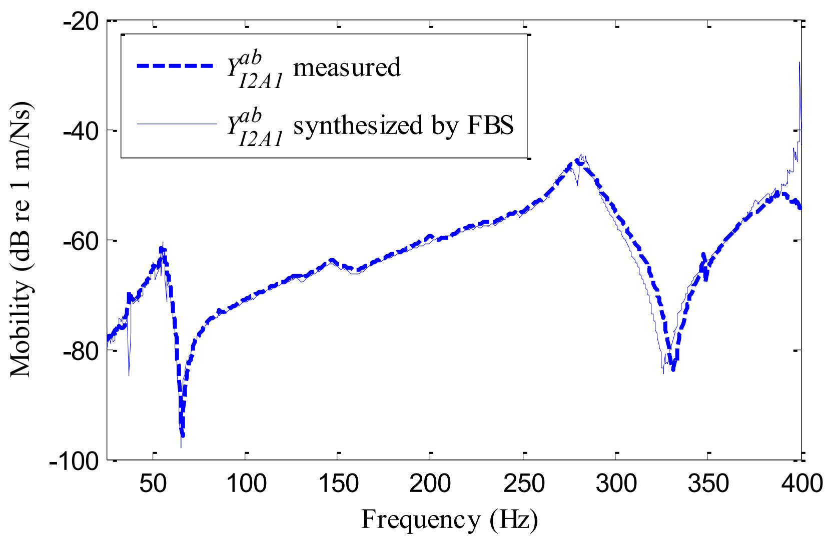

Fig. 9. Mobility measured between points *A1* and *I2* on structure *ab*.
Solid line: calculated results; Dashed line: measure where hands are on the handlebar

DISCUSSION

Figures 8 and 9 show that the FBS method succeeds in providing reliable results which gives a strong indication that coupling between a human body part and a compliant structure is possible using this method. These results cannot invalidate the assumptions that the hands are well uncoupled; that for a vertical excitation, only Z axis results need to be considered and finally, that the left and right hand have similar intrinsic characteristics and the same influence on structure a.

This work highlights the following characteristics of the FBS method

- Merits:
  - Direct use of shaker test data
  - Combination of substructures when only interface data is known
  - Direct and relatively simple calculation
- Limitation

One important disadvantage of the technique is the requirement of measuring a full matrix of FRFs for all the points and degrees of freedom involved. According to the results in some specific cases such as the one described in this paper, only degrees of freedom of interest would be needed to be considered to get appropriate results.

The hand-arm systems input mobilities are sensitive to several factors such as position, orientation, etc. Also, the human body input mobility depicts some non-linear behavior. The technique used in this paper to measure the hand-arm dynamic characteristics allows us to obtain data while taking into account the specific real life posture, attitude and hand preload of the cyclist. It is believed that this minimizes the non-linear effect and enables measurements under real operating conditions. Another interesting feature of this approach is that it does not require any complex setups or instrumentation using large electromagnetic shakers, instrumented handles, etc. because in this case, the same basic structure studied (stem) is also used to get the hand-arm characteristics. However, a legitimate question is: are these results fundamentally intrinsic to the hand-arm segment. Answering this question will require further investigation.

Despite its limitation and the need to process a large amount of data when several structures are coupled through several contact points, the preliminary results disclosed in this work indicate that the FBS method is a promising solution to study vibration interaction mechanisms between a structure and a human body part.

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