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Acoustic Energy Transfer by Friction Induced Vibrations

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Abstract

Friction-induced vibrations are often investigated for their unwanted effects, such as surface wear and dynamic instabilities. This article focuses on the exploitation of friction-induced vibrations to transfer the energy between different acoustic fields by an interface under frictional contact. One of the main possible applications is the use of the generated acoustic field for passive structural health monitoring (SHM). A mechanical device (secondary acoustic source, SAS), able to perform the energy transfer, is here tested on a simplified benchmark. The energy transfer is obtained between two vibrational fields: a primary field, which is the ambient acoustic field on the structure and is generated by a known source, and a secondary field with a different frequency content produced with the developed device by friction-induced vibrations. The test bench analyzed in this work is composed by a main structure, which is excited by the primary (ambient) acoustic field, and the SAS, able to absorb part of the acoustic energy of the primary field and radiate it within the secondary acoustic field. The device is composed by a main resonator, excited by the primary acoustic field, in frictional contact with a secondary resonator to provide a broadband secondary acoustic field. The objective of the article is to analyze and estimate the power flows from the main structure to the SAS and vice versa, within the two acoustic fields.

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Keywords: friction-induced vibrations; energy transfer; force identification; power flow

1. Introduction

Friction between surfaces in contact has been always a challenging object of study, due to the complexity of the phenomenon and its effects widespread from everyday life issue to industrial applications [1]. The most common effects are the negative ones, such as wear [2] and dynamical instability [3, 4, 5, and 6].

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On the other side, an interesting field of study concerns the exploitation of friction, and in particular friction-induced vibrations, for applications in energy transfer, for example to dissipate the energy [7, 8]. In this research framework, an attractive application is the SHM [9, 10]. Carrying on the interest on the SHM application, the objective of this work is to exploit the friction-induced vibrations to transfer the energy from a primary acoustic source to a secondary source with a wider and higher frequency range. For allowing the energy transfer, a mechanical device has been developed, to generate the secondary acoustic field. Named secondary acoustic source (SAS), the device is composed by a main and a secondary resonator under frictional contact. A main issue, in the development of such device, is the optimization of the energy transfer and, to this end, it is necessary to quantify the power flows exchanged between the main structure and SAS. The quantification of the power flows is subjected to the knowledge of velocity and force at the connection with the structure. Consequently, a method for the identification of the force has been developed in order to calculate the force exchanged at the connection between the system and the SAS (in practice unknown). Then, the power flows have been calculated when the SAS is activated.

2. The secondary acoustic source for SHM

A mechanical device, the SAS, has been developed to allow the acoustic energy transfer. The SAS is composed by two main parts (Fig. 1a): a spring-mass system (main resonator) and a U beam (secondary resonator). A shaker is connected with the structure (the plate) at point 1 in Fig. 1b, while the SAS is mounted on the structure at point 2. The plate is excited by the shaker in a low and narrow frequency band to simulate the ambient vibrations. Fig.1c presents a diagram of the experimental set-up. Two main configurations of the system can be distinguished: the first one in absence of contact between the U beam and the mass-spring system, the second one putting in contact the tip of the U beam with the lateral surface of the spring-mass system. Fig. 2 presents the PSD (Power spectral Density) of the accelerometer placed on the structure for both cases: in absence of contact the plate has a response only within the frequency band of the ambient field; in presence of contact, instead, the acceleration of the plate presents a larger frequency band. This result shows that the presence of friction induced vibrations allows to produce a secondary acoustic field due to the broadband excitation at the contact interface. The frictional contact produces a random excitation, which results in friction-induced vibrations, enabling the energy transfer from the primary acoustic field, generated by the shaker, to a secondary field with a higher and wider frequency content.

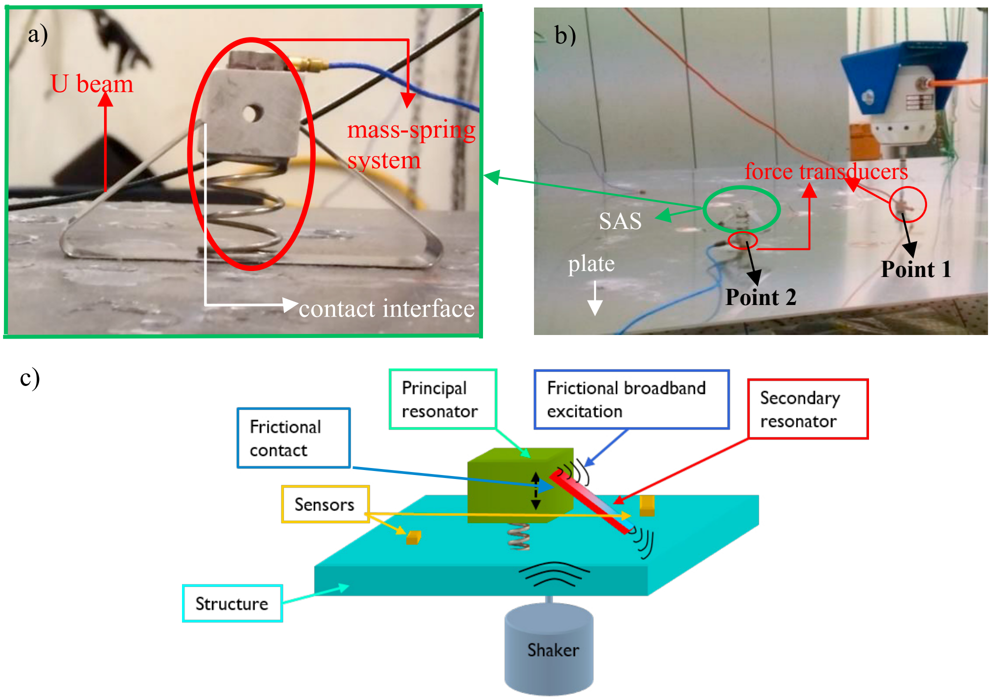

Fig. 1: a) The SAS, composed by the U beam and the mass-spring system, b) the test bench, c) diagram of the experimental set-up.

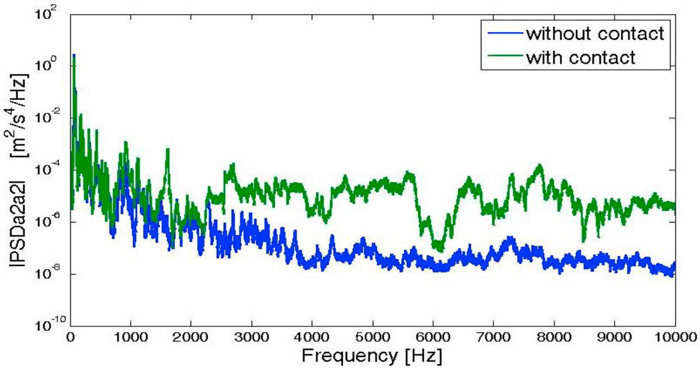

Fig. 2: Overlapping of the acceleration spectrum on the structure with and without contact between the U beam and the mass-spring system

In particular, for the application in the SHM, the shaker can simulate the ambient noise on the structure in which there is a defect; the secondary acoustic field produced in a large frequency range by the SAS can then be used as the input noise for passive defect detection based on acoustic noise correlation [9,10]. This kind of structural monitoring becomes completely passive thanks to the exploitation of part of the energy the ambient acoustic field (engine noise, aerodynamic noise …).

3. Approach to quantify the energy flow

To optimize the energy transfer and to characterize the SAS, it is necessary to realize a quantification of the power flows between the structure and the SAS within the different frequency bands. The definition of power flow between substructures is subjected to the knowledge of the velocity and the force at the connection point. The excitation from the SAS will be considered as an external force, knowing that the insertion of the SAS does not change significantly the dynamics of the structure (Fig. 3). The forces at point 1 and 2 have been calculated with an identification method and then compared with the measured forces. The will of calculating the excitation forces with an inverse method lies in the technical restrictions to introduce a transducer in real applications.

3.1. Identification of exchanged forces

The forces on the structure are defined from equation 1, which describes the relation between inputs and outputs in a system subjected to a random excitation [11]:

$$S_{aa} = H^c \, S_{ff} \, H^t \tag{1}$$

The input of the system is represented by the PSD of the forces, $\mathbf{S_{ff}}$, while the output is the PSD of the accelerations, $\mathbf{S_{aa}}$. **H** is the transfer function of the system (inertance), with $\mathbf{H^c}$ its conjugate and $\mathbf{H^t}$ its transpose. Considering only two points of the plate, the dimensions of the matrix shown in equation 1 are 2x2. To define the forces from the knowledge of the accelerations, equation 1 has been inverted:

$$S_{ff} = (H^c)^{-1} S_{aa} (H^t)^{-1} \tag{2}$$

Equation 2 has been used to calculate the PSD of forces at point 1 (connection with the shaker) and at point 2 (connection with the SAS) knowing the accelerations in the same points.

3.2. Quantification of power flow

The quantification of power flow has been computed to characterize the SAS, defining the quantity of energy that is absorbed by the SAS and the quantity reinjected into the structure. The computing of power flow is subsequent to the definition of the CPSD (Cross Power Spectral Density) between the force and the velocity S_{fv} [11], as shown in equation 3.

$$S_{fv} = M\, S_{ff} \tag{3}$$

In equation 3, **M** represents the mobility matrix of the system, retrieved by the inertance matrix **H**. Multiplying the mobility by the known force spectrum $\mathbf{S_{ff}}$, it is then possible to calculate the $\mathbf{S_{fv}}$.

$$P = \int real(S_{fv})df \tag{4}$$

Equation 4 shows the relation between the power flow P and $\mathbf{S_{fv}}$ [11]. The integral has been computed within two different frequency bands: the band of excitation (ambient vibration field) and the higher frequency band. A positive sign of the power flows means a flow direction from the shaker to the structure at point 1, and absorbed by the SAS in point 2. A negative sign characterizes instead a power flow from the SAS to the structure in point 2, meaning a power reinjection into the structure within the secondary acoustic field.

4. Excitation from the secondary acoustic source

As stated before, the identification of the force injected in the structure is a necessary step to quantify the power flows between the structure and the SAS. Two external forces are applied to the structure: the force generated by the shaker in point 1 and the broadband excitation produced by the SAS in presence of contact between the main and the secondary resonators. The accelerations are determined by placing two accelerometers on the structure. The force applied at point 1 is a white noise in the frequency band [60-90 Hz].

4.1. Dynamics of the system

The exploitation of equation 2 to retrieve the forces is subjected to the hypothesis that both the excitations can be treated as external forces. To assure this condition, the FRFs of the structure have been measured in two conditions: with and without the presence of the SAS at point 2. Fig. 3 shows the frequency response at point 1 and 2 for the two cases: the presence of the SAS doesn't affect significantly the dynamic of the system, then the force produced at the connection with the SAS will be considered as an external force directly applied to the structure.

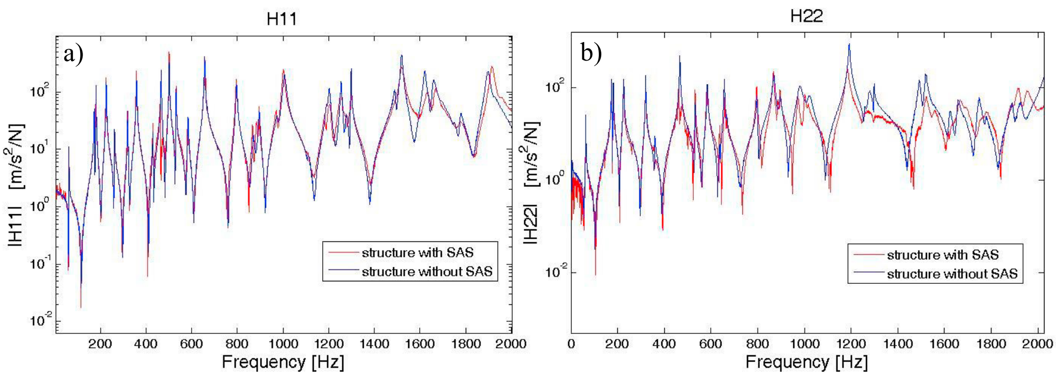

Fig. 3: Comparison of dynamic structure response with and without the presence of the SAS. a) H11, measured at the point 1 b) H22, measured at point 2

4.2. Calculation of the forces

Fig.4 presents a comparison between the forces calculated (blue line) by equation 2 and the forces measured experimentally by the force transducers (red line). The left figure shows the force from the shaker (point 1), while the right one the force between the structure and the SAS. In this configuration the tip of the U beam is in contact with the spring-mass system, so that the SAS generates a broadband excitation. The signal calculated by the acceleration and the inertance has a good correspondence with the measured one; it is then possible to retrieve the excitation provided by the SAS from the inversion of the transfer matrix. For the future analysis and applications the use of the transducer interposed between the plate and the SAS can be avoided.

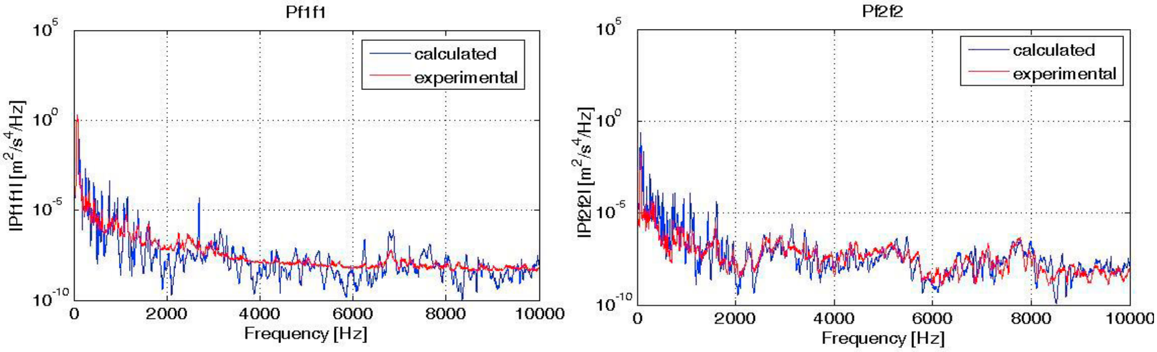

Fig. 4: Comparison between the measured and the computed forces in term of PSD for point 1 and point 2. The forces are measured in presence of contact between the U beam and the mass spring system.

5. Quantification of the power flows

The quantification of power flow allows to characterize the efficiency of the SAS, quantifying the power reinjected into the structure by the SAS within the secondary acoustic field. The power flows are computed exploiting equation 3 and equation 4; for this analysis, the forces measured experimentally are used. Fig. 5 and Fig.6 show the quantity of exchanged power by means of bar graphs. The integration bands chosen for the power flow are two: the excitation band, between 60 Hz and 90 Hz (left), and the higher band, from 91 Hz to 10000 Hz (right).

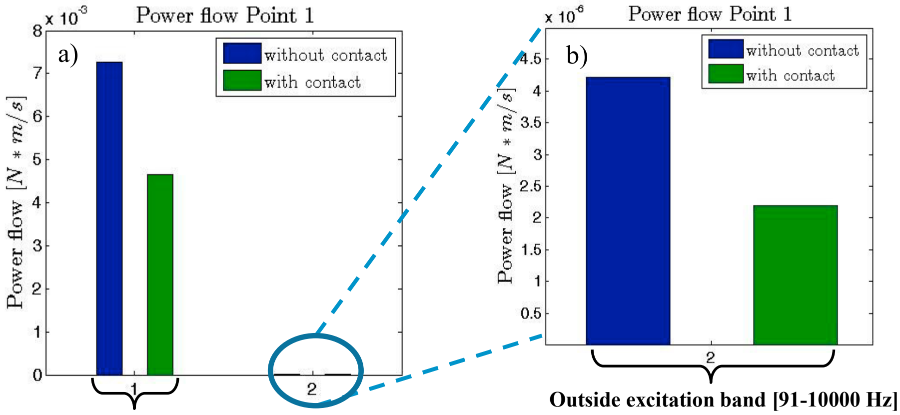

Fig. 5: Power flows inside the excitation band (60-90 Hz) (a) and outside the excitation band for point 1 (b). The green bar represents the condition with frictional contact in the SAS, while the blue bar the case without contact.

Fig. 5 presents the flows in point 1 (connection with the shaker) in presence and in absence of contact between the main and the secondary resonator of SAS. The flows are positive for both cases, and the power is injected from the shaker into the structure. At point 1 the quantity of power exchanged outside the excitation band is mainly due by the interaction between the shaker excitation and the dynamic response of the structure.

Fig. 6 shows the power flow at the connection between the structure and the SAS (point 2): into the excitation band (ambient noise) the power has a positive sign, i.e. the structure injects power into the SAS; outside the excitation band, instead, the sign is inversed. The negative sign identifies a flow from the SAS to the structure, quantifying the power

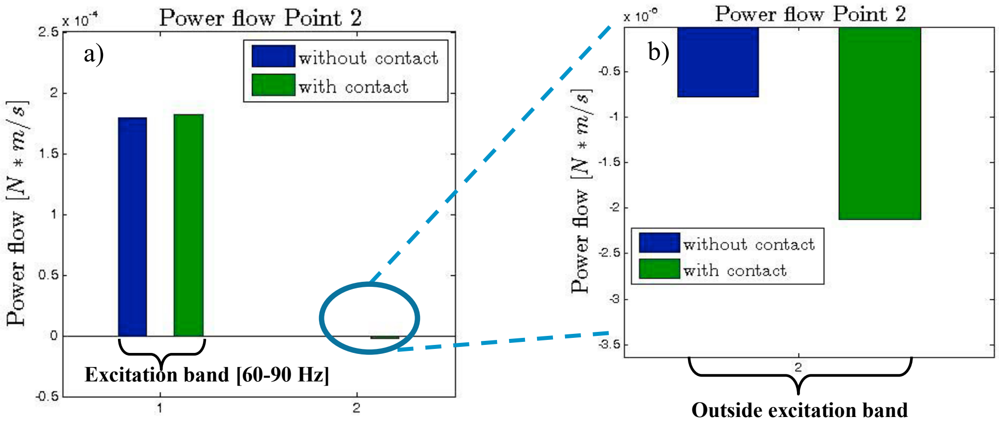

Fig. 6: Experimental power flow inside the excitation band (60-90 Hz) (a) and outside the band for point 2 (b).

reinjected into the structure by the broadband excitation produced at the contact interface. In absence of contact there is a small quantity of power reinjected, due to the dynamic response of the system; in presence of contact there is a substantial increase of the power reinjected into the structure, due to the broadband excitation generated at the contact.

Conclusions

This work focused on the exploitation of friction-induced vibrations to transfer the energy from a known frequency band (ambient acoustic field) to a higher and wider frequency band (secondary acoustic field). A test bench, composed by a structure and a secondary acoustic source (SAS), has been the object of the analysis. This paper proposes a method to retrieve the force and the energy flows produced by the SAS. First, the comparison between the measured forces and the computed ones, by the acceleration and the inertances, showed a good agreement. Then, a quantification of the power flows by the measured forces has been carried out. The results show that the presence of frictional contact between the main and the secondary resonators of the SAS, generating a broadband excitation, determines a power flow from the SAS to the structure in a wide frequency band. Future analyses will be addressed to the exploitation of the computed forces instead of the experimental ones and to the optimization of the energy transfer by searching for the optimal contact conditions and device dynamics.

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