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DESIGN OF A MODULAR SUSPENSION RIG FOR AEROELASTIC STUDIES IN A WIND TUNNEL

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Abstract. *A new modular suspension system for aeroelastic studies in wind tunnels is presented. Although it was initially designed for sectional bridge tests, the whole system proved to be versatile and therefore useful for many investigations concerning aeroelastic phenomena. The structure was made of commercial aluminum beams in order to be easily adaptable for different configurations. In-house designed air bearings were machined and tested to verify their load capacities. The translational system was tested, resulting in 0,2% damping ratios up to 40 N of radial load on the bearing. The substitution of the rotational air bearings for low damping ball bearings might be necessary when dealing with larger and heavier models. The alignment of the air bearings proved to be a challenge as a consequence of the tight tolerances required.*
Keywords: *suspension rig, aeroelastic phenomena, wind tunnel, air bearing*

1. INTRODUCTION

The design of a new modular suspension rig for aeroelastic investigations in wind tunnels is presented. The apparatus employs in-house designed air bearings with very low damping. Although the design of the whole system considered two independent degrees of freedom (2-DOF) — because it was initially developed for wind tunnel studies of bridge sectional models — the air bearings were designed in a way that the system can be assembled in other configurations.

The idea for the apparatus came from some problems found during a bridge sectional test performed at the boundary layer wind tunnel of the Institute for Technological Research (IPT), located in São Paulo, Brazil. Many papers in the literature provide insight into the aeroelastic phenomena concerning bridges, usually flutter and vortex-induced vibration. Some of them are related to the identification techniques of flutter derivatives in wind tunnels, such as Ding et al. (2010), Bartoli et al. (2009), Pina and Caracoglia (2009), Janesupasaeree and Boonyapinyo (2009) and Chowdhurry and Sarkar (2003). Others are concerned with the comparisons of the flutter derivatives obtained in different laboratories for some reference geometry (Sarkar et al., 2009) and (Caracoglia et al., 2009) or studies of specific cases, such as Zhu et al. (2002) and Starossek et al. (2009).

As highlighted before, the new system designed and built in IPT will be useful for other aeroelastic studies. It can be applied for VIV, galloping, flutter as well as buffeting investigations, provided that the model weight and the dynamic forces are small enough to keep the low mechanical damping. The beneficial aspect of using air bearings is the possibility to restrain unwanted degrees of freedom maintaining very low mechanical damping. Sarkar et al. (2004) designed a suspension rig specific for bridge applications using commercial porous air bearings. The present suspension rig, on the other hand, is composed of in-house designed air bearings to allow for the desired versatility of the apparatus. Two kinds of air bearings were constructed for the rig proposed, one to deal with radial loads and the other to deal with both axial and radial loads.

2. THE SUSPENSION RIG DESIGN

The whole idea behind the suspension system was to use air bearings in order to increase stiffness, restrain undesirable degrees of freedom and keep mass and structural damping to a minimum. Air bearings were designed for both heaving and torsional movements. A design parameter was to keep everything modular so experiments can be done using just the heaving motions, just the torsion motions or both heaving and torsion motions simultaneously. Also, other DOF can be added and different configurations can be made with little extra effort.

Initially, the rig was designed to deal with free-vibration techniques but some changes can be made in the future to work with forced-vibration techniques as well.

2.1 Air bearings

Air bearings that restrict radial translation (linear air bearings) and both radial and axial translations (rotational air bearings) were designed for the suspension rig. Numerical studies, based on simplified versions of the models proposed by Czolczynski (1999), have been performed in order to determine some geometric parameters, such as bush-tube clearance, diameter and position of the feeding holes, bushing inner diameter and length. After these studies, the inner diameter chosen was 40 mm with a diameter/length ratio equals to 1. Feeding holes of 1 mm were drilled in two lines of 12 holes each. Each line was located 10 mm from one of the bush edges.

The tolerance class was carefully chosen because sufficient clearance between the bush and the tube that runs inside it must always be provided. On the other hand, this clearance cannot be too big so pressure is high enough to withstand the acting loads. Therefore, the tolerance chosen was H6/f6, which, for 40 mm, corresponds to a fluid film between 12.5 μm and 28.5 μm

A mock-up of the linear air bearing was machined to validate the initial concept. All parameters were kept the same for the rotational air bearing, but some geometric changes, which will be explained below, were necessary to provide the restraints desired.

The final linear air bearing is composed of 3 main elements identified in Fig. 1. The element number 1 is the housing cover. It is fixed on the housing (element 3) and prevents the axial motion of the bearing bush (identified by number 2). The lateral openings that can be seen in the covers act like jet deflectors, avoiding extra damping near the end of the tube that runs inside the air bearings. The housing is a central piece that provides the interface between the bearing and the rig. All bearing parts were made of aluminum to reduce the sprung mass, apart from the bush which was made of brass. No touch between the brass bush and the aluminum tube is expected, but better to have different materials and the brass self lubricating properties can be beneficial in such situations.

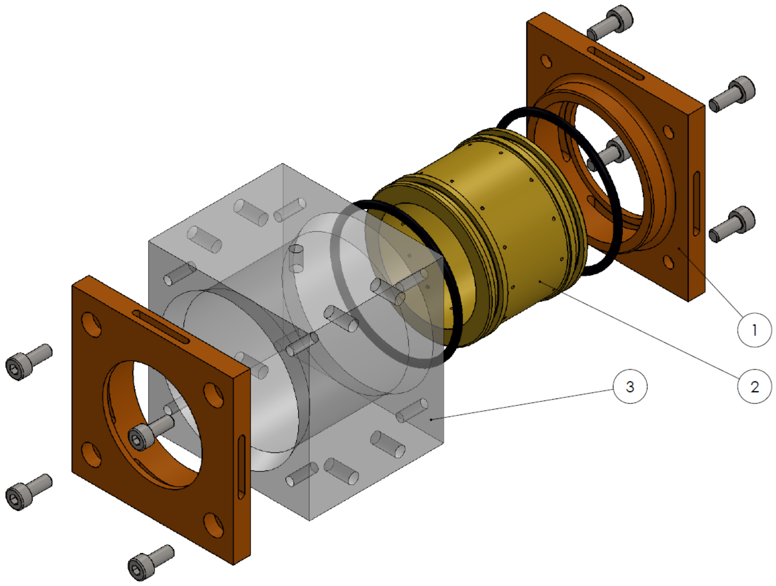

Figure 1. Exploded view drawing of the linear air bearing: (1) cover with jet deflectors, (2) bearing bush and (3) housing.

A prototype of the linear air bearing was machined and tested as mentioned before. A six-component RUAG load cell was used with this purpose. A steel cable linked the bearing to the load cell as shown in Fig. 2. For each pressure inlet the radial load on the air bearing was increased (by increasing tension on the steel cable) until the bearing could not move due to excessive friction. Table 1 shows the results obtained and takes into account the bearing weight of 8.2 N.

Table 1. Air bearing load test results

Pressure inlet ($\times 10^5$ Pa)	2	3	4	5	6	7	8
Maximum load (N)	23	39	62	88	128	163	198

The main design parameters for the rotational air bearing were the same of the linear air bearing. The inner diameter, total length, feeding hole diameters and tolerances were all the same. However, some geometric differences can be seen

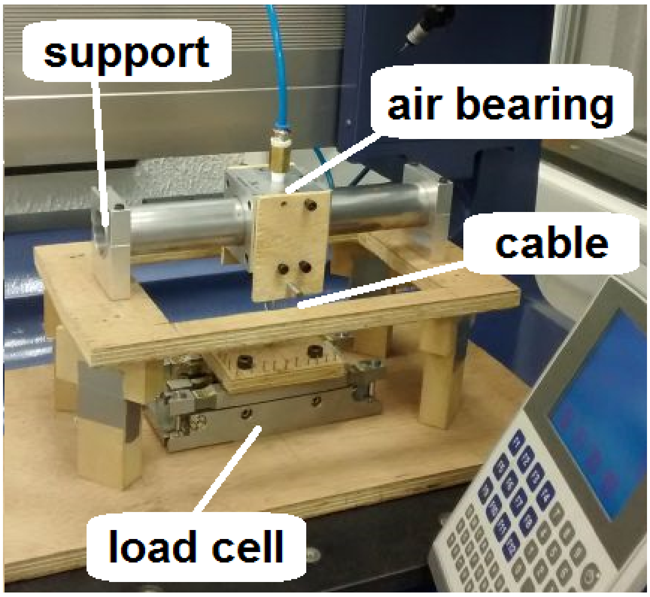

Figure 2. Linear air bearing load test.

in Fig. 3 as a consequence of the restraints required for this air bearing. The main elements are the same, but the housing covers (element number 4) were made smaller and the assembly is composed of two additional pieces, identified by numbers 1 and 5, which restrain the axial motion. Moreover, the bush laterals were made wider and with 24 additional feeding holes on each side.

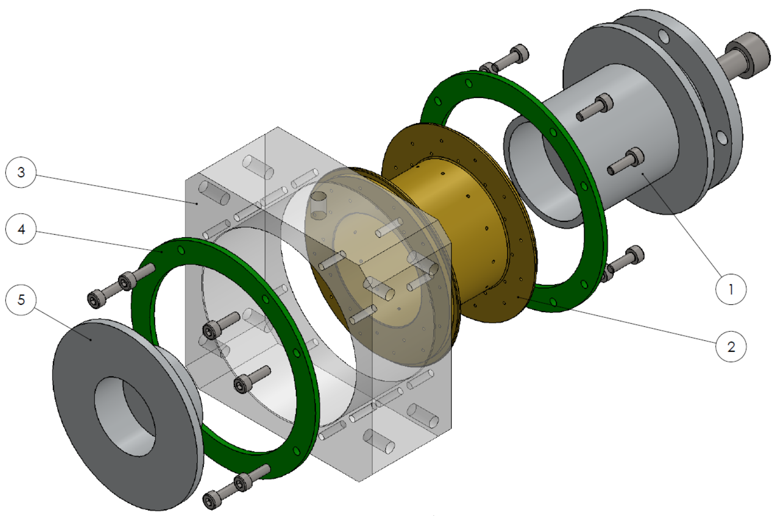

Figure 3. Exploded view drawing of the rotational air bearing: (1) internal tube with traverse support, (2) bearing bush, (3) housing, (4) bush stop and (5) element that restrains axial motion and controls lateral clearance.

During the rotational bearing tests it was observed that the additional feeding holes drilled on the bushing laterals made the system withstand greater axial loads but reduced the radial load capacity. Therefore, one can choose to have the lateral feeding holes opened or covered depending on the phenomena studied and on the experimental configuration. Moreover, the element that controls the lateral clearance, indicated by number 5, can be eliminated depending on the apparatus configuration.

For the configuration shown in this paper, the lateral feeding holes were closed so the air bearing could provide greater radial load capacity. The element number 5 (Fig. 3) was also discarded because the alignment without it proved to be easier.

Figure 4. Lateral feeding holes covered for greater radial loads.

2.2 Translational and rotational systems

Linear and and rotational air bearings were assembled as independent modules, so translation and rotation of the system could be easily added or removed depending on the experiment to be done. This was a design input regarding rig's ability to deal with different aeroelastic problems.

The translational system is basically composed of linear air bearings and tubes that run inside them and support the rotational system. Coil springs connect the tubes to the main frame and provide the heaving stiffness desired. Figure 5 shows the exploded view of one side of the translational system.

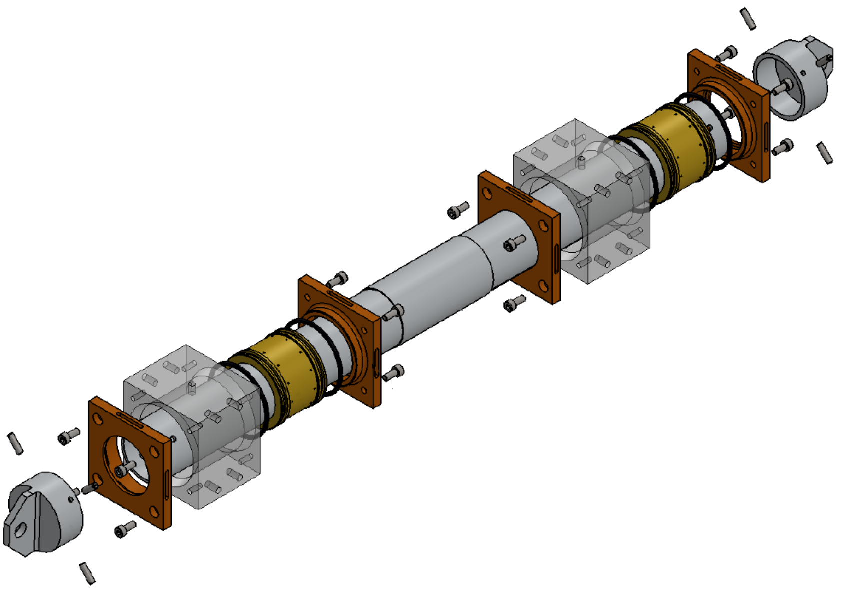

Figure 5. Exploded view of one side of the translational system.

The rotational system is attached to the aluminum tubes of the translational system by the element number 1 of the Fig. 6. It has many elements other than the rotational air bearings.

With the traverse in blue, identified by number 2, it is possible not only to connect the model to the rig, but also to set the torsional stiffness, the mass and the mass moment of inertia by correctly positioning coil springs and blocks of known masses. Moreover, the angle of attack can be changed with 1° resolution using the positioning holes shown in Fig. 7. This figure indicates the purpose of each element on the traverse.

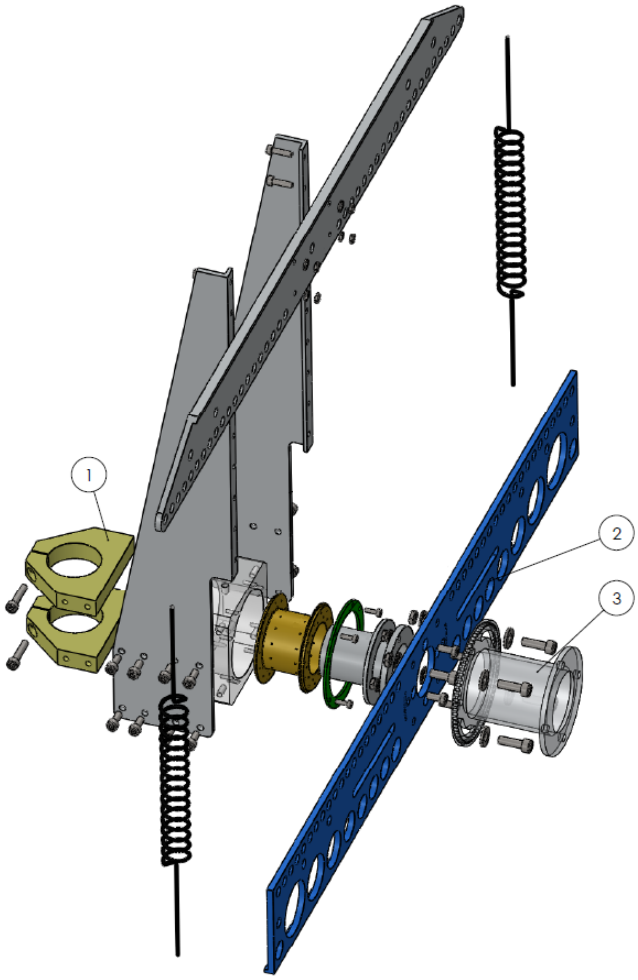

Figure 6. Exploded view of one side of the rotational system: (1) elements that conect the rotational system to the translational system, (2) main traverse and (3) model connection.

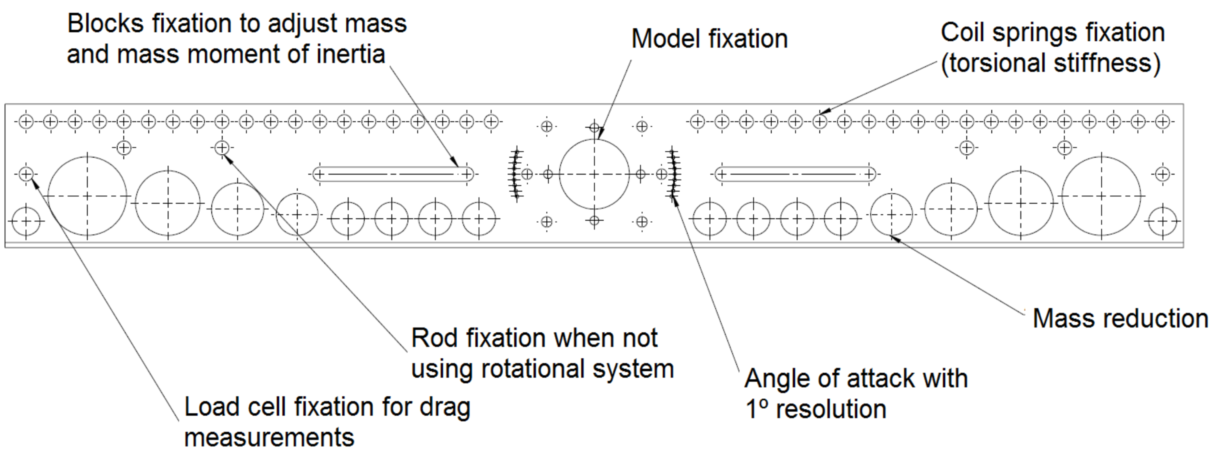

Figure 7. Traverse elements.

2.3 Frame

The frame was constructed with commercial aluminum beams, providing easy attachment of many elements such as springs, displacement sensors and load cells. When everything is put together, the result is the apparatus shown in Fig. 8. This configuration can be used to explore vortex-induced vibration, galloping and flutter of different geometries. For VIV and galloping studies just the heaving motions are required so the coil springs shown in Fig. 6 should be substituted by rods. The whole rotational system can be eliminated if the sprung mass is a problem. If that is the case the model must be connected directly to the aluminum tube of the translational system.

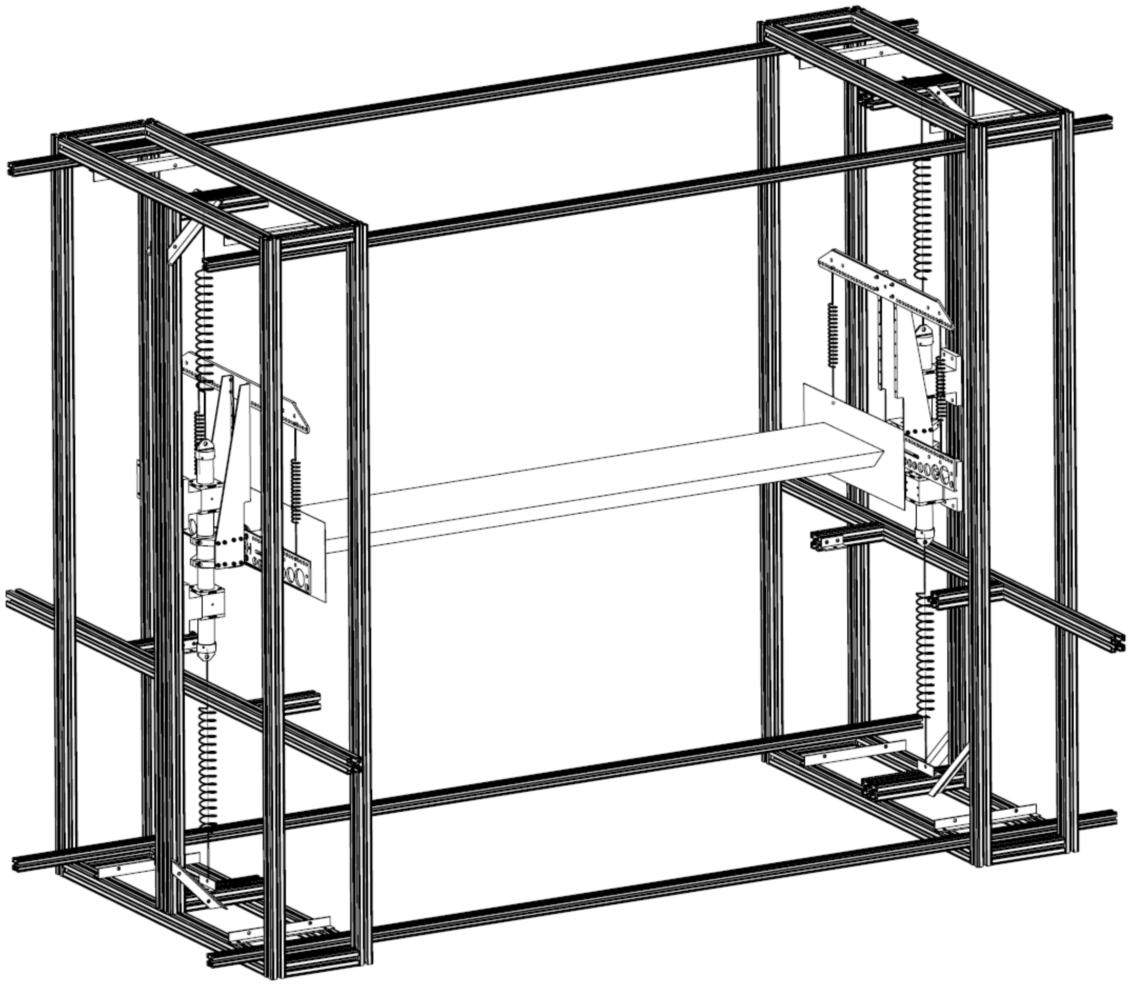

Figure 8. 3d view of the complete system designed and configured for bridge application.

3. RESULTS AND DISCUSSION

The alignment proved to be a challenge as the tolerance between the bearing bush an the tube had to be very tight in order to produced enough pressure to support the static and dynamic loads. Therefore, each air bearing was mounted on a rubber base.

After the translational system was completely installed, it was verified if the drag force would not produce additional damping as the bushes are forced against the tubes walls. A test similar to that of the singular air bearing was done. A long cable was used to prevent additional damping. The system was put to oscillate with different loads and the damping ratios were identified using a Iterative-Least Squares technique. Three measurements were done and the mean values of damping ratio against the applied load are presented in Fig. 9.

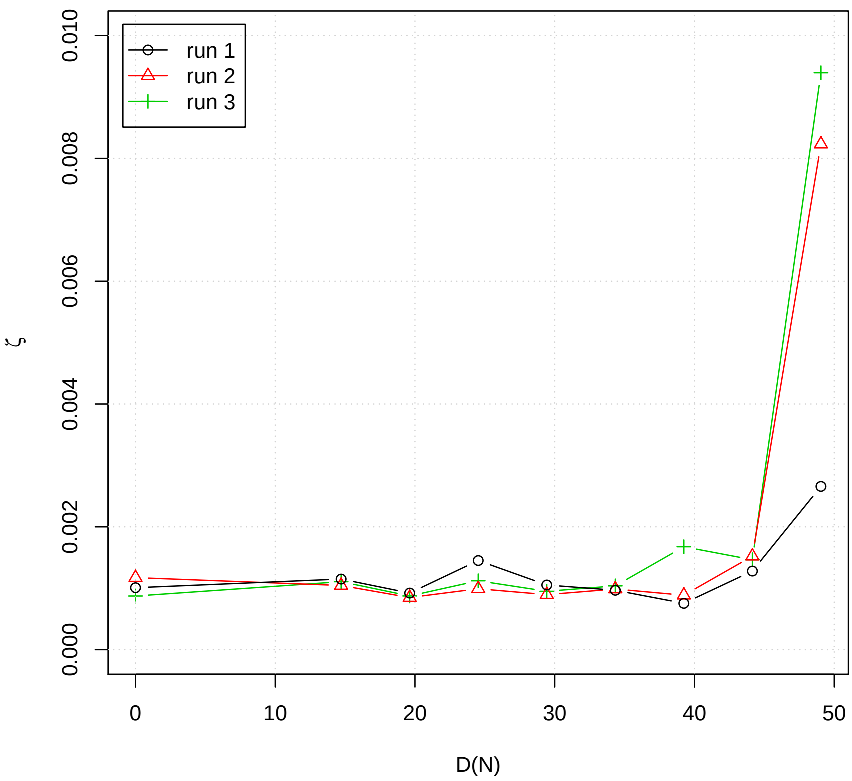

Figure 9. Damping ratios against applied loads.

Figure 9 shows that for drag forces up to 40 N the damping ratio is kept constant and below 0.2% (for heaving motion only). This load is sensitive to the alignment done. Therefore, damping should be investigated each time the system is mounted, which is clearly a disadvantage of the rig proposed. However, it can be seen that for dynamic forces up to a limit value, the mechanical damping is kept really small, which is interesting for many aeroelastic studies such as bridge deck investigations.

Just a few tests were done with the rotational system. Generally speaking it performed well for small models. The mechanical damping ratio was always kept below 1% in those situations but it was observed that some problems may arise for bigger and heavier models. Exchanging the rotational air bearings by low damping ball bearings might be an interesting solution. The whole system would withstand greater loads and some alignment issues could be solved as well.

Table 2 shows the mechanical characteristics of an example with 2-DOF. These properties are measured without any air flow. The air flow will change the original mass, stiffness and damping matrices. In fact, when dealing with free-vibration techniques, system identification techniques such as the Iterative-Least Squares are required to identify these matrices and then separate the aerodynamic contribution.

Table 2. Mechanical characteristics of an example using 2-DOF

	m	k	ζ	f
Heaving	9.06 kg	3146.16 N/m	0.15%	2.97 Hz
Torsion	0.0502 kg.m^2	38.94 N.m/rad	0.64%	4.43 Hz

4. CONCLUSION

From the analysis performed it was found that the suspension system proposed works well for heaving motion. Therefore, it will be useful when investigating galloping and vortex-induced vibrations of prismatic structures.

The air bearing system employed for the torsional motion is slightly different and its performance is strongly related to the weight of the model, considering the configuration presented. Therefore, more investigation is needed when working with both systems together, for example, during investigations of flutter and other torsional instabilities. It might be interesting to substitute the rotational air bearing by a low damping ball bearing depending on the situation. The tests done indicate that the substitution can be beneficial to both load capacity and alignment.

The aluminum support proved to be very versatile, in a way that other configurations could be adopted to investigate other phenomena, such as buffeting. Moreover, the instrumentation can be easily installed.

Although alignment was not easy to be done at first, air bearings eliminate efficiently the unwanted DOF without introducing much damping to the system up to a load limit.

5. ACKNOWLEDGEMENTS

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