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A comparison of the vibration characteristics of a rotating machine with a linear and a keyed shaft

F. Oliveira, G. Peláez, M. P. Donsión

Abstract -- **This paper presents some results of an ongoing work aimed at studying a number of characteristics of rotating machines and how they are influenced by both constructive features and the way they are driven. The following will present the main results obtained when a simple one-stage inertia turbomachine is built with a linear, cylindrical shaft or, instead, with a shaft that has a small slot such as those used in many mechanical couplings. Experimental results will show some significant differences in the behavior of the machine, both in terms of the orbit and in the resonance frequencies, as well as in the phase and amplitude of mechanical vibrations.**

***Index Terms*—Vibration measurement, Vibrations.**

I. Introduction

VIBRATION analysis and control of rotating machinery involves areas of active research including linear and non-linear shafts. Methods of vibration suppression at machinery startup or shutdown include increasing the damping of the system, stiffening the structure, developing a sophisticated controller *i.e.* automatic disk balancer including dynamic vibration absorbers and finally shaping the command signals.

The main focus of this paper will be on the mechanical response of a mechanical machine, comparing the behavior of the machine with a linear and a keyed rotor, based on the measurement of a number of mechanical variables and its integration in well-known mechanical models. The results thus obtained can then be used to test the theoretical models, estimate mechanical parameters more accurately and generally increase knowledge on the mechanical response of the prototype set.

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II. Laboratory Equipment

In order to study the influence of the electric supply to the motor on the overall behaviour of a mechanical load, a specially designed, dimensioned and built one-stage inertia flexible rotor (OSIFRO) set was used. This provided a simple mechanical load with a well-fitted (and well-known) dynamic model with which to work. Fig. 1 shows a view of the OSIFRO model.

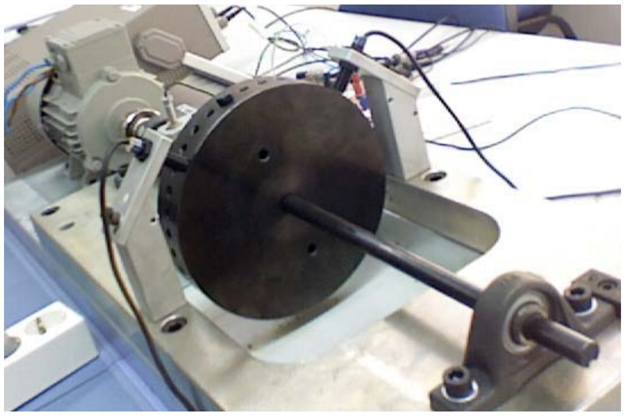

Fig. 1. A view of the OSIFRO

To drive the OSIFRO, a 0,37 kW squirrel-cage induction machine was connected using a three-phase input/output, 15 kVA programmable AC power source from California Instruments, which provided perfect voltage sine waves of a range of amplitudes and frequencies, used to sweep the rotational speeds in the desired range.

The OSIFRO mechanical load is constituted by a cylindrical inertia with either a flexible, non-linear (keyed) shaft or a cylindrical, linear shaft. This mechanical load is, in any case, intrinsically slightly unbalanced, and adequate correction masses can be added to balance the rotor.

This work required a number of electrical and mechanical quantities to be measured. In order to acquire and accommodate the several quantities to be measured, a PC-based, high-precision data acquisition card was used, along with voltage and current active probes, accelerometers, proximity inductive sensors and a keyphasor.

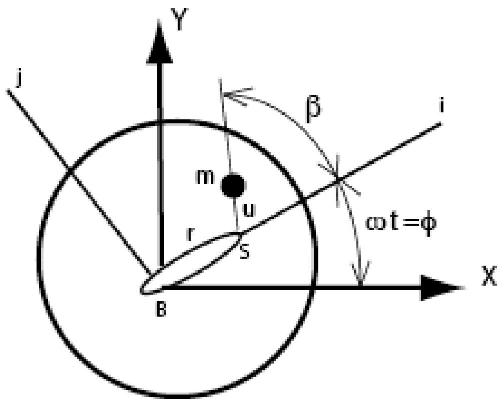

Fig. 2. One degree of freedom Jeffcot model for the flexible rotor over rigid bearings

Fig. 2 depicts the one degree of freedom Jeffcot model for

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the flexible rotor over rigid bearings, and fig. 3 shows the corresponding modelled natural frequency; due to the simplifications of the Jeffcot model, this natural frequency is valid for both the linear and the keyed shaft.

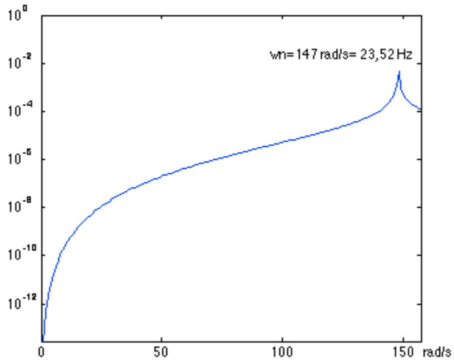


Fig. 3. Natural frequency for the OSIFRO obtained from the Jeffcot model

III. . EXPERIMENTAL TESTS AND RESULTS

In order to study the behaviour of the mechanical load connected to the induction motor, a number of trials were devised and performed for both the linear rotor and the keyed rotor, and the main results are presented in this section.

Firstly, in both cases the rotor had to be balanced using the methods described in [2] and applied in [1], so that the crossing of the natural frequency of the OSIFRO would cause a lesser strain on the shaft and bearings of the machine, especially important in the case of the keyed shaft. With this process completed, a thorough frequency sweep was conducted, for both natural response and forced response.

Figs. 4 a) to 4 c) depict the unforced frequency response in the case of the linear rotor, with a starting point above the main resonance; the machine is then left to free-wheel stop, sweeping through all frequencies (including the main resonance) – (blue - keyphasor signal; green and red – distance to the shaft in the x and y directions of figure 2)

In fig. 4 a) there seems to be a very slight sub-harmonic resonance, visible on the right side of the figure, which is probably due to the small slots needed for the couplings

Fig. 5 depicts the unforced frequency response in the case of the keyed rotor, again sweeping all frequencies from above the main resonance down to free-wheel stop.

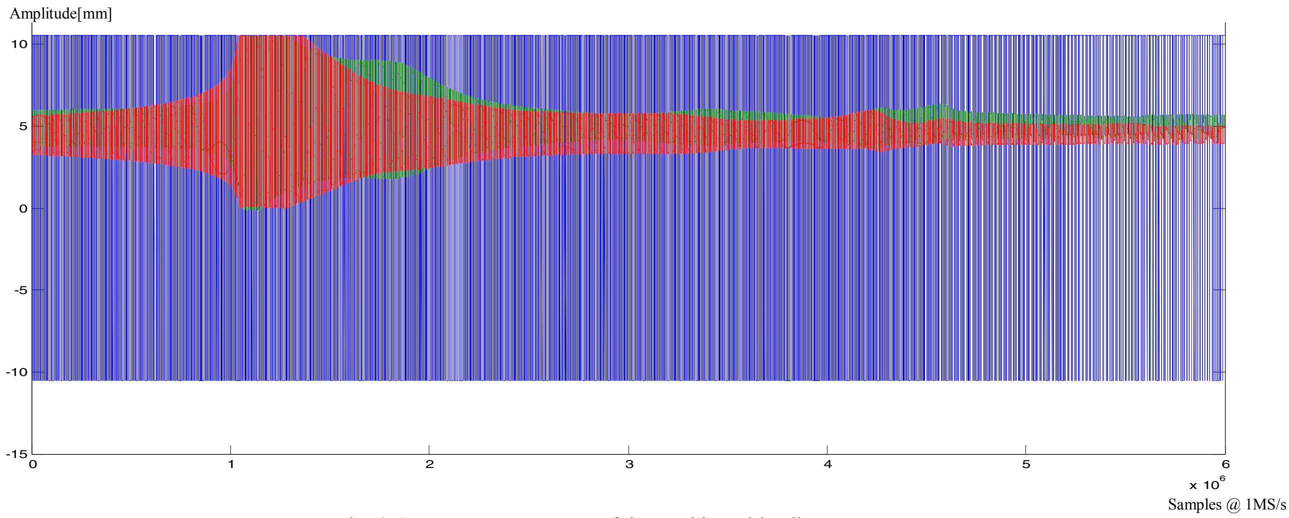


Fig. 4 a). Frequency response of the machine with a linear rotor.

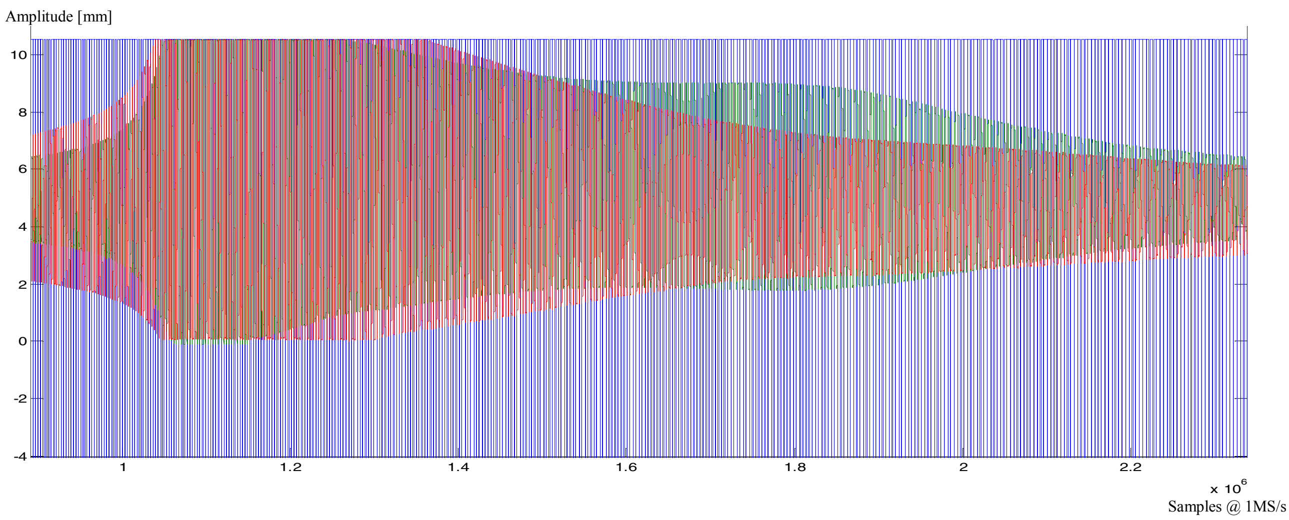


Fig. 4 b). Frequency response of the machine with a linear rotor – zoom in on the main resonance

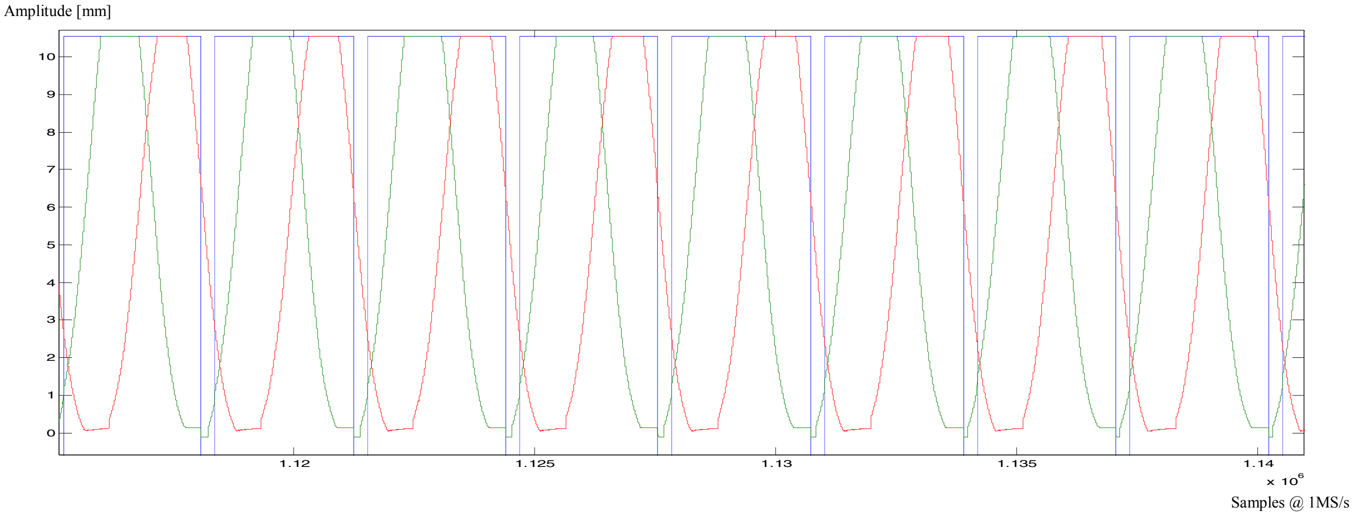
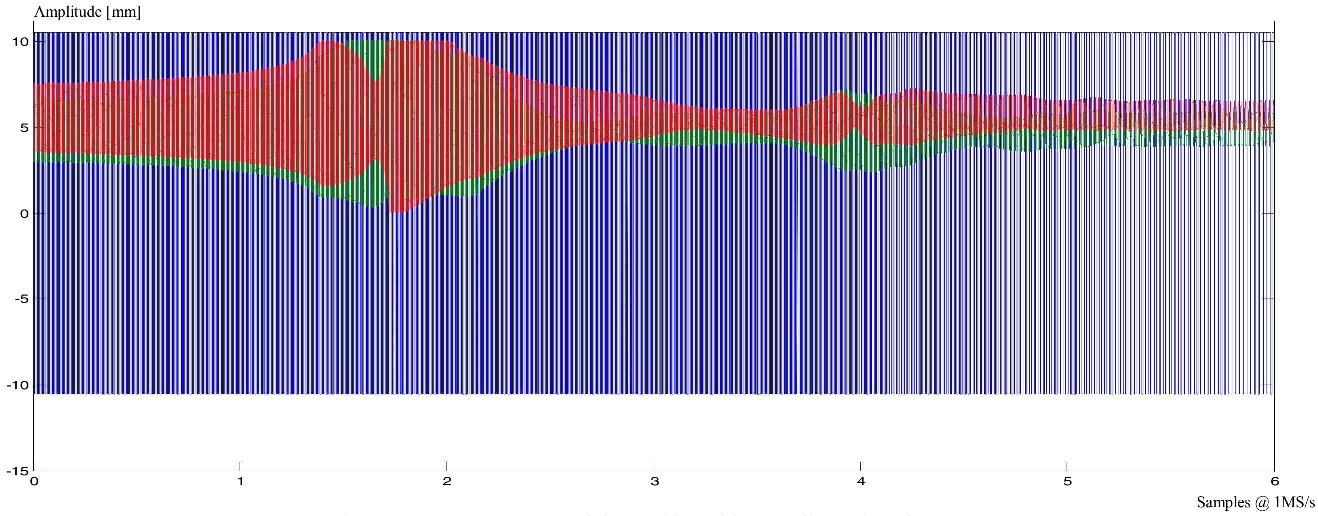


Fig. 4 c). Frequency response of the machine with a linear rotor – detail of the main resonance.



. Fig. 5. Frequency response of the machine with a non-linear, keyed rotor.

In this case, a sub-harmonic is very clearly visible, highlighting the fact that it is due to the non-linearity of the keyed rotor. Also, vibration levels at the lower frequencies are also higher than in the case of the linear rotor, which is not so clearly the case near the resonance frequency, since the machine was balanced for this frequency.

Furthermore, both the main resonance and the sub-harmonic resonances seem to be "double", that is, there is an overlap phenomenon in both of them, resulting in an added difficulty to find the actual natural frequency from the data.

An important detail is that, both for the linear and the non-linear shaft, the phase of the mechanical vibrations, *i.e.* the angular distance to the minimum distance to probes X and Y, changes throughout the sweep, making a near-180° sweep when crossing the main resonance. This is visible in figs. 6 and 7.

Fig. 6 shows the frequency response of the machine with the linear rotor in terms of phase and amplitude, and fig. 7 shows the same characteristic for the non-linear keyed rotor.

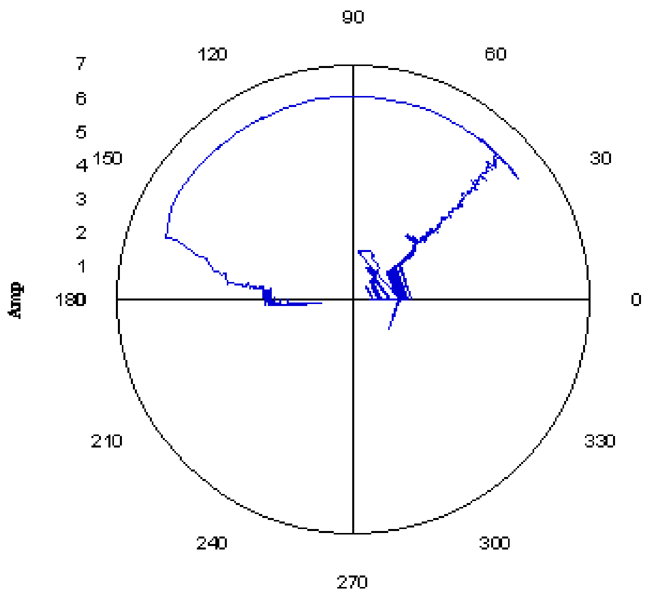


Fig. 6. Phase-amplitude polar plot of mechanical vibrations for the linear rotor (phase in degrees; amplitude in mm)

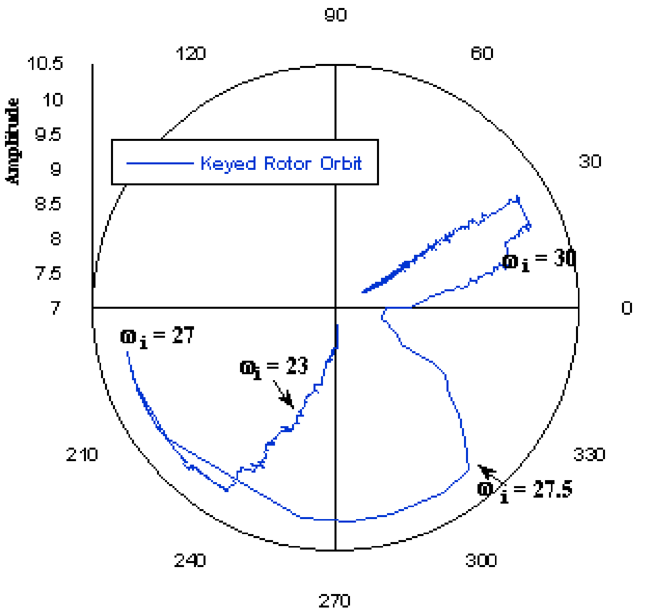


Fig. 7. Phase-amplitude polar plot of mechanical vibrations for the non-linear keyed rotor (phase in degrees; amplitude in mm)

Comparing figs. 6 and 7, it is patent that the phase-amplitude behavior of the linear rotor is much "smoother", where the non-linear keyed rotor show some twists when approaching the lower frequencies. It is also visible that the 180º-sweep does not occur during the sub-harmonic resonance in the non-linear rotor.

On the other hand, the linear rotor "orbit" resembles the theoretical model in [1].

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IV. Conclusions and Outlook

The work presented here shows a comparison between a linear rotor and one with a slot that creates a non-linearity, and the results show significant differences in the behavior of the machine concerning mechanical vibrations.

The non-linearity of the keyed rotor has a number of effects, namely changing the main resonance frequency and adding an extra sub-harmonic resonance that causes added strain to the equipments and materials.

Also, because important changes to the phase plot occur when the keyed rotor is in place, vibration amplitude is much more significant, even when the rotor had been balanced in order to reduce vibrations.

Results also imply that even small constructive characteristics in a machine, such as the slots used for couplings, can have significant effects in the machine behavior, and that those effects are difficult to predict using theoretical models.

The conclusions drawn and the methods used can then be also used for other machines, including larger scale machines.

V. References

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