On Non-Ideal Simple Portal Frame Structural Model: Experimental Results Under A Non-Ideal Excitation

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**Abstract**

We present measurements of the non-linear oscillations of a portal frame foundation for a non-ideal motor. We consider a three-time redundant structure with two columns, clamped in their bases and a horizontal beam. An electrical unbalanced motor is mounted at mid span of the beam. Two non-linear phenomena are studied: a) mode saturation and energy transfer between modes; b) interaction between high amplitude motions of the structure and the rotation regime of a real limited power motor. The dynamic characteristics of the structure were chosen to have one-to-two internal resonance between the anti-symmetrical mode (sway motions) and the first symmetrical mode natural frequencies. As the excitation frequency reaches near resonance conditions with the 2nd natural frequency, the amplitude of this mode grows up to a certain level and then it saturates. The surplus energy pumped into the system is transferred to the sway mode, which experiences a sudden increase in its amplitude. Energy is transformed from low amplitude high frequency motion into high amplitude low frequency motion. Such a transformation is potentially dangerous.

We consider the fact that real motors, such as the one used in this study, have limited power output. In this case, this energy source is said to be non-ideal, in contrast to the ideal source whose amplitude and frequency are independent of the motion of the structure. Our experimental research detected the Sommerfeld Effect: as the motor accelerates to reach near resonant conditions, a considerable part of its output energy is consumed to generate large amplitude motions of the structure and not to increase its own angular speed. For certain parameters of the system, the motor can get stuck at resonance not having enough power to reach higher rotation regimes. If some more power is available, jump phenomena may occur from near resonance to considerably higher motor speed regimes, no stable motions being possible between these two.

**Introduction**

Usually, an experimental structural analysis supposes that the excitation devices are ideal or, in other words, non-dependent of the dynamic response of that structure. Electric motors are an example of non-ideal excitation devices, because the mechanical output power depends on the motion of its armature and on the dynamic characteristics of its rotor, among other factors. When motors are attached to structures that need excitation power levels similar to the power capacity of those motors, interesting non-linear phenomena may happen, such as: modal saturation and Sommerfeld effect. There are excellent theoretical and experimental researches about this subject; the well known ones, but not recent, are: [1], [2], [3], [4] and [5]. Some researchers have carried out theoretical and experimental analyses of portal frames excited by non-ideal excitation devices [6], [7] and [8]. A first announcement of this work was done in [8].

A non-linear experimental analysis of a metallic portal frame excited by a DC motor is presented in this work. The two columns of the structure were clamped in their bases to a large seismic mass and the motor was attached to the center of the horizontal beam. In order to allow for non-linear phenomena observation possible, the dimensions of the structure were chosen in such a way that there was a ratio of one-to-two between the first two frequencies of the first two natural modes (anti-symmetrical or sway mode and symmetrical or bending mode); for the same reason, all joints between the columns and the horizontal beam were welded, in order to
reduce the structural damping. Modal saturation, Sommerfeld effect and other interesting phenomena were observed by using modern experimental techniques.

**Experimental Set Up**

All tests were performed with the columns of the structure clamped to a seismic mass of 4000Kg, in a temperature-controlled room (See Fig 1). First, the structural system was analyzed with its motor turned off, in order to confirm the 1:2 ratio between the first two natural modes. Modal analysis was used to confirm the frequencies values as well as the mode shapes (nine low-weight accelerometers, a small electrodynamics shaker and a force transducer were attached to the structure; a digital data acquisition system recorded the dynamic signals). Free vibration tests were also performed. Vertical and horizontal static displacements were independently set and, right after, suddenly released by a device specially built for that purpose. Vertical and horizontal acceleration components in the middle of the horizontal beam were recorded during the motion dissipation. A third set of tests was carried out with the DC motor running. During those tests, the vertical and horizontal acceleration components in the middle of the horizontal beam were also obtained, as well as the electrical power characteristics delivered to the DC motor (current and voltage) and its angular velocity. Basically, the test procedure was the following: with the motor stopped, a certain voltage was set to the electric power supply and, at the same time, data acquisition was started. The test was considered ended when the motor reached a constant angular velocity. Finally, some tests were carried out with the DC motor running, passing through the second system resonance. The same physical parameters obtained in the previous tests were recorded (accelerations, angular velocity of the motor, voltage and electric current). The characteristics of the instrumentation used during the tests played an important role in the acquisition of useful dynamic data. Some details are mentioned below. ICP accelerometers were used in order to reduce low frequency noise, usually found when the piezoelectric type is used. Besides, pre-amplifiers with filters guaranteed a good signal-to-noise ratio between 1 to 1000Hz. A fast optical encoder was used to get the angular velocity of the DC motor. By this sensor, it was possible to observe small variations of rpm every 1/12 of turn of the rotor. A low noise, fast, simultaneous multi-channel data acquisition was fundamental to get reliable dynamic data. The PC-based equipment used had four channels, 85 dB signal-to-noise ratios and a variable sampling rate (up to 44KHz).

![Fig 1: Multiple flash exposure of modal saturation phenomenon in the portal frame analyzed. Angular motor speed: 1298rpm; lateral acceleration in the middle of the horizontal beam: 23m/s²; vertical acceleration: 99.8m/s²; lateral sway frequency: 10.9Hz; vertical frequency: 21.8Hz.](image)
Results for Free Vibrations:

Fig 2: Acceleration peaks measured in the middle of the horizontal beam during free vibrations of the system. Initial horizontal static displacement: 4.0 ± 0.1 mm

![Fig 2](image1)

Fig 2 shows the horizontal and vertical acceleration component measured in the middle of the horizontal beam for an initial horizontal displacement of 4.0 ± 0.1 mm.

Results for Forced vibrations

Figs 3, 4 and 5 present the motor angular velocity and the acceleration peaks in the middle of the horizontal beam when a constant voltage is supplied to the motor. Three quite different dynamic behaviors can be observed, depending on how close the angular velocity of the motor is to the 2\(^{\text{nd}}\) system resonance

![Fig 3](image2)

Fig 3: Acceleration peaks in the middle of the horizontal beam during acceleration of the DC motor
Power Supply Voltage 2.70±0.05V
Fig 4: Acceleration peaks measured in the middle of the horizontal beam during acceleration of the motor. Power supply voltage: 2.83±0.05V.

Fig 5: Accelerations peaks measured in the middle of the horizontal beam during acceleration of the motor. Power supply voltage: 3.00±0.05V.

Fig 6 shows the occurrence of the modal saturation phenomenon. The sudden increase of the horizontal acceleration peak measured in the middle of the beam is observed; in the same instant, occurs a short variation of the vertical acceleration peak; during the phenomenon, the vertical acceleration stays stable. In the same figure, the rotation of the electric motor deserves special attention. Some variation is observed around the value corresponding to 2\textsuperscript{nd} resonance during elapsing of the modal saturation phenomenon.
Fig 6: Acceleration peaks measured at the middle of the beam during occurrence of the modal saturation phenomenon.

Fig 7 and 8 show the behavior of the measured behavior of the system during the passage through the 2nd resonance with increasing rotation of the motor. There is an instability zone near the resonance (shown shaded) where abrupt accelerations of the angular velocity of the electric motor were observed. When raising continually the electric tension delivered to the motor (when its angular velocity is close to the 2nd resonance of the system), its rotation is increased, until the moment that it is stabilized around a certain value (around the 2nd natural frequency of the system). Successive increments of the tension only elevate the electric power absorbed by the motor; all energy is used by the structural system to increase its vibration amplitudes. The process possesses a limit: when the structure is not more able to absorb the energy, a sudden increase of the angular velocity is observed. After a certain period, the rotation of the motor stabilizes at a proportional value to the feeding tension.

Fig 7 Electric power absorbed during motor Acceleration through 2nd mode resonance

Fig 8 Acceleration peaks in the middle of the beam during motor acceleration through 2nd mode resonance
Conclusions

Considering the results presented and several other experiences performed with the structure of Fig.8, some conclusions are drawn: modal saturation phenomenon can happen in structures subject to small displacements; in the analyzed case, the manifestation of that phenomenon was observed with displacements of the order of 1:200; changes of energy between the first two natural modes depends on the relationship between their frequencies and on the structural damping; the transients observed before and after the modal saturation phenomenon are related to those factors; Sommerfeld effect depends on the electric and dynamic characteristics of the motor; kinetic energy (stored in the flywheels and in the rotor) and torque (related to the feeding current, motor temperature and conditions of the brushes and of the collector) dictate the way as the motor will be captured by the resonance of the system, as well as the fast acceleration of the angular speed of the rotor after the modal saturation phenomenon; electric brush motors are not very well appropriate for the analysis of dynamic events as those presented in this work.; the commutator temperature and the incapacity of the system that presses the brushes against the commutator segments in keeping a constant pressure (when the structural system is in resonance) affects the observation of the Sommerfeld effect and of the modal saturation phenomenon. We also remarked that, in the general, the success of the kind of analysis presented here is due to three factors: to the judicious choices of the structural parameters, which allowed only two natural vibration modes to characterize the dynamic response of the system; to the constructive characteristics, which contributed to the reduction of the structural damping; to the instrumentation, which made it possible to record low amplitude transients and time-consuming phenomena. Although not presented here, many other non-linear phenomena were observed, such as: transfers of energy between the electric motor and the structure, transients during the deceleration of the motor, the dependence of non-linear phenomena with the excitation magnitude and the changes of energy between the first two vibration modes when the excitation frequency was close to the first natural mode.

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