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Experimental study of a methodology for the dynamic characterization of systems using unbalanced mass excitation

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ABSTRACT

The experimental determination of the frequency response functions in mechanical systems requires accurate experimental tests. In this paper, an experimental study of the optimal parameters of a sine sweep excitation generated by an unbalanced mass excitation device is presented. In order to evaluate the accuracy of the frequency response functions, non-parametric identification method is used to find a good signal-to-noise ratio and a best confidence region of the estimated frequency response functions. For this, an experimental test-rig based on mass-spring-damper system excited by an unbalanced mass excitation device has been designed and implemented at the laboratory. Then, linear sweep is used to control the rotating speed of the unbalanced system generating a sweep sine harmonic excitation. The proposed study of the experimental methodology demonstrates that excitation parameters such as amplitude, sweep rate and test

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time affect signal-to-noise ratio, reducing the accuracy of the measured frequency response functions in the case of noisy environment.

Keywords: Sweep rate, Non-parametric method, Noisy environment.
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1. INTRODUCTION

Nowadays, impact hammer or shaker testing are the usual methods for dynamic parameter identification of mechanical systems [1–4]. The main effect in characterization of the mechanical systems is distortion (bias error and variance) of FRF by sinusoidal sweep which resulting in a modification of the response envelope due to transient behavior. However, there are other distortion effects due to measurements of FRF with background noise and signal acquisition [5]. The nonparametric identification method is used to estimate the noise in the experimental measurements to obtain the FRF [6]. Measurements of input and output signal of the systems are made considering the background noise of experimentation site [7]. The sinusoidal sweep method is chosen due to high energy input and short test duration in the experimentation [8]. In addition, the excitation source attachment according to the system, the signal processing and the excitation control are determined [9]. This article investigates based on the experimental measurements the distortion of FRF minimization methodology due to the lower variance and good signal-to-noise ratio using an unbalanced mass device. In Section 2, the experimental methodology is explained considering the background noise and different sinusoidal sweep rates. In addition, the experimental tests of the LEAM-UPC laboratory are indicated considering different experimental parameters, the location of the eccentric mass and the rotation speed of the disc, as indicated in Section 3. Finally, the results of the excitation parameters that cause the lower variance and good SNR are obtained using a sinusoidal sweep rate close to the steady state limit.

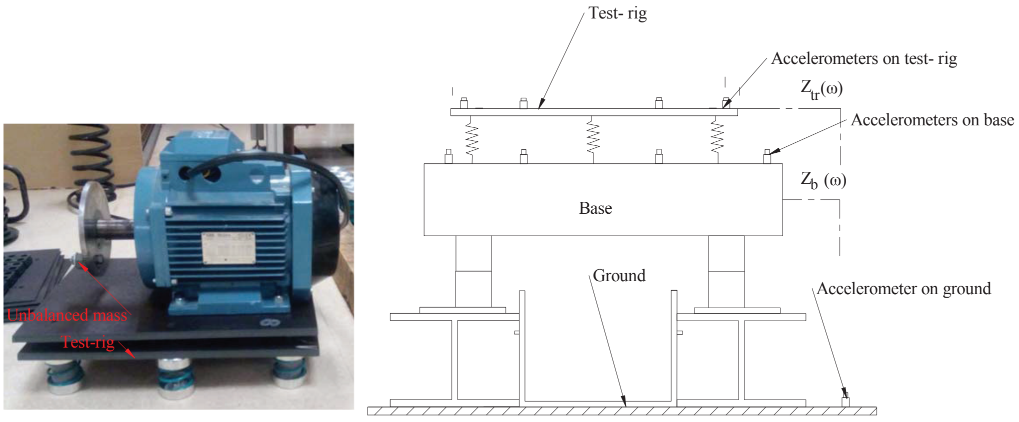
2. EXPERIMENTAL METHODOLOGY

2.2.1. Model description

In this experimental study, the mechanical system with an unbalanced force applied of swept sine is presented considering only vibrations in direction-z due to effect of system load [10]. In Figure 1(a), an unbalanced mass device with mass $M = 40$ kg is located over the test-rig with $\zeta = 0.0006$, natural frequency $\omega_n = 150.72$ rad/s, an unbalanced mass $m.e = 1.8.10^{-3}$ or $2.8.10^{-3}$ $kg.m$, respectively. The analytical model shown in Figure 1(b) is used for experimental comparison of FRF with $m_{tr} = 11.16$ kg.

$$\left|\frac{Z_{tr}}{Z_b}\right| = \sqrt{\frac{1+\left(2\zeta_n\frac{\omega}{\omega_n}\right)^2}{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2+\left(2\zeta_n\frac{\omega}{\omega_n}\right)^2}} \tag{1}$$

The theoretical model of the test-rig of Equation 1 is used to analyze the distortion of the sweep sine experimental model, which is shown in Section 3.



(a) (b)

Figure 1: Model of a mechanical system or test-rig in direction-z for validation of the non-parametric identification method: (a) Unbalanced mass device on the test-rig, (b) Analytical model.

2.2.2. Non-parametric method

In the experimental study of the methodology is defined the non-parametric identification system [11] for the realization of dynamic measurements of a test-rig, applying sine sweep. This method is described by location of the excitation source above of test-rig, and best signal-noise-rate using different sweep rates, amplitudes and excitation length times. The vibrational contributions of the measurements of the input signal $\mathbf{z}_{tr}$ are considered in this experimental identification method, $\mathbf{z}_g$ including the an unbalanced mass device excitations and $\mathbf{n}_{tr}$ the process noise due to test-rig motion. The output signal $\mathbf{z}_b$ depends of $\mathbf{z}_{mtr}$ base motion by test-rig vibration, and $\mathbf{n}_g$ including the environmental ground vibrations due to background noise. In the FRF measurements, $\mathbf{m}_{tr}$ and $\mathbf{m}_b$ are input-output measurement errors. In Figure 2, a visual description of the method is presented. In this methodology, the known dynamic parameters of the test-rig are used, as shown in Table1. The measurements of the input signals $\mathbf{z}_{tr}$ and output $\mathbf{z}_b$ are processed by applying the spectral analysis method. The acquisition of measurement data is performed for a long time depending on the sweep rate with a length N time points split Δt each. Additionally, the full record of the measurements is split into M blocksizes of equal length. In Section 3, $\hat{\mathbf{H}}$ estimated of the test-rig is acquired using Equation 2 by

$$\hat{H}(i\omega) = \frac{\hat{\mathbf{S}}_{\mathbf{Z_b Z_{tr}}}(\omega)}{\hat{\mathbf{S}}_{\mathbf{Z_{tr} Z_{tr}}}(\omega)} \tag{2}$$

The $\hat{\mathbf{H}}$ is assumed as asymptotically circular complex normally distributed thus, covariance matrix is estimated by

$$\sigma^2\left(|\hat{H}(i\omega)|\right) = |\hat{H}(i\omega)|^2 \left(\frac{1-\gamma^2_{z_{tr}z_b}}{\gamma^2_{z_{tr}z_b}}\right)\frac{1}{2BT} \tag{3}$$

The smoothing factor $1/BT$ is estimated by

$$\frac{1}{BT} = \frac{\sigma^2\left(\hat{\gamma}^2_{z_{tr}z_b}(\omega)\right)}{2\gamma^2_{z_{tr}z_b}(\omega)\left(1-\gamma^2_{z_{tr}z_b}(\omega)\right)^2} \tag{4}$$

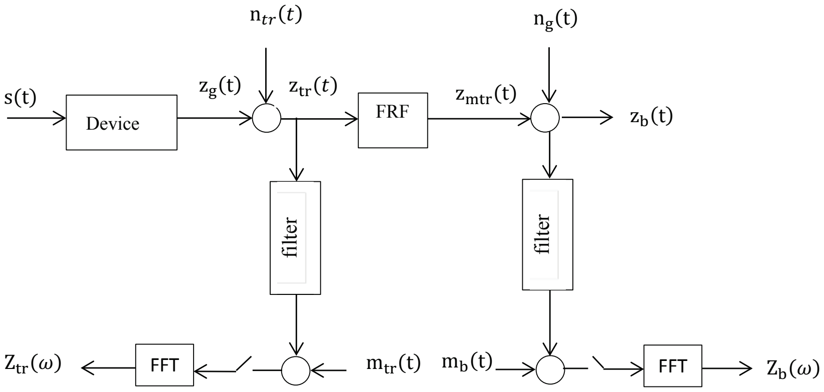


Figure 2: Non-parametric method considering background noise

with, the smoothing factor is a controllable parameter and the $\hat{\gamma}^2_{z_{tr}z_b}(\omega)$ is of the smoothed coherence function [12]. Thus, uncertainty of the measurements is evaluated having a low variance between FRF estimated at different unbalanced mass *m.e.* In Section 3, Equation 3, Equation 4 and uncertainty criterion are presented to determine the contribution of noise to the estimator of FRF [11, 13].

2.2.3. The input excitation analysis method

For the accurate estimation of the FRF is necessary to generate enough spectral power input, due to the presence of background noise using an unbalanced mass device. The experimental determination parameters that produce the best signal-to-noise ratio are chosen, as showns in Section 3.

$$(SNR)_p(\omega) = \frac{\left(\hat{\mathbf{S}}_{\mathbf{Z_{tr}Z_{tr}}}\right)_p(\omega)}{\sigma^2_{acc,input}(\omega)} \tag{5}$$

The powerful of input excitation in $\mathbf{z_{tr}}$ is checked to obtain the best signal-to-noise ratio using the result of Equation 5. The $p-en$ spectral power density $\left(\hat{\mathbf{S}}_{\mathbf{Z_{tr}Z_{tr}}}\right)_p$ of the input excitation are dependent of sweep rate, amplitude and signal time due to an unbalanced mass device.

The results of Equation 5 are used to determine if the excitation power at the input of the system has at low $\sigma^2\left(|\hat{H}(i\omega)|\right)$ of the estimated FRF with respect to the signal-to-noise ratio $(SNR)_p(\omega)$.

2.2.4. Sine sweep effect on test-rig

A sine sweep excitation $\frac{d^2z_b}{dt^2}$ of $F(\omega(t))/M$ amplitude can be defined using Equation 6 where $\omega(t)$ is the instantaneous frequency which depends on the specific sweep type defined as

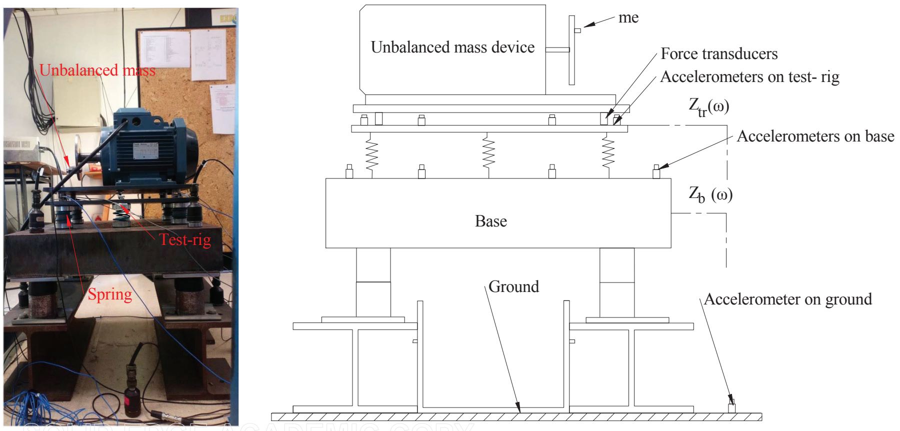
$$\frac{d^2z_b}{dt^2} = \frac{me}{M}\left(\omega_s + at^2\right)^2 \sin\left(\frac{a}{2}t^2 + \omega_s t + \beta\right) \tag{6}$$

Thus, experiments with an unbalanced mass device to find the parameters of experimental determination (amplitude, sweep rate and excitation time) with the best signal-to-noise ratio in the mechanical test system of laboratory are carried out by the variation of the unbalance component ($m.e$) and the rotation speed of the rigid disc $\omega(t)$. For small values of sweep parameter $\eta < 0.1$ the swept response level is very close to steady state [14]. This is important for the evaluation of the sweep and control of the input excitation, as shown in Section 3. 3.1.

3. EXPERIMENTAL TEST

3.3.1. Dynamic testing of test-rig

In this paper, measurements of the input signal of the test-rig are performed by applying a sweep sine with an unbalanced mass excitation device and different excitation parameters such as sweep rate, amplitude and excitation time, as shown in Section 2.1. So, effect sweep sine on the signal-to-noise ratio and excitation signal spectral density power is determined. For this experiment, firstly an unbalanced mass excitation device is turned-off, so the excitation measurements due to the background noise or real test condition and test-rig response are realized, see, Figure 3(b). After, an unbalanced mass excitation device is turned-on, such that the input excitation signal measurements and test-rig response are performed, as are shown Figure 3(b). Therefore, excitation parameters of the transmissibility matrix with of the best confidence region and lower variance the results are shown in Section 3.2.



(a)

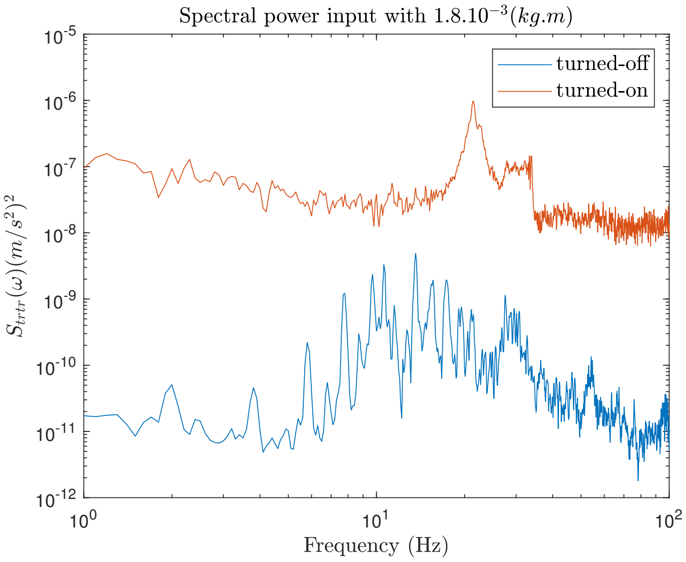
(b)

Figure 3: Model excitation of mechanical system or test-rig in direction-z for validation of the non-parametric identification method: (a) Dynamic testing installation, (b) Scheme of the laboratory structure and test-rig.

3.3.2. Experimental results

A sweep sine signal of [1-35] Hz in the test-rig is applied using an unbalanced mass excitation device. Measurements acceleration in the positions $Z_b(\omega)$ and $Z_{tr}(\omega)$ are made and the theoretical transmissibility ratio is used. For signal processing, a sampling period of 10 s with a DFT optimization in 13 blocksize and sampling frequency of 1 kHz are used, as shown in Figures 4, 5, and 6. With these results, transmissibility ratio and of the analytical model are compared.

The measurements are presented with the different parameters of experimental determination, sweep time, sweep sine rate s and an unbalanced mass $m.e$ to obtain the lower variance of the measurements using an unbalanced mass device, see Figure 3. Figure 4, shows the auto-power spectrum evaluated for sweep sine rate of 35 Hz/min and 70 Hz/min defined by $\hat{\mathbf{S}}_{\mathbf{Z_{tr}Z_{tr}}}$. In Figure 4(a), the experiment performed with an unbalanced mass of $1.8.10^{-3} kg.m$ indicates a slightly lower spectral power value with reference to the spectral power shown in Figure 4(b). It is due to an unbalanced mass of $2.8.10^{-3} kg.m$ located a 0.043 m with respect rotation disc shaft.



(a)

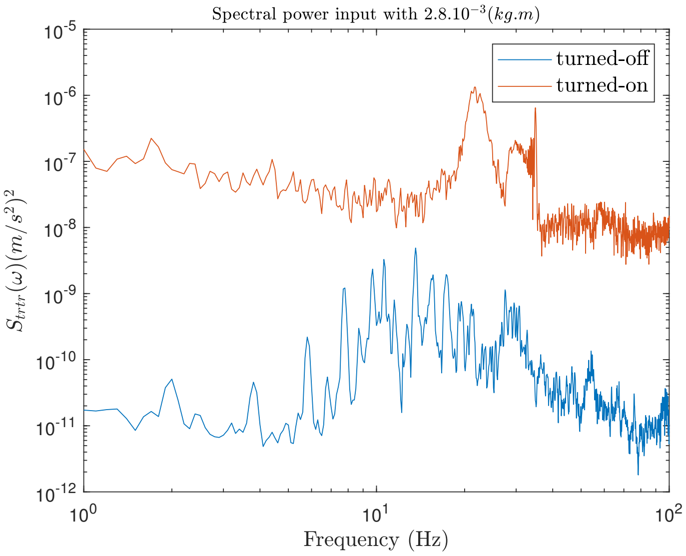


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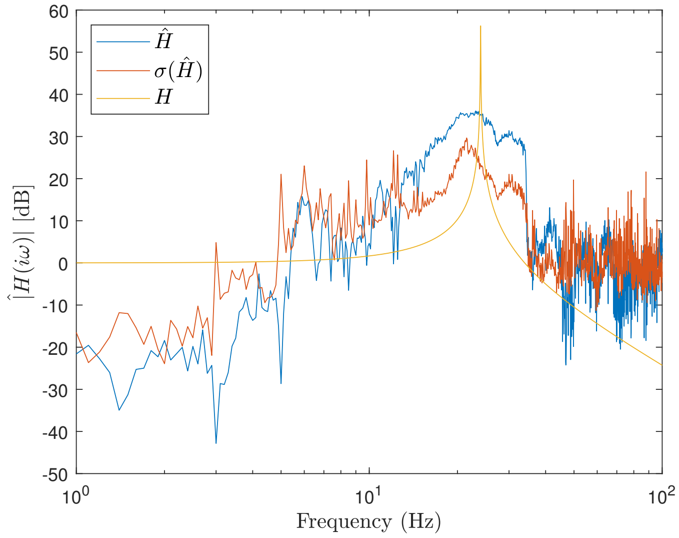
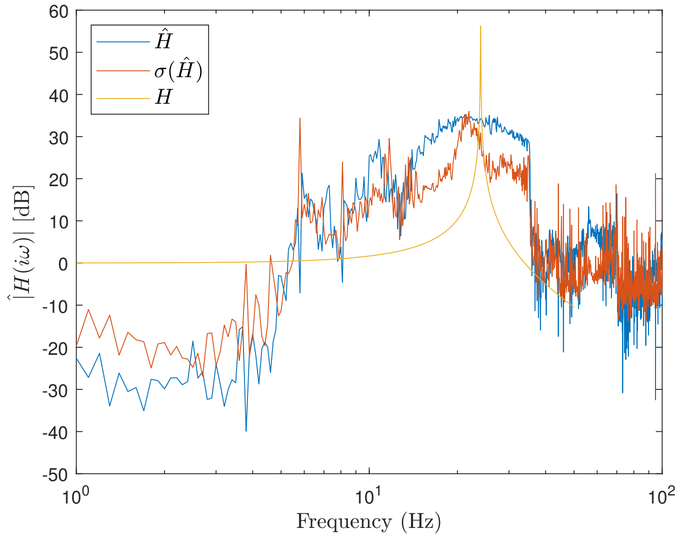
Figure 4: Auto-power spectrum $\hat{\mathbf{S}}_{\mathbf{Z_{tr}Z_{tr}}}$ *for evaluation of spectral power input:(a) 35* Hz/min*, (b) 70* Hz/min*.*

In Figure 5, $\hat{\mathbf{H}}$ is defined in Equation 2 and the $\sigma(\hat{H})$ is obtained using Equation 3 and Equation 4. The analytical model $\mathbf{H}$ has been defined by Equation 1. In Figure 5(a), a standard deviation approximately 30 dB in the peak corresponding to 23.6 Hz is observed. In addition, the distortion estimated $\hat{\mathbf{H}}$ and the analytical model with a slightly lower amplitude than $\hat{\mathbf{H}}$ is shown in Figure 5(b). The distortion due to $\sigma(\hat{H})$ value of 35.11 dB is observed to a frequency of 21 Hz, as shown in Figure 5(b). The location of the maximum peak $\mathbf{H}$ of 24 Hz is evaluated according to the standard deviation $\hat{\mathbf{H}}$, as shown in Figure 5.



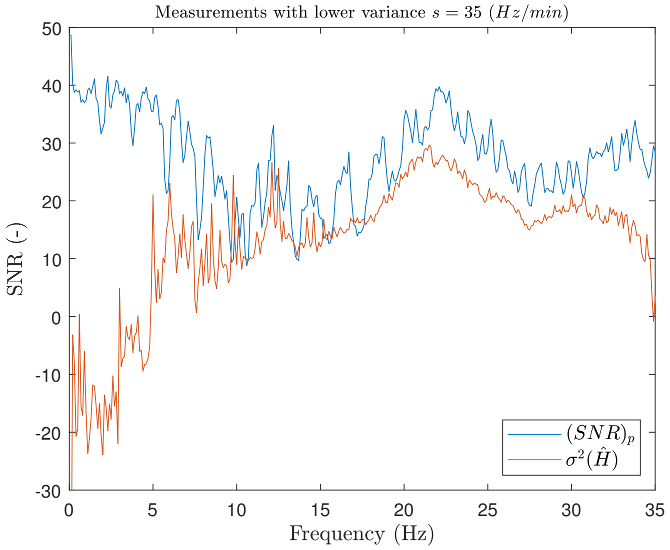
(a)



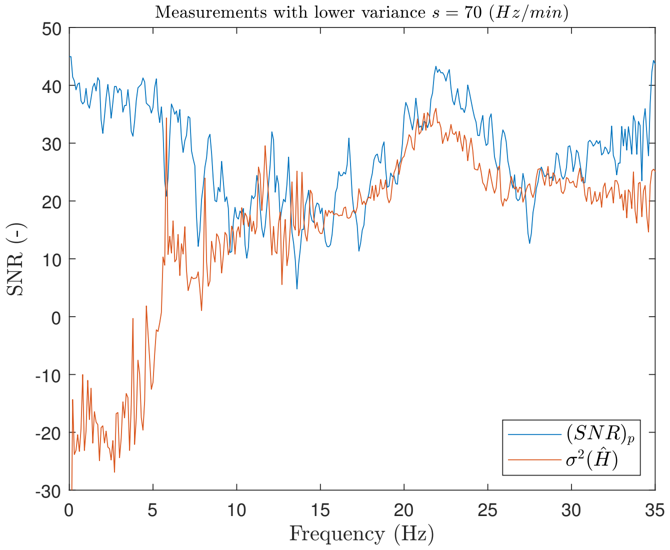
(b)

Figure 5: Measurements $\hat{H}(i\omega)$ by sweep sine: frequency sweep time (a) 60 s, (b) 30 s.

The signal-to-noise ratios (SNR) of measurements input signal $\mathbf{Z_{tr}}(\omega)$ and output signal $\mathbf{Z_b}(\omega)$ are determined using spectral analysis defined in Equation 5. In Figure 6(a), a variance of the measurements with value of 29.66 is observed, also a SNR value of 38.85 is determined for $\hat{\mathbf{H}}$. The SNR value of 43.29 is determined for a variance of the measurements of value 35.11, as shown in Figure 6(b).



(a)



(b)

Figure 6: Measurements with a sufficiently SNR: (a) lower variance, (b) high variance.

4. CONCLUSIONS

A methodology to obtain experimental measurements with lower variance, a good signal-to-noise ratio before the characterization of the dynamic parameters of system is presented in this article. The non-parametric system identification method and the method of analysis of sweep-sine runs during modal identification are used by a new methodology of lower variance in measurements of systems. The best excitation parameters are determined, such as sweep rate, sweep time and unbalanced mass using an unbalanced eccentric mass device. For this, the input spectral power is determined according to the presence of experimental site background noise and the standard deviation of the FRF measurements. Then, the SNR of the measurements due to the excitation parameters of lower variance is compared. Excitation parameters that have a good signal-to-noise ratio are chosen with the lower variance to guarantee accurate measurements. This methodology was developed with the lower estimation variance in the LEAM-UPC laboratory using an unbalanced mass device. The purpose of developing the experimental methodology is to apply in the railway superstructure measurements to obtain the dynamic response. The methodology based on the experimental measurements in the planning of new infrastructures surrounding vibration sources using an unbalanced mass device of great capacity would be used.

5. ACKNOWLEDGEMENTS

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