Estimation of rotor position and speed for Hybrid Stepper Motor under various phase excitation schemes and compensated resonance

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Abstract— **Estimation of rotor position and speed plays an important role to avoid skipped step and reduced resonance in Hybrid Stepper Motor (HSM). In this paper, the effect of various phase excitation schemes on estimation of rotor position and speed in the presence of resonance is studied. A method has been proposed to identify the resonance from the frequency content of measured phase currents well before it is exhibited in the mechanical measurement. It is compensated through excitation voltage. The microstepping excitation is found to provide fastest and smooth tracking of rotor position and speed. The results are validated through experimentation.**

I. INTRODUCTION

A stepper motor is a motor whose shaft moves in precise angular increments for each electrical input. Hybrid stepper motors [1], [2], [3], are used in positioning application due to their durability, high efficiency and small step angle. The applications include positioning control of solar array antenna, medical application and robotics, etc. A. Bellini et al. [4] deals with Pulse Width Modulation (PWM) excitation schemes for HSM that allows high performances and low vibrations without losing efficiency and avoid skipped steps. J. Chiasson et al. [5], and M. Bodson et al. [6], demonstrated that HSM could be fast and accurate with exact feedback linearization for position control. Linearization was done by using direct quadrature (dq) transformation and the detent torque was not considered. S.M. Yang and E.L. Kuo [7], improved the position accuracy through an effective damping algorithm. A phase locked loop based position and velocity observer is developed, which tracks the angle of the motor back EMF. This method makes use of stationary reference frame and produced reliable estimated under various phase excitation schemes and load conditions. But this method fails to recognize the resonance condition. A. Ferrah, et al. [8] gives a basic idea of using Extended Kalman Filter (EKF) for HSM. The method is very much suitable for simulation but experimental realisation of EKF is tedious. J. Persson et al. [9] and C. Obervoiner et al. [10] describe the detail about the kalman filter for HSM. The kalman filter based observers can detect the resonance condition, but are computationally very complex. Alternatively, the resonance can be identified through mechanical vibrations and their effect on measured electrical quantities. A method for reducing mechanical vibrations through sine PWM for Brushless DC motor has been demonstrated by Y. Perriard et al. [11].

Under high mechanical vibrations, it is seen that the current waveforms exhibits high frequency harmonics. The main objective of this paper is to identify resonance well before it occurs and compensate for it, so that simple estimation technique can still be used for speed and position. When compared to other methods for estimation of rotor position and speed, the method used in [7] is very simple to use. In this paper investigations are carried out with complete dynamic simulation of HSM. Resonance conditions are created in the motor, under various excitation schemes. The changes in the level of harmonic content of measured phase current are studied under resonance condition. Resonance is identified upon extracting the high frequency contents and through fixing thresholds. Suitable compensation is applied to overcome response. The results are validated through experimentation.

The paper is organized as follows. Section II presents phase excitation schemes for HSM. Section III presents the mathematical model of HSM and estimation of rotor position and speed. Section IV gives information about the torque speed characteristics and resonance. Finally conclusions are summarized.

II. PHASE EXCITATION SCHEMES FOR HSM

The Phase excitation scheme plays a vital role in the performance of a stepper motor. Generally HSM is driven in full or half step mode. According to specified pattern, the motor currents are switched ON and OFF and the motor shaft moves a step angle for each switching.

TABLE 1
CLOCKWISE PHASE EXCITATION SEQUENCES

Full step	
Phase A	**Phase B**
1	1
1	- 1
-1	-1
-1	1

Half step	
Phase A	**Phase B**
1	1
1	0
1	- 1
0	- 1
- 1	- 1
- 1	0
- 1	1
0	1

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For high speed application, both full and half step switching drives tend to miss steps. This is due to switching time of each step, which can be much less than the mechanical response time of the motor. In microstepping phase excitation scheme the current changes in the windings in small step. The advantages of microstepping are reduced vibrations, improved position resolutions, maximum torque at high step rate. Further the current wave can be shaped into sinusoidal form.

III. MATHEMATICAL MODEL OF HSM

The two phase HSM model can be expressed as in [1], [2], by equation (1).

$$\frac{di_a}{dt} = [V_a - Ri_a + K_m\omega \mathrm{Sin}(N_r\theta)]/L$$
$$\frac{di_b}{dt} = [V_b - Ri_b - K_m\omega \mathrm{Cos}(N_r\theta)]/L \qquad \text{---- (1)}$$
$$\frac{d\omega}{dt} = \frac{1}{J}[-K_m i_a * \mathrm{Sin}(N_r\theta) + K_m i_b * \mathrm{Cos}(N_r\theta) - B\omega - T_L - K_D \mathrm{Sin}(4N_r\theta)]$$
$$\frac{d\theta}{dt} = \omega$$

Where i_a, i_b and V_a , V_b are the currents and voltages in phases A and B respectively. K_m is the motor torque constant. J is the rotor inertia, N_r is the number of rotor teeth, B is the viscous friction, ω is the rotor speed, and θ is the rotor position. R and L are the resistance and inductance of each winding. T_L is the load torque. The detent torque term $K_D \mathrm{Sin}(4N_r\theta)$ is due to permanent magnet interacting with the magnetic material of stator pole. The value of K_D is very much less than K_m and hence is generally neglected. The dq model of a 2 phase HSM in the stationary frame [7] is given by equation (2)

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta_s) & \sin(\theta_s) \\ -\sin(\theta_s) & \cos(\theta_s) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \end{bmatrix} \qquad \text{----- (2)}$$

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \begin{bmatrix} r + L.p & 0 \\ 0 & r + L.p \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + K_m\omega \begin{bmatrix} \cos(\theta) \\ -\sin(\theta) \end{bmatrix} \qquad \text{--- (2a)}$$

$$T_s = K_m \left[\mathrm{Cos}(\theta) \; - \mathrm{Sin}(\theta)\right] \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad \text{----(3)}$$

Where θ_s is the angle between the ab and dq axes, p=d/dt, V_{qs} ,V_{ds} and i_{ds} and i_{qs} are winding voltages and currents in dq frame. T_s is the generated torque.

A. Estimation of rotor position and speed

The speed and position are estimated from equation (2) as described in [7]. Let $\hat{\omega}$ and $\hat{\theta}$, be the estimated value of speed and position respectively. Upon multiplying V_{qs} by $\sin(\hat{\theta})$ and V_{ds} by $\cos(\hat{\theta})$ and summing the following results are obtained.

$$Verr = K_m\omega\sin(\theta - \hat{\theta}) \qquad \text{----- (4)}$$

$$V_{qs}\sin(\hat{\theta}) + V_{ds}\cos(\hat{\theta}) - (r + Lw_e)(i_{qs} + i_{ds}) = Verr \quad - (5)$$

When $\hat{\theta}$ is converges to θ, Verr reduce to zero. By equating the equations (4) and (5), the right hand side of equation (4) can be used to estimate $\hat{\omega}$ and $\hat{\theta}$, when passed through an appropriate Proportional Integral (PI) filter. The gains of PI filter are adjusted to achieve the required error convergence dynamics [7].

Fig.1, 2 & 3 show the simulation results about rotor position, excitation voltages, phase currents and the rotor velocity for half stepping, full stepping and microstepping phase excitation schemes. In half stepping phase excitation, speed settles at t = 0.22 sec. In full stepping excitation, speed settles at t = 0.25sec, compared to full stepping mode, the half stepping mode shows reduced oscillations. In microstepping phase excitation, speed settles smoothly at t = 0.2 sec. The speed estimation exactly tracks in the microstepping mode compared to half and full stepping modes.

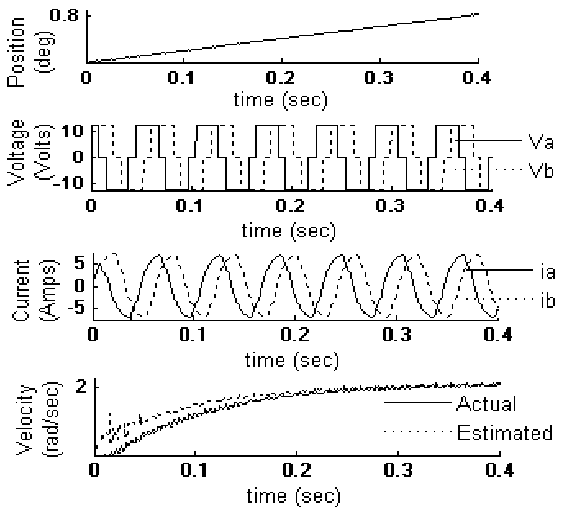

Fig 1. Half stepping phase excitation

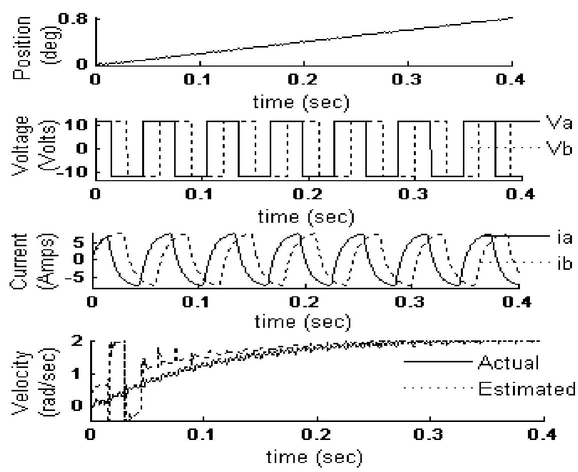

Fig 2. Full stepping phase excitation

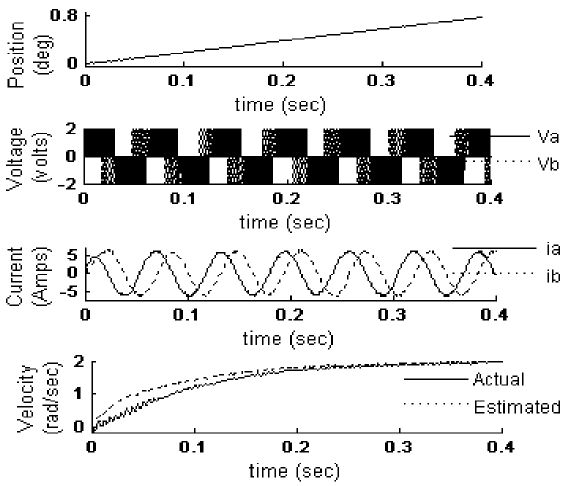

Fig 3. Microstepping phase excitation

IV. TORQUE SPEED CHARACTERISTICS AND RESONANCE

In HSM, the system designer needs to know, how much torque the motor can produce while accelerating, decelerating or running at constant speed. The torque versus speed relationship of a stepper motor is shown in Fig.4. The stepping rate is proportional to speed, when machine does not miss any step.

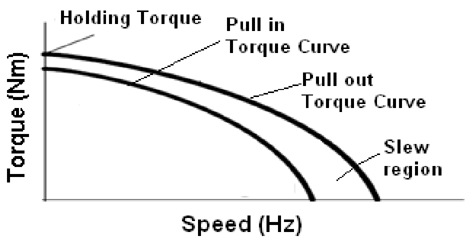

Fig. 4. Torque speed characteristics

The pull out torque is the maximum friction torque that a stepper motor can drive before losing synchronism at a specified stepping rate. The pull in torque curve represents the maximum frictional load at which the stepper motor can start without failure of motion when a pulse train of the corresponding frequency is applied. It depends on the inertia of the load connected to the motor. The holding torque is defined as the maximum torque produced by the motor at a standstill condition. [1], [2], [3].

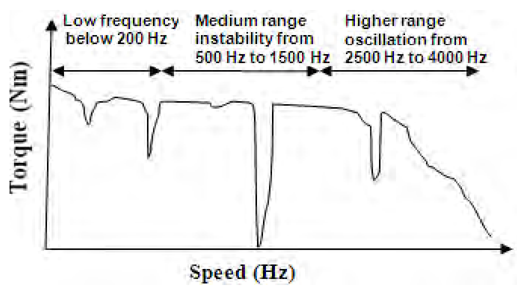

Fig.5. Torque speed characteristics with resonance

Resonance is the oscillatory phenomena which disturbs the normal operation of the stepper motor. In some cases the magnitude of oscillation increases with time and eventually the motor loses synchronism. Resonance and instability may be classified into three categories, namely the low frequency, medium range instability, and higher range oscillation as shown in Fig.5. The oscillation that occurs below 200 Hz is called low frequency resonance. Medium range instability occurs between 500 Hz to 1500 Hz. The higher range oscillation occurs in the range of 2500 Hz to 4000 Hz.

The low frequency resonance is considered in this paper. For investigation, ST601 HSM motor with the following specifications is chosen.

TABLE 2
ST601 HSM MOTOR SPECIFICATIONS

Motor Parameter, units	ST601
Rotor load inertia (J), Kgm^2	0.000045
Viscous friction (B), Nms/rad	0.00008
Self inductance of winding (L), Henry	0.012
Resistance in phase winding (R), Ω	1.55
Number of rotor teeth N_r	50
Motor torque constant(K_m), Nm/A	0.19

The HSM dynamics is simulated as described in equation (1). The pull in torque characteristics of chosen HSM is shown in Fig 6. for the three cases of excitation, namely the full step, half step and microstepping phase excitation. The low frequency resonance is clearly visuvalised in the simulation and experimental results shown in Fig.6 and 7.

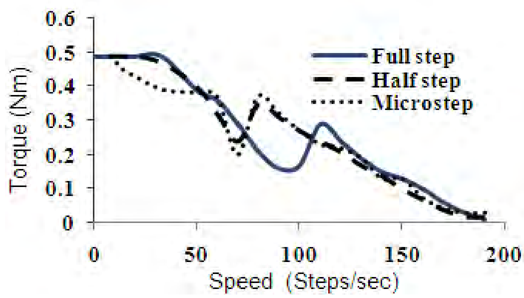

Fig.6. Simulation result of HSM pull in characteristics

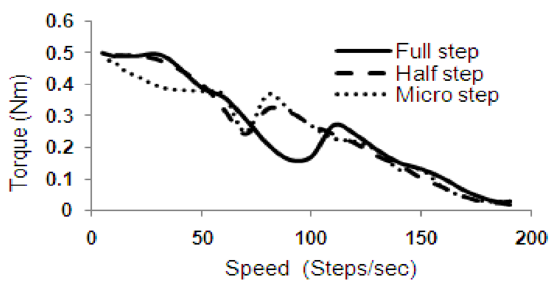

Fig.7. Experimental result of HSM pull in characteristics

The resonance condition is made to occur during the normal running condition to notice any difference in the measureable variables. Fig.8 shows the result of resonance condition, when the load torque and speed are changed from T_L= 0.38 Nm, speed = 70 steps/sec to T_L = 0.40 Nm, speed = 100 steps/sec at t = 0.3 sec. At the resonance point, the motor is not able to supply the torque and hence the speed and position drop down. The estimated speed still shows the new set speed (as given by the excitation frequency). The current magnitude remains almost the same, but contains increased magnitude of high frequency oscillations.

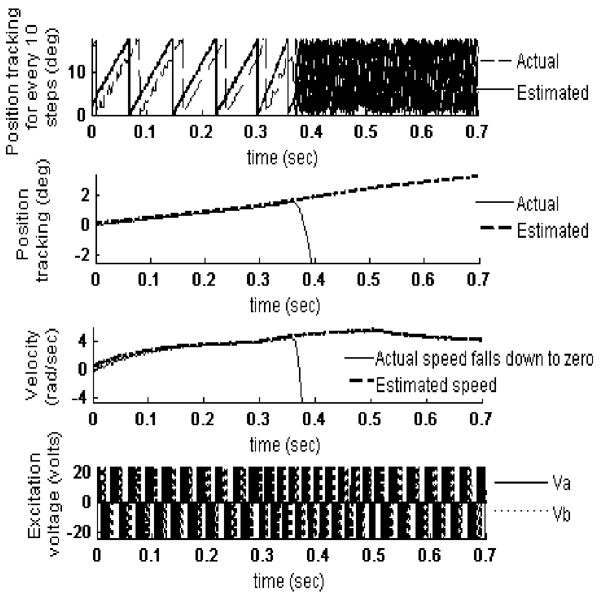

Fig.8. Machine characteristics with resonance condition for microstepping

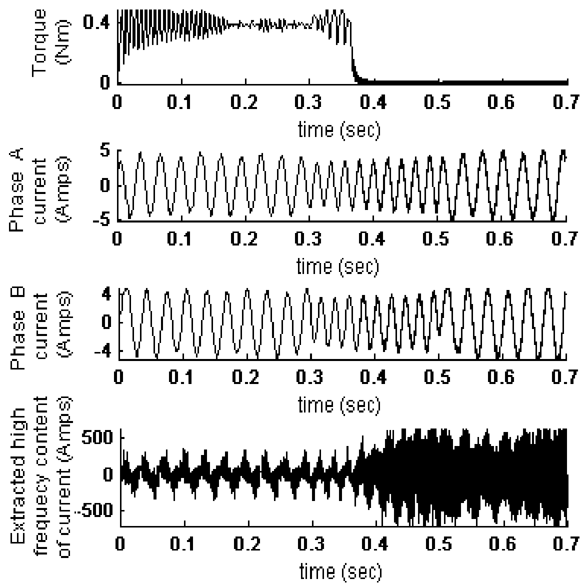

Fig.8.a Frequency content of current waveform under normal and resonance conditions for microstepping

The extracted high frequency content of the current under normal and resonating condition is shown in Fig. 8a. A threshold has been chosen to detect the resonating condition and the excitation voltage is increased till the resonance is overcome. The results are shown in Fig.9. and 9a. It is seen that the required speed is reached with compensated excitation, at t = 0.32 sec. The torque and speed requirements are altered at t = 0.5sec to bring back again normal condition. The excitation voltage is again corrected back to its nominal value at t = 0.5sec.

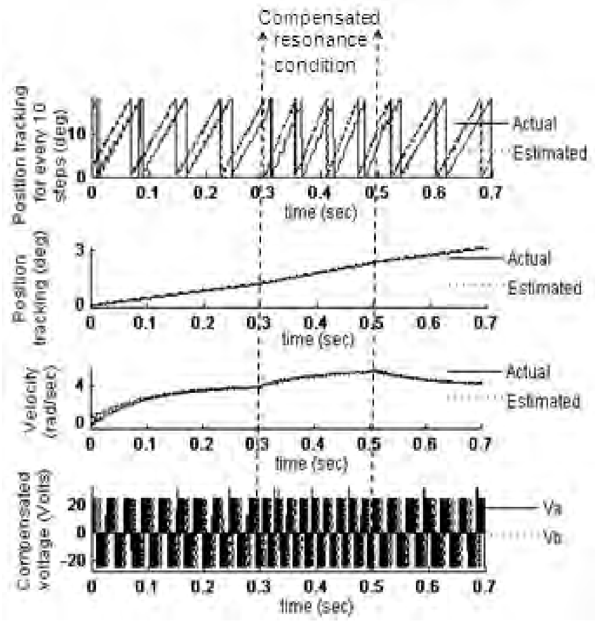

Fig. 9. Excitation voltage under normal and compensated resonance conditions for microstepping

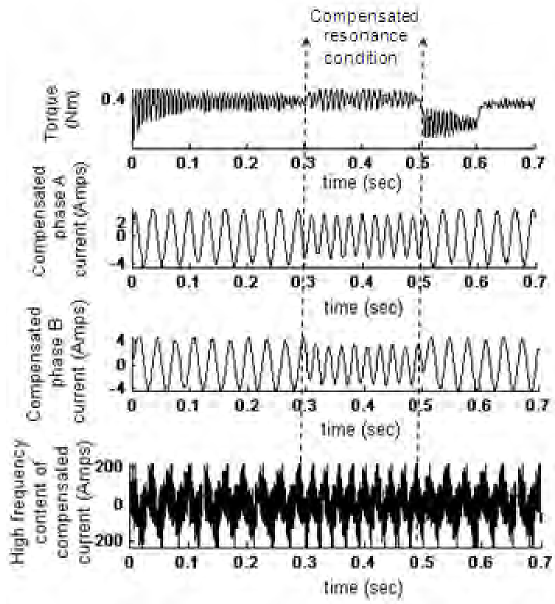

Fig.9.a. Machine characteristics under compensated resonance condition for microstepping

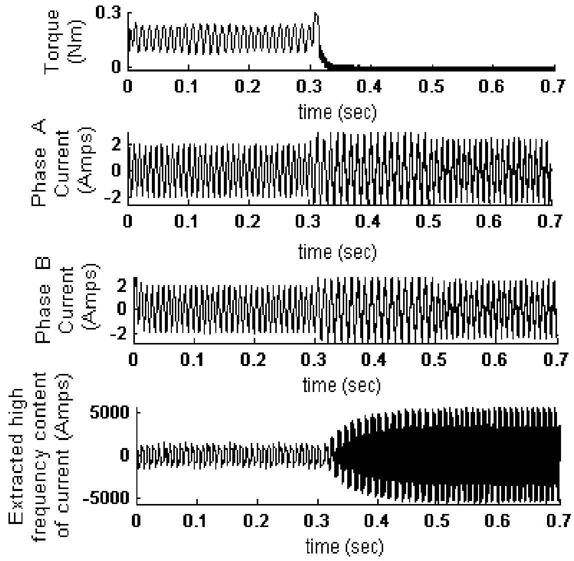

Fig.10. Frequency content of current waveform under normal and resonance conditions for full stepping

The procedure is repeated for full stepping and half stepping excitation schemes. Fig.10 and 11 show the results for full and half stepping cases respectively. The resonance occurs at different speed and torque levels for each excitation schemes as evident from Fig.9. When compared to microstepping, the full and half stepping scheme produce non sinusoidal phase currents. Fixing of threshold needs to be done carefully. The resonance occurs for a wider range of speed in half and full stepping modes. Another factor that affects the threshold is the increase in phase current due to increase in excitation voltage. The experimental setup of HSM is shown in Fig.12. The experimental result for full stepping is shown in Fig.13.

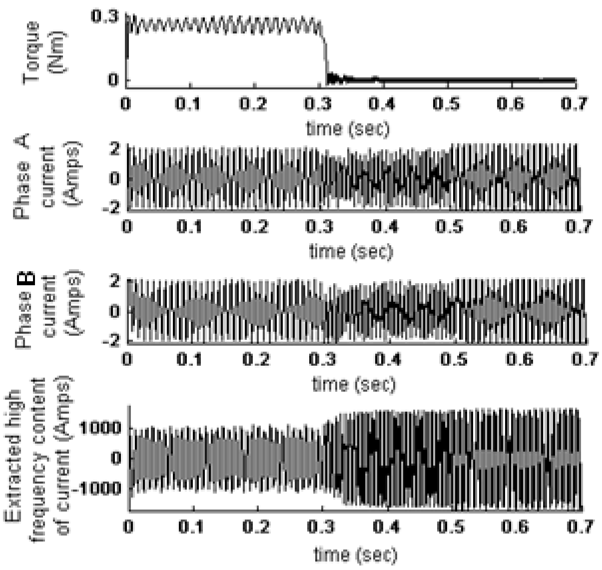

Fig.11. Frequency content of current waveform under normal and resonance conditions for half stepping

Fig.12. Snapshot of experimental setup

The estimated value of speed and position are shown to settle smoothly. The high frequency content of the current are within the limits during normal operation. The estimated values are tested for various speed and loading conditions found to be matching except at the resonance point. The high frequency content of current is found to increase at the resonance point as evident from Fig.13. In the resonance condition, the actual pulse drop from t =0.3 sec to 0.6 sec and current wave form exhibit the high frequency content but the estimated position and velocity still proceed. Hence the theoretical investigation has been validated through experimentation.

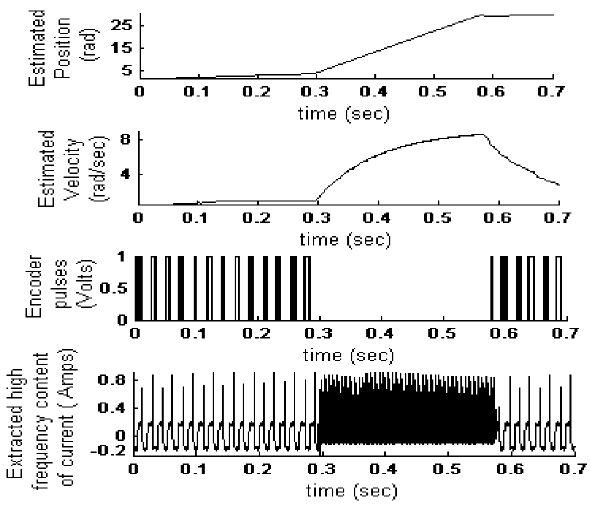

Fig.13. Experimental result of full stepping for frequency content of current waveform under normal and resonance condition.

V. CONCLUSIONS

This paper investigated the rotor speed and position estimation under various excitation schemes. The resonance is identified from the frequency content of measured current. The excitation voltage is compensated to overcome the resonance effect. Under compensated resonance condition, simple estimation techniques are found to work satisfactory. In the microstepping excitation, the estimator tracks the actual speed more precisely, when compared to other excitation schemes. The fixing of threshold needs to be done carefully under half and full stepping excitation modes due to non sinusoidal phase current.

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