REVIEW OF FUNDAMENTAL TWO POLE INDUCTION MOTOR MECHANICS

by

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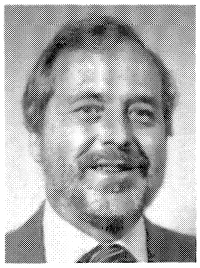

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ABSTRACT

An introduction to two pole motor mechanics is presented, with the goal of promoting an understanding of normal and abnormal vibration sources to assist in the diagnosis of the field problems of such motors. Motor force vectors are reviewed, which define sample frequencies and magnitudes for the normal mechanical and electrical causes. Tables of sources of both normal and abnormal forces are presented which enable the reader to calculate the frequencies involved and possible causes for excessive levels. Sum and difference frequencies (beat) are complicating factors in such motors and a brief nonmathematical discussion of such processes is presented, in terms of two pole motor vectors. A case problem is presented, showing an example of two pole motor beat frequencies and the associated sidebands in such problem cases.

INTRODUCTION

Field vibration analysis of two pole 3600 cpm motors is a relatively complex problem which most mechanical engineering personnel are not well equipped to handle. Such motors have a strong load sensitivity and can run very smoothly in the idle condition, leading to difficulty in separating mechanical and electrical problems. The cause for the complexity in such analysis is a failure to define the basic force vectors in such motors and deal with them in terms of electrical and mechanical sources. Additional complications arise from the extreme nonlinearity in the forces generated, leading to some very excessive sum and difference frequencies, or beat. To deal with such motor problems more effectively, a fundamental review of such two pole motor forces is most helpful.

FUNDAMENTAL FORCES

Two pole motors are complicated machines to deal with in terms of field vibration problems, since they can be quite load sensitive due to electromagnetic and mechanical force interaction. A two pole motor can run quite well in the idle condition, but immediately becomes rough when load is applied, leaving the impression that a severe electrical problem is present. An actual case was experienced with a 600 hp two pole motor where the idle operation produced velocities of 0.05 in per second (ips) at the bearing housing, but the loaded condition resulted in a strong beat with peaks in excess of 0.4 ips. Such cases of low idle vibration are quite common and must be sorted through in two pole motor diagnoses. Fundamental reviews of the mechanics of both the electrical and mechanical forces are required to understand such occurrences of two pole problems.

Dealing with two pole motor vibration problems requires an understanding of the forces generated by the normal mechanical and electrical systems within such units. In this way, possible sources of the abnormal forces can be separated from the normal ones in terms of frequency or magnitude and identified as electrical or mechanical in origin. A motor has the normal rotating unbalance and associated mechanical forces present, along with substantial electromagnetic radial forces, which are components of the applied torque forces. Mechanical unbalance and the associated harmonics in an induction motor follow normal rotating machine dynamics experienced in other machines. Electromagnetic forces generated in motors are a bit foreign to most mechanical engineers and technicians and a review of the fundamental aspects of their sources can be most helpful in dealing with field problems.

Torque is generated in an induction motor by a relative "slipping" condition between the rotating electromagnetic field and the rotor cage. It is this slipping relationship which induces a counter electromagnetic field in the rotor to drive the resisting driven machine load. This process results in a pair of electrical forces at the magnetic poles rotating at 60 Hz and a mechanical unbalance force rotating at a slightly lower speed. The amount of slip is determined by both the electrical design and the applied load and it is quite low in the idle operating condition. A basic task in vibration analysis of two pole motors is to identify the magnitude and frequency of these forces and how they are summed in the motor.

Two pole motors are discussed here in terms of 60 Hz power supplies and all frequencies are based on such systems. The principles are, however, identical for 50 Hz system motors, differing only in terms of frequency and slightly lower centrifugal loads. Basic vibration analysis should follow the same procedures and tests.

MECHANICAL FORCES

Unbalance in two pole motors is typical of all rotating machinery and must conform to a balance standard such as International Standard Organization (ISO) 1940 Grade G2.3 (0.0005 in radius of gyration), or less, depending on whether it is flexible or stiff shaft design. A flexible shaft is one which operates above the first critical, while a stiff shaft is one which operates below the first critical speed. This distinction is important to the balance procedures applied, in that a flexible shaft design requires more elaborate processing, since the operating speed shaft design deflections have an impact on the results. Two pole motors in the vicinity of 2000 hp and above are usually flexible shaft designs, due to rotor core inner diameter (ID) restraints and are balanced to 0.00025 in radius of gyration levels or lower.

The mechanical unbalance force of a two pole rotor rotates at a speed lower than that of the 60 Hz electric field. Differing by the load induced slip, a typical 59.4 Hz value at load can be given. Note that this slip difference provides a means to isolate balance from other problems. The balance level for a flexible shaft 2000 hp rotor would be 0.00025 in and would weigh close to 1400 lb, giving an unbalance force of 64 lb at the bearings.

$$
\begin{aligned}
F_u &= \text{unbalance force} = \text{centrifugal force for rotor} \\
&= mrn^2 \\
&= (1400\ \text{lb}/386\ \text{in/sec}^2)\,(0.00025\ \text{in})\,(3600\ \text{cpm})^2\,(6.28/60\ \text{sec/min})^2 \\
&= 129\ \text{lb total bearing force} = 64\ \text{lb per bearing}
\end{aligned}
$$

Significant mechanical energy also exists at the second harmonic of rotation, which, in terms of this example, would be 2 × 59.4 Hz or 118.8 Hz. Such harmonic mechanical energy comes from nonlinearity and misalignment in the motor bearings or the driver/driven shaft connection, which again is typical of all rotating machinery. This second harmonic energy can cause significant vibration problems during the summation with the 120 Hz electrical field forces which will be described in later sections.

ELECTRICAL FORCES

The stator winding produces three phases of sine wave magnetic fields from the three power phases. This electrical input is summed to give a single sine wave magnetic field in the air gap, forming a north and south pole, as shown in Figure 1, at any instant of time. This summed flux field varies, or rotates, at a 60 Hz rate in the air gap, as determined by the frequency of the power supply. The magnetic flux lines forming a pole in the cross-section view of a motor are indicated in the plot in Figure 2. Since the magnetic field and the two poles are rotating at 60 Hz, any point in the air gap will have these poles pass at a frequency rate of 120 Hz. A radial magnetic pull occurs across the air gap at these poles, acting between the rotor and stator to give a major level force acting on the motor.

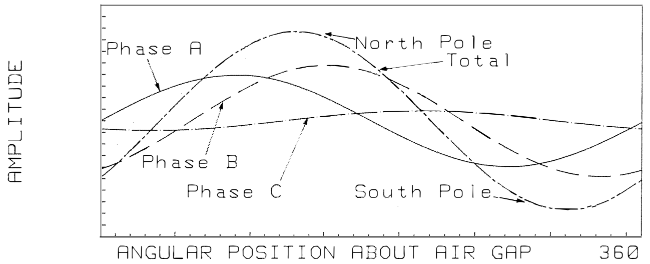

Figure 1. Flux Density in Developed Air Gap at Instant of Time t.

Note that the flux line density is not really a continuous sine wave variation in the air gap, but has discrete steps of flux increase formed by the individual stator coil slots. Each slot adds an additional step increase in flux at the air gap, giving an approximate sine wave variation. The rotor bars also add stepwise variations in the flux density (Figure 2), since the rotor tooth alignment also affects the flux flow across the air gap. Since both of these variations are almost step increases, very high frequency "slot" forces and substantial harmonics are generated. Using a real time analyzer, it is quite typical to see harmonic energy between ten and twenty times the 60 Hz energy level and to see slot frequencies in the 1000 Hz to 2500 Hz area. To be noted at this point is the fact that in the process of summing the three phases of flux spaced at 120 degree positions, any phase imbalance in terms of resistance of voltage will add very significantly to the 120 Hz vibration force with harmonics.

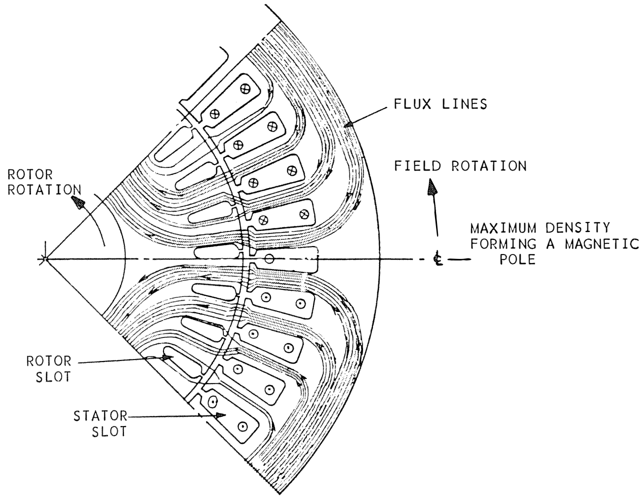

Figure 2. Cross Sectional Diagram of Induction Motor Showing Stator and Rotor with Flux Lines.

A very important factor is that the level of these magnetic pull forces is extremely high, giving a major motor design and field operation concern. An approximation of this force level can be derived using the rule of thumb that it is approximately 35 psi times the rotor projected area [1]. A typical force level for a 2000 hp two pole motor would be about 13800 lb:

$$
\begin{aligned}
F_m &= \text{magnetic pull} \\
&= (35\ \text{psi})\,(14.5\ \text{in rotor diameter})\,(27.5\ \text{in stack length}) \\
&= 13800\ \text{lb}
\end{aligned}
$$

Asymmetry in the electric field, such as unbalanced phases or unequal air gaps, can create devastating forces at the bearings and is likely to result in major damage to the bearings. If this same 2000 hp motor had a ten percent eccentricity in the air gaps (nominally 0.125 in), there would be an unbalanced magnetic pull level of 1500 lb acting on the rotor. Any further eccentricity would give disproportionally greater forces, with respect to eccentricity. Magnetic pull forces are generally understood to be nonlinear over ten percent eccentricity, and in the maximum case can give unbalanced pulls equal to several times the weight of the rotor.

The mutual attraction force, or magnetic pull, acting at the air gap does place a strong action on the housing, causing stator core deflections, even with a perfectly symmetrical electric field. Thus, some 120 Hz forces will always exist. Such forces will be present in all two pole motors, and in themselves will not cause any damage at the bearings. These forces can be seen in many successful motor operations and should not automatically be considered bad. Many two pole motors have been diagnosed as having a significant problem due to the presence of what appears to be excessive second harmonic energy, based on experience with purely mechanical machinery. Before classifying a two pole motor with this 120 Hz condition as being a problem, examine its past history and determine whether the overall level is satisfactory.

SUMMATION OF THE FORCES AT THE BEARINGS

A summary of the forces which act at the bearings of a typical two pole motor is presented in Table 1. The mechanical rotation is assumed to be at 59.4 Hz and is only a representative level for the loaded condition. Analysis of two pole motor problems will usually revolve around these regions, or at least verifying that they are satisfactory. The magnitudes and frequencies of these individual forces are of particular interest, along with the summation effects which may be occurring to greatly amplify their level.

Table 1. Table of Forcing Frequencies.

Source	Frequency	Comments
Rotor unbalance	59.4 Hz (typical)	Typical level gives 0.40 ips vibration
Electromagnetic field unbalance	60 Hz	Approx. 0.01 ips vibration
2nd harmonic of rotation	2 (59.4) = 118.8 Hz	Content dependent upon alignments
Electromagnetic poles	2 (60) = 120 Hz	Always present as normal condition
Stator slot forces, fundamental	n (60) ± 120 Hz	n = number of stator slots
Rotor slot forces, fundamental	m (60) ± 120 Hz	m = number of rotor slots

The electrical and mechanical vectors near the rotation speed can be graphically depicted (Figure 3), while the 120 Hz area vectors are shown in Figure 4. These sets of vector pairs are quite close in frequency and are summed at the bearings, leading to modulated vibration levels and "beat," causing rather complex results. A practical way to understand this modulation process is to visualize both rotating vectors as coming in and out of phase at a rate determined by their difference in speed. For instance, the rotation vectors at 60 Hz and 59.4 Hz would be in phase at the slip or difference speed of 0.6 Hz, giving a pulsing or beating sound; a vibration meter monitoring the bearings would swing between two levels at this same rate. Similarly, the 120 Hz area vectors would be in and out of phase at twice the slip rate, giving a 1.2 Hz pulsing vibration and sound.

The waveshape summation process, as it might be seen on a real time analyzer if only the two rotational area frequencies, 59 and 60 Hz, were present, is shown in Figure 5. The result of this summation gives a 1.0 Hz difference modulation frequency, with a period of 1.0 second per cycle. A real signal from a two pole motor would have all of the frequencies given in Table 1 producing a much more complicated waveshape, such as that shown in Figure 6. This figure shows a two pole motor waveshape, with both the time plot and the frequency analysis of that wave for idle operation. Note that several harmonics are present on the 400 Hz frequency plot; but the high slot frequencies are not shown on this data, since they are off scale. For this idle condition, the slip speed would be so low that the period of the modulation would be in minutes rather than seconds and, thus, it is not really shown. Significant beat is not usually seen in the idle condition and is normally only present under load, as seen in the case problem presented forthwith.

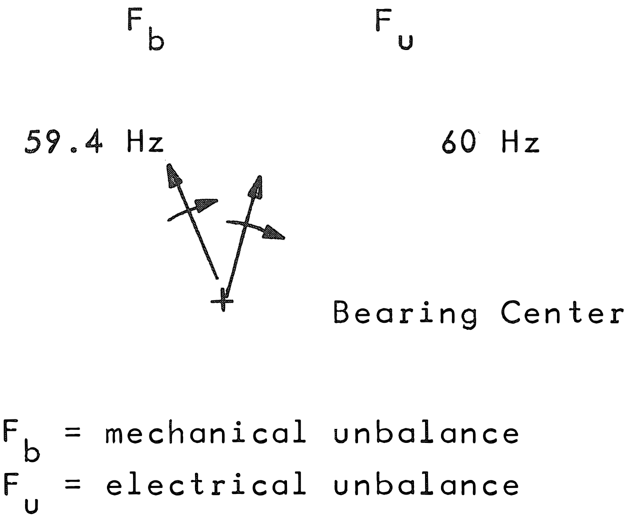

Figure 3. Rotation Forces at the Bearing.

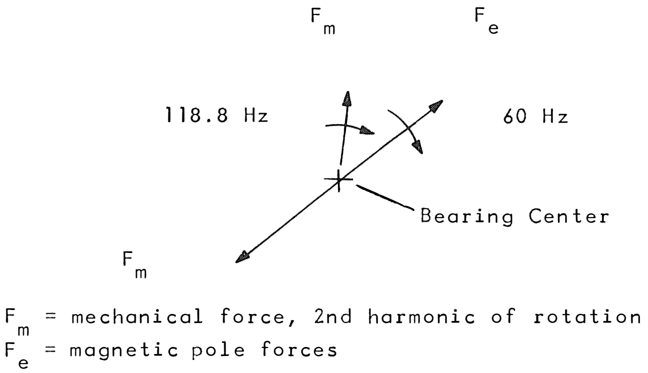

Figure 4. Twice Rotation Area Forces at the Bearings.

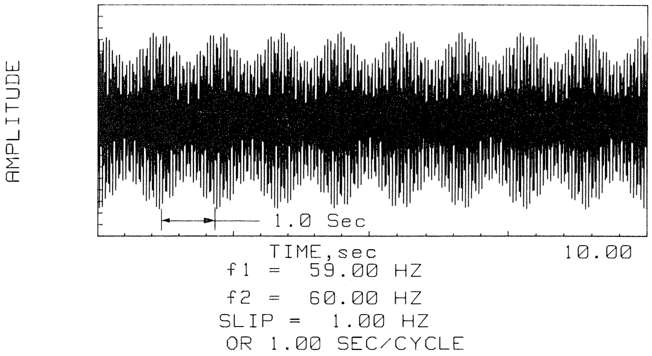

Figure 5. Summation of Two Frequencies.

It is important to note that rotationally related variations in either, or both, the rotor magnetic field or mechanical unbalance will impact the rotation area forces leading to higher one times rotation speed area modulation. In a very similar fashion, geometrically stationary variations in the electric field or mechanical alignment will cause higher 120 Hz area modulation levels. It is these two observations which can provide significant diagnostic tools for two pole motor problems.

The summation process of these mechanical and electrical forces also can take on linear or nonlinear results, depending upon the motor condition, giving further complication to the waveshape [2,3]. The waveshapes depicted in Figures 5 and 6 are linear summations, but there are nonlinear processes which exist in two pole motor operation, leading to very harsh vibrational conditions. In fact, these nonlinear processes are

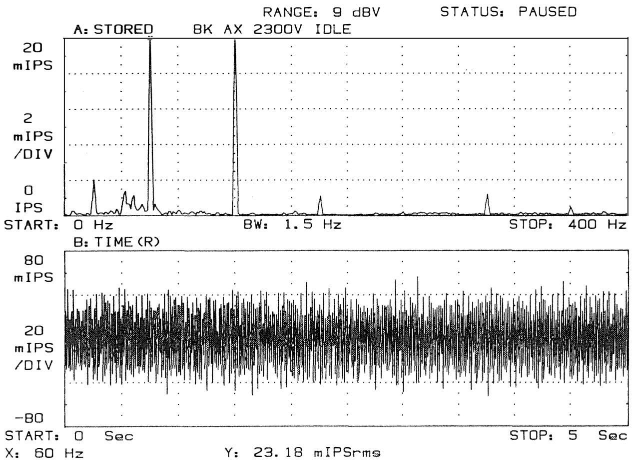

Figure 6. Vertical Bearing Housing Vibration Level in Time and Frequency Domains.

a major factor to be considered in many two pole motor problems.

Nonlinear summation of two sine waves is, at first, quite complex to understand, but with some basic review, successful analysis of waveshapes from such processes is possible. A linear summation of the two sine waves would sum just as that shown in Figure 5, from which an audible 1.0 Hz beat could be detected and observed on a vibration meter. Note, however, that in a frequency analysis of this signal, no low slip frequency level would be present—only the two original frequencies would result. In a nonlinear summation process, this would not be the case. For instance, suppose that the waveshape in Figure 5 is the vertical shaft vibration which was clipped, or restrained, on the negative downward side by the bearings. This means that each downward summation excursion would be clipped at the 1.0 Hz slip frequency rate. This process would be somewhat like adding a slip frequency square wave to the two sine waves. If a frequency plot of this summation was obtained, a 1.0 Hz slip frequency component would be found along with the two original 59 Hz and 60 Hz sine waves. A very similar result would be obtained if the upward extreme summation points were magnified by the magnetic pull, producing a distortion frequency rate equal to the slip speed. Additional sidebands come along with this low frequency which are further sums and differences from the two original sine waves [4]. Such nonlinear processes are quite easily attained in induction motors due to the high degree of nonlinearity in the magnetic forces and are a major contributer to two pole motor vibration problems. In fact, air gap forces are so nonlinear that the low frequency slip component can become far greater than the original 60 Hz or 120 Hz components (such a condition shown in the following case problem).

Sources of nonlinearity in a two pole motor include air gap eccentricity, rotor eccentricity, strong variances in the mechanical stiffness with respect to rotation, phase imbalance, rotor/stator core asymmetry, loose or broken rotor bars, and supply voltage imbalance. The electromagnetic field in an induction motor air gap creates a very nonlinear force with respect to eccentricity, which must be carefully controlled in motor manufacture and field operational installation. In practical terms, the nonlinearity of the magnetic pull requires that the air gap eccentricity be maintained less than ten percent and rotor core runout, with respect to the bearings, be restricted to less than three to four mils. Excessive shaft orbit, with respect to baring clearances, caused by either bearing problems or very high imbalance, can result in clipping the motion or magnifying the magnetic pull, giving a moderate nonlinear beat condition. In such cases, trim balancing or changing the bearings can solve the problem.

Diagnosis of two pole motor vibration problems should start with an examination of the 60 Hz and 120 Hz areas for the presence of excessive sidebands and whether slip or twice slip sideband frequencies predominate. The severity of the problem can be gauged by the presence of slip and twice slip low frequency levels in the frequency or time plot. If numerous slip sidebands predominate at 60 Hz in magnitude and level, then the problem is likely to be rotationally related. If strong 0.6 Hz slip frequency is present, the problem is more severe. Strong twice slip sidebands at 120 Hz, with or without a twice slip frequency level, indicate a stationary problem related to the bearings or the effective concentricity of the stator field. Again the severity of the problem can be gauged by the presence of the twice slip frequency at 1.2 Hz.

A summary of possible motor/installation faults with typical effects is presented in Table 2. This table is a general guideline to help investigate two pole motor problems in operation under load. Each type of fault appears to be easy to diagnose alone, but in the real case there are multiple faults requiring some interpretation as to which is the main culprit. Only experience and practice in resolution of such problems can finally give any large degree of success with two pole motors, but practical results can be obtained. Diagnose the problem in terms of the ideas presented and give alternative faults which can be verified by other testing or inspection.

CASE PROBLEM

The case problem data in Figures 7, 8, 9 and 10 are from full load dynometer tests on a 600 hp motor which experienced severe vibration at 0.4 ips to 0.5 ips levels in the field. In the idle condition, the highest vibration level at the bearings was 0.05 ips, a very acceptable result. Full load tests on the dynometer, however, gave results similar to the field condition. An averaged bearing signature for the outboard bearing showing 0.35 ips vibration is shown in Figure 7. The shaft vibration (in mils), with an exceptionally strong low frequency 0.6 Hz nonlinear beat summation occurring, is depicted in Figure 8. The smaller variations riding this low frequency "square wave" are the 60 Hz and 120 Hz vibrations. A "zoom" with a real time analyzer on the rotation area showing both 1X and 2X slip sidebands is presented in Figure 9, but the 2X slip predominates. The 120 Hz area shows very strong 2X slip sideband energy present. Audibly, the motor had a very strong pulsating roar at this same 0.6 Hz rate. Such results are a strong indication of stationary electrical eccentricity, which was verified in subsequent motor teardown. The air gap was found to be 20 percent eccentric, due to the stator core offset, with respect to the bearing bracket to housing headfit. Removal of the condition cured the problem.

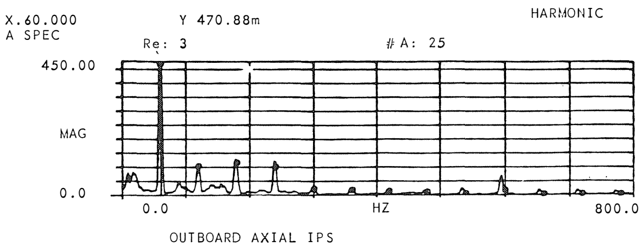

Figure 7. Bearing Signature at Full Load.

Table 2. Diagnostic Table of Motor Faults.

Problem	Effect	Comments
Eccentric air gap	(1) 120 Hz (2) 2(s) sidebands with some low frequency s (3) 120 Hz will be much higher than 2(rotat.)	(1) Air gap variance should be less than 10% eccentric in vertical or horiz. (2) Usually will operate quite smoothly in idle condition. (3) Twice slip sidebands will occur at 120 Hz very strongly but will also be at 60 Hz with less predominance. (4) In stronger cases of 20% eccentricity, very high slip frequency will occur at levels greatly exceeding the 60 Hz or 120 Hz levels.
Rotor runout	(1) 60 Hz (2) 1(s) sidebands	(1) Rotor runouts should be less than 4-5 mils. (2) Hot rotor runouts can occur effecting the 60 and rotation level giving strong beat at slip frequency. (3) Rotor cage can loosen with temp. leading to rotor bow.
Phase imbalance	(1) 120 Hz (2) Can give 2(s) sidebands	(1) Similar impact as air gap eccentricity. (2) Phase imbalance can be caused by —resistance imbalance, —voltage imbalance, 5% from average is acceptable.
Interrupted rotor circuit	(1) 60 Hz (2) Several 1(s) sidebands (3) High rotor slot frequencies can occur	(1) Broken rotor bars, cracked bar/end ring joints, or cracked end ring. (2) Frequency of vibration depends on no. of faults such as the no. of broken bars. (3) Very load sensitive and can run quite smoothly in idle condition. (4) Rotor slot frequencies under load in a two pole application is typically 0.02-0.04 ips.
Mechanical unbalance	(1) Rotational frequency, approx. 59.4 Hz at load.	(1) Mechanical unbalance should be less than 0.5 mil at the bearings and more like 0.25 mil. (2) Large imbalance can give 60 Hz or 120 Hz effect.

s = slip frequency

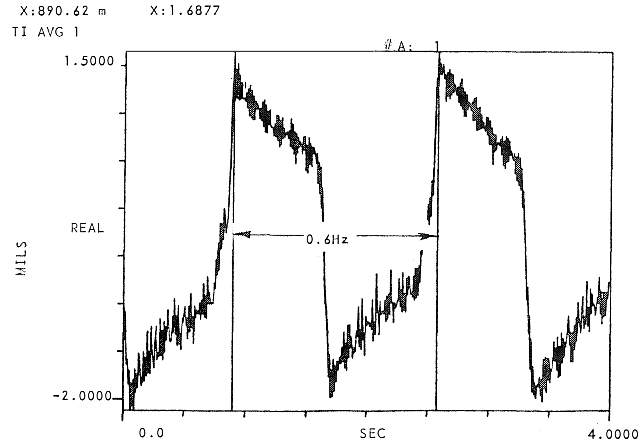

Figure 8. Full Load Shaft Vibration in Mils.

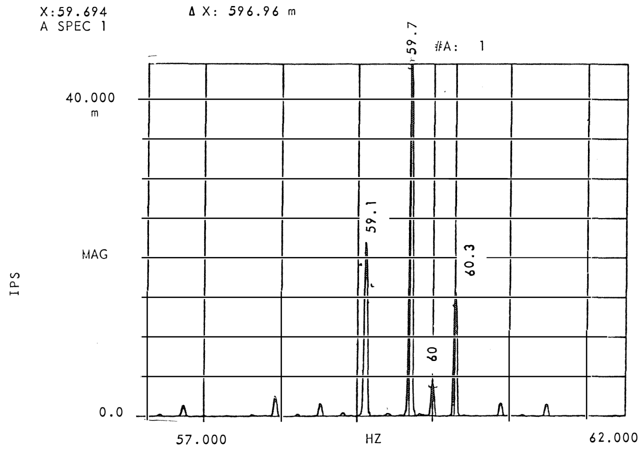

Figure 9. Analyzer "Zoom" on the Rotation Area.

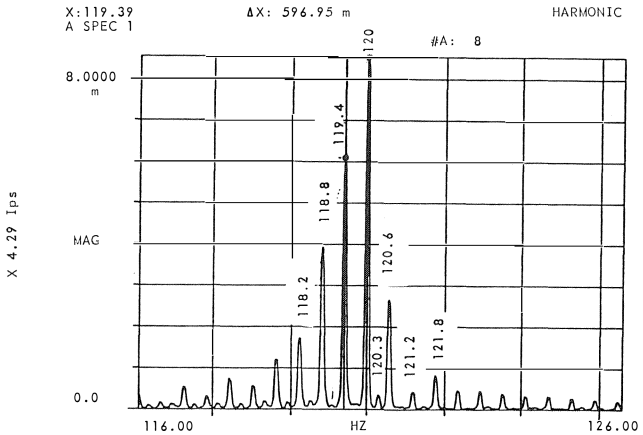

Figure 10. Analyzer "Zoom" on 120 Hz Area.

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