

A Study of 2sf Beat Phenomena in Induction Motors

— Found out of AKIYAMA'S WAVE —

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Abstract

An induction motor with an eccentric rotor sometimes generates vibrations and noises caused by a 2sf beat phenomenon. The author's group has proved that the 2sf beat phenomenon takes place only when dynamic eccentricity or partial dynamic eccentricity is involved in the type of eccentricity.

Further proved was a fact that the 2sf beat phenomenon does rarely occur only with a single factor of a dynamic eccentricity rotor and mechanical resonance plays a role in generating the phenomenon. In the course of the study, we found that Akiyama waves as shown in Fig. 4 to 6 exists during the 2sf beat phenomenon. Fig. 1 shows typical four types of eccentricity and the phenomenon was seen only with types B and D and not with A or C.

1. Introduction

It is known that the induction motor sometimes produces beat-like vibration and noise at 2sf Hz, i.e. the frequency twice as high as the slip frequency (2sf beat phenomena). Such phenomena are sometimes observed in devices with long bearing spans such as wound-rotor type motors and 2-pole machines. Sometimes, capacitor motors for household machines (totally enclosed slots) also produce the 2sf beat phenomena with electromagnetic noise.

Details of such phenomena have been described in the papers the author have already published, but the cause of the phenomena has not been completely clarified. The author has formulated a hypothesis that the phenomena are caused mainly by rotor eccentricity in the induction motor, or more precisely, by electrical, magnetical and mechanical asymmetry of the rotor, (1), (3). This hypothesis, however, has not been demonstrated through experimental means.

This paper is a report of experiment where the relation between the eccentricity form and the 2sf beat phenomena is proved. For the experiment, the authors classified the rotor eccentricities into four forms and prepared four experimental motors corresponding to the four forms. The authors have newly found in this experiment that the 2sf phenomena is strongly related to the resonance of the mechanical system in the motor.

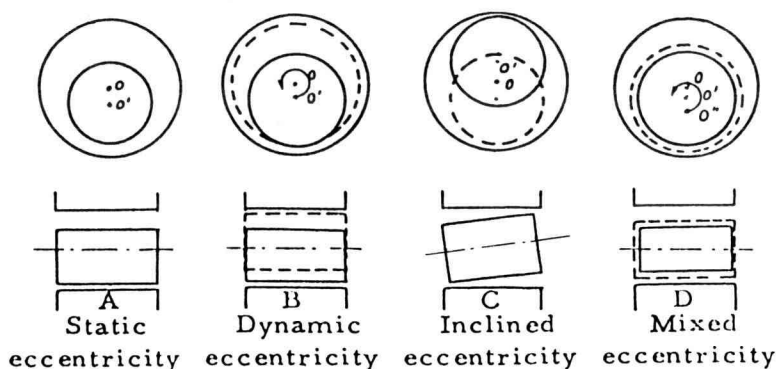


Fig. 1. Classification of four forms Mechanical Rotor Eccentricity

2. Four Forms of Rotor Eccentricity in Induction Motor and Their Examples

As mentioned above, 2sf beat phenomena are caused not only by mechanical eccentricity, but also by electric and magnetic asymmetry. This report, however, addresses the mechanical rotor eccentricity only. The authors classified eccentricities into four forms as shown in Figure 1.

(Note) It can be proved that 2sf beat phenomena resulting from other factors (electric or magnetic asymmetry) fall within either of these four mechanical eccentricity forms.

Among the forms shown in the figure, A) and B) are usually called “static eccentricity” and “dynamic eccentricity” respectively. In addition to these, Akiyama identified C) and D) and named them “inclined eccentricity” and “mixed eccentricity” respectively.

The static eccentricity A) concerns an improperly located bearing center, the dynamic eccentricity B) involves a bent shaft (which causes whirling), the inclined eccentricity C) is caused by improper alignment of right and left bearing centers, and the mixed eccentricity D) comprises some of the eccentricity forms A, B and C. Almost all of the mechanical eccentricities fall either of these four forms.

(Note) In rotors of totally enclosed slots used in single phase motors or made by aluminum die casting, thickness of the teeth tip tends to be unbalanced during processing of rotor profile. It can be proved that difference in tip thickness (asymmetry) results in magnetic asymmetry of the rotor, which causes the same effect (influence) as the dynamic eccentricity B). In fact, the authors have investigated the rotor eccentricity ($\epsilon = (\Delta_{\max} - \Delta_{\min}) / 2\delta_0$) of various motors from manufacturers in many countries and found that the eccentricity of induction motors is about 40%.

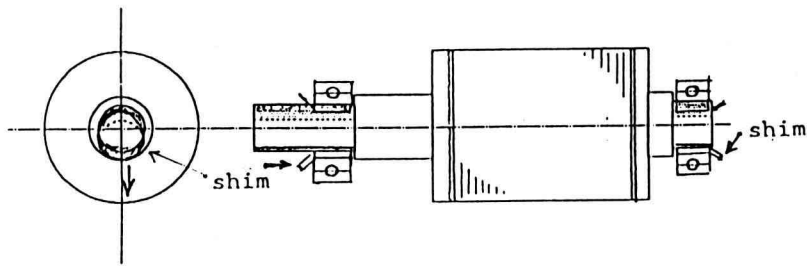


Fig. 2. Preparation of Dynamic Eccentricity Rotor

3. Preparation of Motors with Various Eccentricity Forms (four forms)

A) Static eccentricity motor

This can be obtained by designing right and left bearing brackets so that they are loose fitted (at lower part inside). A thickness gauge is used during rotor assembly to provide a desired amount of eccentricity.

B) Dynamic eccentricity motor (rotor)

It is quite difficult to prepare this type of motor. The shaft can be forcibly bent under pressure using a press, for example, but it is extremely difficult to obtain a desired eccentricity rate.

For this experiment, the authors adopted the method using a shim as shown in Figure 2. Specifically, the diameter of the shaft to support the bearing is designed to be thin, and a shim having arbitrary thickness is inserted between the shaft and the bearing. This causes the center of the ball bearing not to be aligned with the center of the shaft (See Fig. 2).

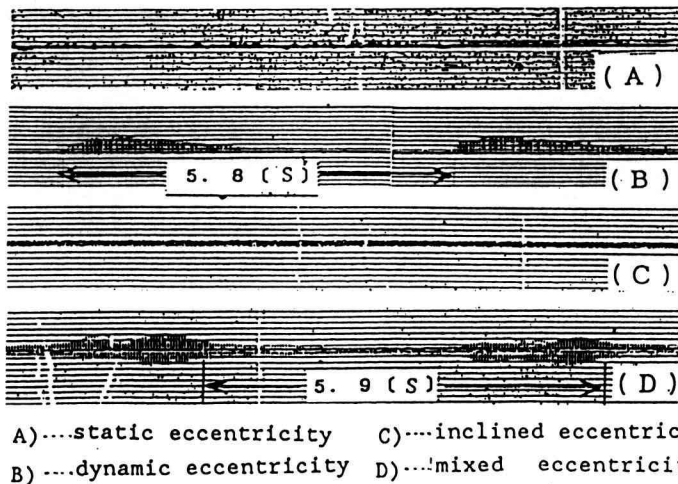


Fig. 3. Examples of 2sf Beat Phenomena (Four Forms)

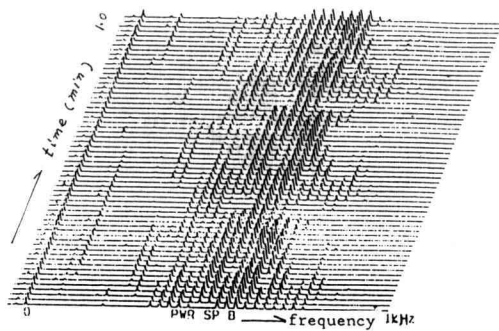
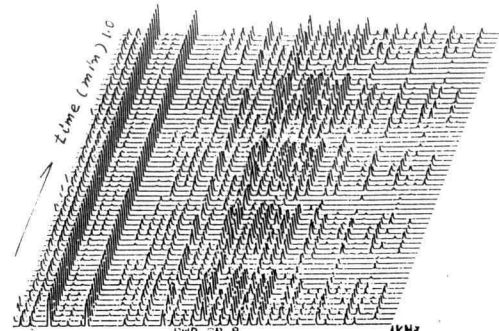
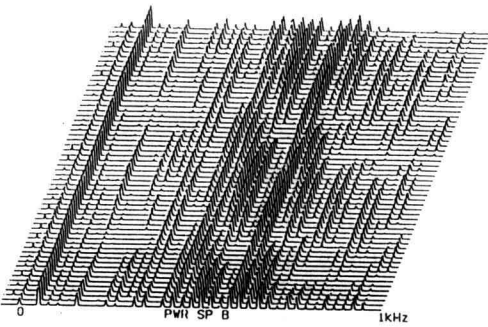
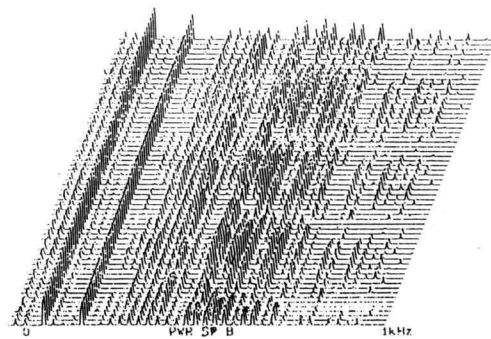
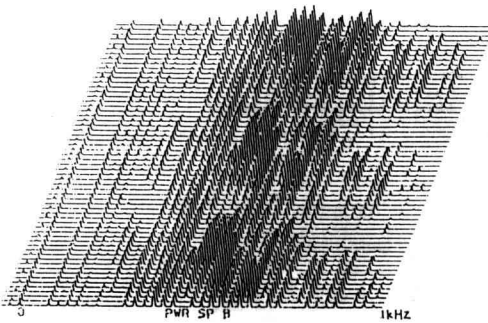
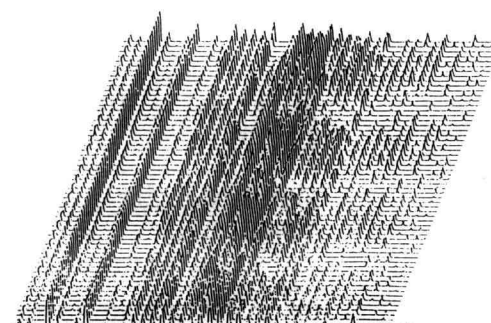
(4-1 , $\epsilon = 0.3, 80V$)(5-1 , $\epsilon = 0.5, 80V$)(4-2 , $\epsilon = 0.3, 100V$)(5-2 , $\epsilon = 0.5, 100V$)(4-3 , $\epsilon = 0.3, 140V$)(5-3 , $\epsilon = 0.5, 140V$)

Fig.4. 4. pole 1.5 kW squirrel-cage induction motor (prepared model motors)
B)···dynamic eccentricity $\epsilon = 0.3$ (80V ~140V)
FFT Analyzer Frequency Analysis of Frame Vibration in 2sf Beat Phenomena

Fig.5. 4. pole 1.5 kW squirrel-cage induction motor (prepared model motors)
B)···dynamic eccentricity $\epsilon = 0.5$ (80V ~140V)
FFT Analyzer Frequency Analysis of Frame Vibration in 2sf Beat Phenomena

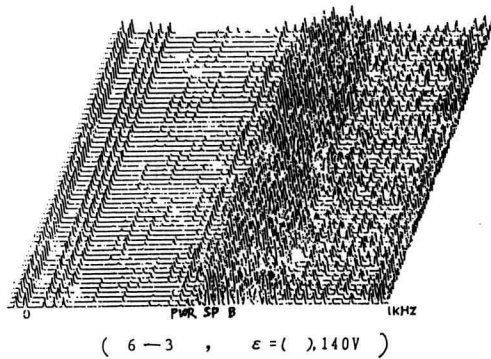
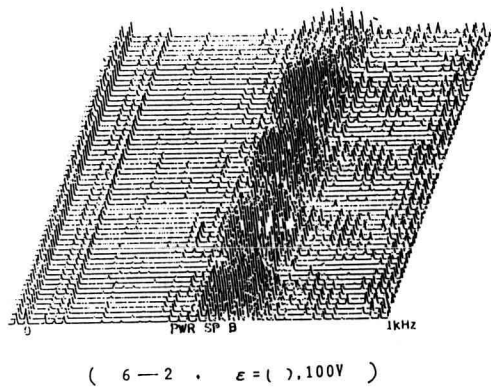
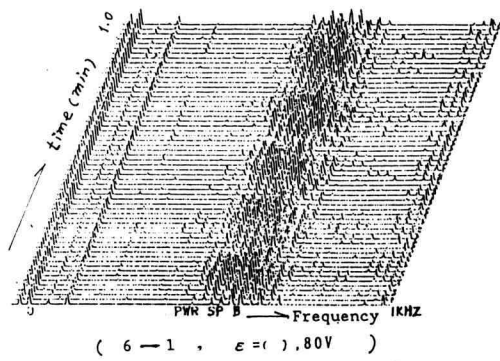


Fig. 6. 4. pole 1.5 kw squirrel-cage induction motor prepared model motors
 D) 'mixed eccentricity $\varepsilon = ()$ (80V ~ 140V)
 FFT Analyzer Frequency Analysis of Frame Vibration in 2sf Beat Phenomena

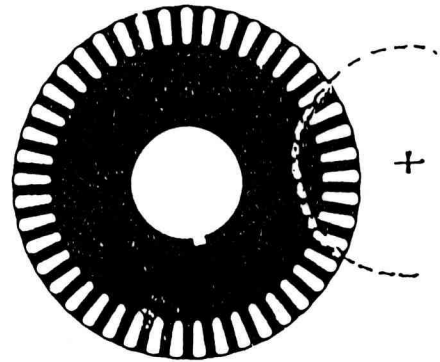


Fig. 7. Partial cutting of Rotor Bar by Milling Cutter

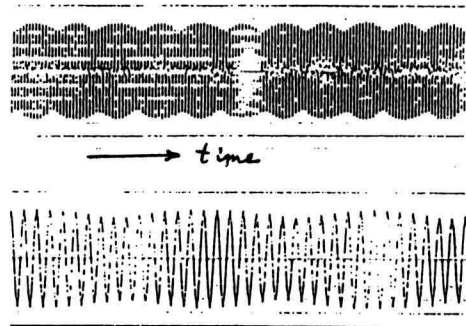


Fig. 8. 2sf Beat Current due to Electrical Asymmetry

C) Inclined eccentricity motor

Theoretically, this may be provided by adjusting the center of right and left bearing brackets as in the static eccentricity motor A) or by mounting a shim to the rotor as in the dynamic eccentricity motor B). For this experiment, the authors adopted the method of A), which is the simplest.

D) Mixed eccentricity motor

For this, we used the methods in A) and B). The author first prepared a rotor with a certain dynamic eccentricity as in B) and then incorporated it into a motor using the method in A) (adjustment of bearing bracket center) so that the motor had a certain static eccentricity.

Thus, the authors successfully prepared model motors for four forms of eccentricity. Following is the report of experiment using the eccentricity motors thus prepared.

4. Various Eccentricity Forms and 2sf Beat Phenomena

The authors actually operated the experimental motors for various eccentricity forms prepared as described above so as to study 2sf beat phenomena (In this experiment, the author used a standard 4-pole 1.5 kW squirrel-cage induction motor from Toshiba).

In the experiment, the motor was operated under no load so as to avoid the influence of load and the applied voltage was adjusted so that the slip became close to the actual value (0.5 to 2%) (if the voltage is fully applied, the beat cycle will be too long).

Figures 3 shows the experiment result.

Fig. 3 (A) shows the vibration on the frame measured with an acceleration pickup for a static eccentricity motor. This indicates no 2sf beat phenomena.

Fig. 3 (B) is for a dynamic eccentricity motor. The frame vibration obviously shows 2sf beat phenomena. This case is naturally accompanied by characteristic sound of the phenomena.

Figures 4 to 6 show vibration components with their frequencies analyzed with an FFT analyzer as the elapse of time. From these figures, we can learn that only a limited frequency component (with strong resonance) generates 2sf beat phenomena. In other words, the phenomena do not occur for all frequencies.

Fig. 3 (C) is for an inclined eccentricity motor. Obvious 2sf beat phenomena were not observed here (similar to the case of static eccentricity motor).

Fig. 3 (D) is for mixed eccentricity. We can observe 2sf beat phenomena, (but they are smaller than those observed for dynamic eccentricity). (It is assumed that they will be almost the same for the same dynamic eccentricity, but this is not verified.)

Fig. 7 shows a standard squirrel-cage rotor. Some of its bars or conductors are cut with a milling cutter to artificially provide electrical unbalance. Fig. 8 shows an oscillogram of current ripple in no load test with this rotor. From these figures, it is understood that electrical, magnetical and mechanical asymmetry of the rotor is concerned with 2sf beat

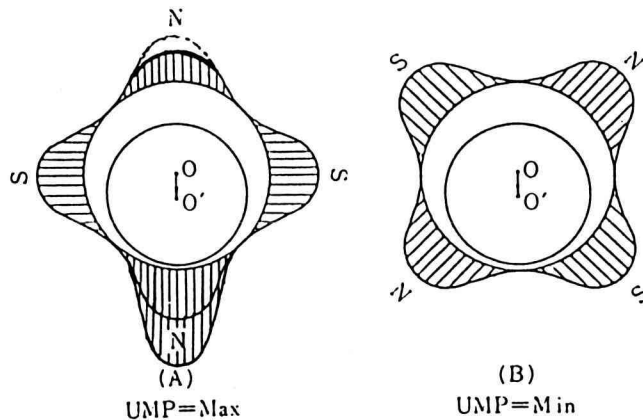


Fig. 9. 2sf Beat Phenomena in a 4-pole Machine
(Akiyama and Summers 2sf Beat model)

phenomena.

5. Examples of 2sf Beat phenomena

Although 2sf phenomena are rarely observed, the authors have had opportunities to observe such phenomena many times. Following is examples of 2st beat phenomena experienced by the authors. All of these are accompanied by vibration so strong that they may affect the lifetime of the motor and seriously complained. In addition, the author recently utilize 2sf beat sound to know the rotor quality and processing accuracy level. For example, we can learn broken rotor bar, eccentric processing of rotor for totally enclosed slot, bending of shaft and assembling accuracy by listening to 2sf beat sound. (Fig. 7, 8). Fig. 9 shows Akiyama and Summers 2sf Beat models.

5.1 Example of 2 pole 150 kW squirrel-cage induction motor

In this case, no particular problem was observed at the early stage of operation. Dozens of minutes after the start of operation, however, 2sf beat sound and 2sf vibration occurred and they became larger with the elapse of time. Fig. 10 shows the change in noise level at the motor recorded with a noise meter (level recorder). Large beat sound is observed here. The main frequency component was 100 Hz (98 Hz).

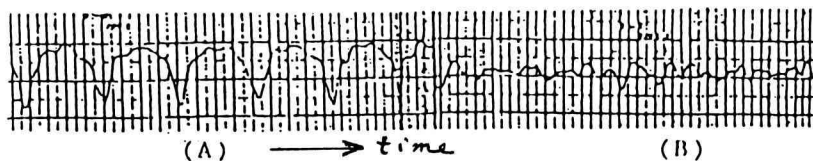


Fig. 10. Noise beats in a 2P-150 kW IM

Table 1. Relationship between Slip and 2sf Beat Count in Load Current in 2P-150 kW IM

| load current | Beat count per minute | Slip frequency per minute |
|--------------|-----------------------|---------------------------|
| 25 | 32 | 16~17 |
| 28 | 36 | 18~19 |
| 30 | 42 | 21~22 |

Fig. 10 (A) shows the change in noise level with the elapse of time when no load is applied, (crest) and (B) shows values under (trough). As shown in Table 1, the beat cycle becomes shorter as the load increases and corresponds to the cycle of 2sf [Hz]. In this case, the noise level was higher than normal products by 10 to 20 dB, and the motor frame vibrated strongly. The vibration was so strong that it might affect the lifetime of bearings and insulations. The beat vibration had crests and troughs, and at the troughs, the motor operates very quietly with vibration and noise at the same level as normal products. When the motor was operated under no (or light) load the motor current fluctuated largely corresponding to the beat cycle. Thus, 2sf beat noise and vibration are strong when the motor is operated under no load or light load and smoothed and reduced with the increase of load.

Fig. 11 gives the result of noise frequency analysis. The upper part shows the change in noise level with elapse of time; the middle part shows frequency components when vibration and noise are at a high level (crest) and the lower part shows frequency components when they are at a low level (trough). It is learned from these figures that the frequency component which shows change is 98 Hz (100 Hz) only, and other frequency components change little. In this case, the carrier (main) frequency of 2sf beat phenomena was 98 (100) Hz.

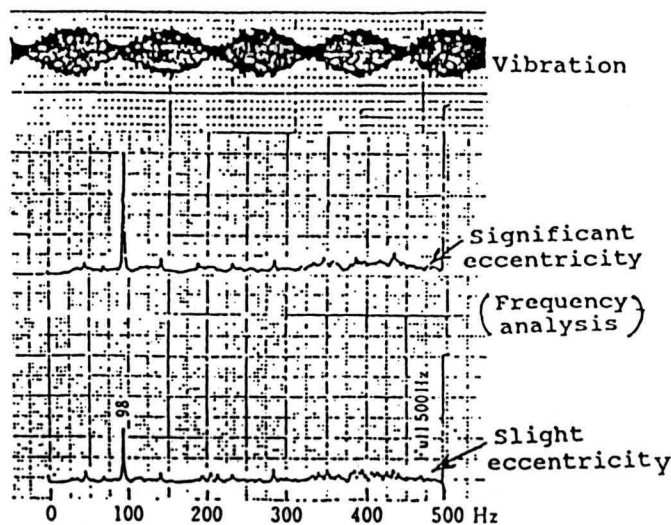


Fig. 11. 2sf Beat Phenomena in 2P-150 kW IM

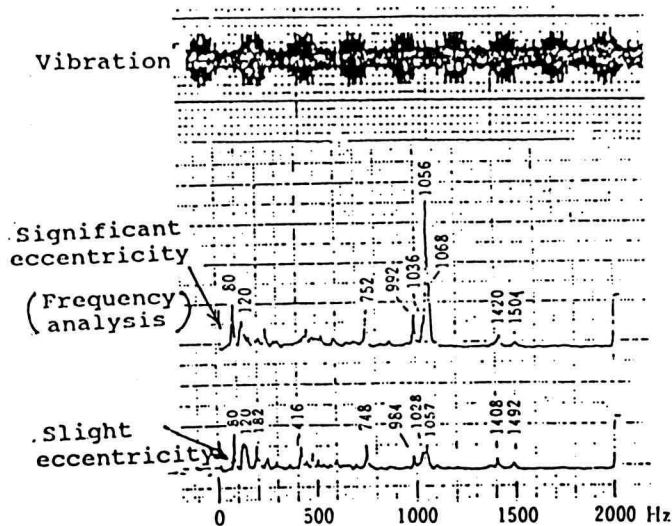


Fig. 12. 2sf Beat Phenomena in 16P-480 kW

5.2. Example of 16 pole 480 kW induction motor

This was an upright type pump motor provided with a squirrel-cage rotor for which we analyzed the noise frequencies when 2sf beat phenomena occurred. The upper part shows the change in noise level with the elapse of time, the middle part shows analyzed frequencies at crests with strong beat phenomena, and the lower part shows those at troughs with weak beat phenomena. The figure tells that the main or carrier frequency of noise (vibration) is 1056 Hz and other frequency components show little change. This is the slot ripple frequency for the rotor. Of the five motors we prepared for this experiment, only one showed 2sf phenomena. This motor showed some 2sf beat phenomena from immediately after being switched on (Fig. 12)

5.3. Example of 6 pole 75 kW wound rotor induction motor

This was a wound rotor type crane motor provided with slip rings. It had wide bearing spans and the first order critical resonance frequency of the rotor system is naturally low. In this case, vibration and noise at the carrier frequency of 120 Hz showed 2sf beat phenomena (for operation at 60 Hz).

One of the two motors manufactured was defective. It showed no problem immediately after being switched on, but after about 30 minutes of operation without load, it started to vibrate abnormally. An hour later, it vibrated so strongly that it could not stand still on the testing plate. It was then fixed at the legs with anchor bolts, but the vibration nearly broke the bolts. As in the case of 5.1, vibration corresponded to 2sf beat.

5.4. Example of 4 pole 370 kW motor for LNG pump at extremely low temperature

In this case, since the motor operated in an LNG tank at extremely low temperature, we could not directly measure the noise and vibration. However, we could find the defect because the motor current abnormally increase when the motor was operated with no load or light load. It was learned that the deflection frequency at ammeter changed in proportion to the increase of (slip) load, which meant that 2sf beat phenomena were occurring. Since the bearings were made of graphite, there was fear that the bearings may be damaged by the vibration of the rotor. To cope with this, we made a new rotor. Thus, even though vibration and noise could not be directly checked, 2sf beat phenomena was found from observation of the ammeter, so that we could take actions in advance. We did not actually take data, but we suppose the carrier frequency in this case was 120 Hz (for operation at 60 Hz) as in the case of 5.1.

6. Summary of 2sf Beat Phenomena

6.1. Points common to the above mentioned four examples

The points commonly observed in these four examples are :

- ① 2st beat phenomena with noise and vibration occur only at a certain frequency. We call this frequency "main frequency" or "carrier wave".
- ② There exists a resonance point of the mechanical system corresponding to the carrier wave of the above 2sf beat phenomena.
- ③ 2sf beat phenomena are mainly related to the dynamic eccentricity component due to bending of the shaft. In this case, the phenomena are observed after operation for a while.
- ④ In the experiment with four eccentricity forms, it was proved that the 2sf beat phenomena were caused by the dynamic eccentricity component. The relation of (1) and (2) above has been also proved.
- ⑤ The concept given by E.W. Summers (Fig. 9) will help understanding of the principle of the 2sf beat phenomena.

6.2 Causes of dynamic eccentricity and examination on them

As described above, it is quite difficult to provide a dynamic eccentricity component (b). It is hardly generated from usual manufacturing processes. In other word, when the rotor is processed with a lathe, processed shape is round in principle and the cutting is straight. Dynamic eccentricity cannot be given under normal temperature. If the temperature changes, however, there may be thermal deformation. For example, temperature at the rotor may increase during operation or the motor may be placed under extremely low temperature in an LNG tank. In such cases, large difference in temperature from usual temperature condition when the rotor is processed (normal temperature) may cause the material (of shaft, in many cases) to be deformed due to residual stress. This can be

considered as the main cause of the dynamic eccentricity.

For large machines, the assembly accuracy of the iron core may be another cause. In case of motors for indoor applications such as electric fans and air conditioners where quiet operation is required, if the motor is designed with totally enclosed slots, imbalance of magnetic resistances due to difference in teeth tip thicknesses and directionality of iron plates (difference in magnetic permeability μ between direction of rolling and the direction at right angles to the direction of rolling) has an effect equivalent to the dynamic eccentricity and may cause 2sf beat phenomena. These are the findings from the experiment this time.

7. Conclusion

As the result of experiment for various eccentricity forms, the authors concluded that 2sf beat phenomena are caused by the dynamic eccentricity component at the rotor. The experiment demonstrated the rightness of Akiyama's hypothesis.

Cuses of the 2sf beat phenomena have been mostly clarified from the experiment using model motors (for four forms of eccentricity) and examination on four examples of 2sf beat phenomena.

In short, the 2sf beat phenomena in induction motors are caused by dynamic eccentricity component (they are not caused by static eccentricity or inclined eccentricity). Significant 2sf beat phenomena are accompanied by resonance phenomena of the mechanical system.

The 2sf beat phenomena occur at a certain frequency (carrier wave) and are substantially not related to vibration and noise of other frequency components. It should be noted that the residual stress in the material of shaft system may largely affect the occurrence of dynamic eccentricity. As described above, the 2sf beat phenomena left unsolved for a long time have been mostly clarified in this experiment.

The author with to acknowledge the assistance received from Mr. Nakamura of our laboratory, who was in charge of actual experiment for this study.

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