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June 1985

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(Received May 13, 1985)

An examination and vibration measurements were conducted on the gas bearing type high speed helium gas circulator after the failure on April 1984 and the repairing on August 1984. The examination made clear that the cause of the failure and scratching of gas bearing pads and journal shaft was found.

The vibrational spectra showed a clear difference between failed and repaired conditions, and a frequency analysis technique by means of fast Fourier transform and a small-scale computer is expected as a useful method of diagnosis for circulators.

A conceptual scheme of gas circulator diagnostic system based on above principle is shown, and a basic process of diagnostic software is described.

Keywords: Gas Circulator, Helium Loop, Vibration, Gas Bearing, HENDEL, Gas Loop, HTGR, Diagnostic System, Fourier Transform, Computer Control

HENDEL 用ガス循環機（B_1）の開放検査及び振動特性

日本原子力研究所東海研究所高温工学部
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（1985年5月13日受理）

ガスベアリング式高速ヘリウムガス循環機に関する開放検査及び振動測定を同循環機の故障発生後の1984年４月と修理後８月に実施した。検査の結果，故障原因が明らかになると共に，ベアリングパッド及びジャーナルシャフトの摩耗が発見された。

故障時及び修理後の振動スペクトルは明白な相違が認められ，高速フーリエ変換及び小規模コンピュータを使用するガス循環機の診断法に関する見通しが得られた。

このような原理に基づくガス循環機診断システムの概念的構成を示すと共に，コンピュータによる診断用ソフトウェアの基本的処理過程を紹介する。

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1. INTRODUCTION

An examination and vibration measurements on the high speed helium gas circurator of HENDEL were conducted. This circulator was gas bearing type, and failed on April 1984.

The examination revealed that scratching of bearing pads and journal shaft had supposedly occurred by an unexpected bearing load and this was caused by losing-off of a tinny pin which was fixed by hammering and led to dynamic unbalance.

As the reference data, vibrational characteristics of this circulator was studied and the development of control and operation systems are now being progressed.

This report deals with the results of the examination, vibrational measurements and diagnostic system.

2. OUTLINE OF GAS CIRCULATOR AND LOOPS

Helium gas is circulated using five gas circulators at maximum pressure of 4 MPa and temperature of 400 °C as shown in Fig. 1.

The four circulators with centrifugal type impellers are connected in series to two gas lines (M_2, A) through B_{21}, B_{22}, B_{23} and B_{24}. The another one circulator with a regenerative type impeller, as shown in Fig. 2, is used in a gas line of smaller flow rate (M_1) of the HENDEL.

All circulators have vertical rotating parts and are sustained by the upper and lower journal bearings and also by the thrust bearing at the lower end of the rotating assembly.

The bearings of each circulator are gas bearing type, and their design are nearly the same. [1),2)]

The design of an electric motor for each circulator is also the same. Required powers for centrifugal and regenerative types, however, are a little different each other, because the hydrodynamical works and efficiencies are different accordingly.

The assembly of each blower and motor is encased in a pressure vessel with a water cooling jacket. Therefore any special sealing is not required except for one set of O-ring gasckets for the upper and lower flanges.

The main specifications of the circulators are shown in Table 1.

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3. OPERATING HISTORY

The gas circulator (B_1) was operated so far since March 1982 for about 3000 hours in total. Helium gas temperature, flow rate and rotating speed were between 100 to 360 °C, 40 to 400 g/s and 3000 to 12000 rpm respectively.

Temperature and rotating speed just before the failure are shown in Fig. 3. Temperatures of journal bearings were found to be low compared with the design temperature of 150 °C. Though the temperature of the thrust bearing was low, it had risen high just after the trip caused by the friction between rotating and stationary parts.

4. FAILURE OF CIRCULATOR

The circulator with a regenerative type impeller (B_1) failed on March 27, 1984, being removed from the loop, and was partly disassembled on site to examine the cause.

Visual observation revealed that a small steel pin which was fixed by hammering in the rotor had lost out. This gave rise to a large unbalanced force and made it impossible to keep gas film between the lower journal bearing and the shaft.

During the operation under this condition, matallic powder torn from worn-out parts caused the electrical short circuit of the rotating signal terminals and made the circulator stopped.

Temperature signals from the bearing pads, however, had kept unchanged as shown in Fig. 3. This is because the cooling capacity is larger than expected.

Besides the failure mentioned above, this circulator had trouble last November. The trouble was due to so-called hydro-mechanical instability or whirling, at the upper journal bearing. At that time, however, the circulator has not been fully examined for the cause of the trouble.

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examined at the factory of A.A. Rateau Co., France, from May to June 1984. The results of the observation were as follows:

(1) The failure was occurred only at the journal shaft and bearing pads of the lower side of the rotor.

(2) Scratched scars were found on the bearing pads and shaft as shown in Photos 1 and 2.

(3) A tinny pin was lost off from the rotor.

The weight of the tinny pin (m) was about 6 grams and generated centrifugal force (F) 10000 times as large as the static weight at maximum speed of 12000 rpm which was calculated by

$$F = (m/g)r\omega^2 = 6/9.8\cdot(62\times10^{-3})\cdot(2\pi\times12000/60)^2 = 6\times10^4 gf = 60\,kg_f$$

where, g: acceleration of gravity force ($9.8\ m/s^2$)
r: radius at which pin is fixed (62×10^{-3} m)
ω: angular velocity of the shaft (rad/s) (equivalent to 12000 rpm).

The maximum unbalanced force produced on the upper and lower journal bearings were recommended to maintain less than 15 kg_f and ascertained that this value was satisfied when manufacturing.

Consequently gas film in the lower journal bearing could not bear this unexpected load, and the journal shaft and bearing pads scratched.

6. VIBRATIONAL MEASUREMENT

Vibrational characteristic of the circulator was studied before and after the repair. Results of the measurement indicated the clear difference of both failed and recovered conditions.

6.1 Measuring Arrangement

Vibrational acceleration on the outer side of the circulator was measured at specified speeds on both failed and recovered conditions. Electric pulse signals generated at specified rotating speeds were detected to find out a correlation and to record rundown times.

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All sinals were recorded in magentic tapes using a 14 channels frequency-modulation data recorder as shown in Fig. 4.

Electrical isolation (electrical contact or non-contact) between rotating and stationary parts was measured to ensure the formation of gas film on the bearings.

Two sets of dual-trace oscilloscopes with 512 words digital memories were used to monitor the signals. The digiatl data of oscilloscopes were transferred to a high performance desk-top computer, YHP-9836C, by a general purpose interface bus (GP-IB) cable. The digital rotating speed signals from a pulse counter were also transferred to the computer.

A dynamic signal analyzer, HP-5423A, was used to transform vibrational signals into frequency domain spectral data by the finite Fourier integral method.

The electrical isolation through the gas bearings was also measured using a optical high frequency oscillograph.

The rotating speed of the circulator was plotted using a digital-to-analogue converter and a chart recorder.

6.2 Results of Measurements

The radial vibrational acceleration signals of the failed circulator at 3000 and 6000 rpm were shown in Figs. 5 and 6 respectively. The driving current, voltage and revolution signals from a magnetic pick-up were shown in these figures. As to the revolution signals, two pulses correspond to one revolution, namely each revolution generates two pulses.

The maximum rotating speed was maintained less than 6000 rpm for the failed circulator. Because, as for the lower bearing, it was feared that a satisfactory gas film could not form for the condition of the failed circulator.

Running time was also maintained as short as possible for the same reason.

Rundown time after turnning off was a little longer than expected as shown in Fig. 7.

The electrical isolation between the rotor and the stator of the failed circulator was found no good. This probably means that the shaft kept in continuous contact with the bearing.

After the circulator being repaired, the same measurement was carried out. Oscillograms of the vibrational signals and others were shown in Figs. 8 to 10.

The rundown time from 6000 to 0 rpm, as shown in Fig. 11, was extended twice as long as that of the failed circulator.

The electrical isolation across the gas bearings was improved as shown in Fig. 12 even at a low speed of 3000 rpm and became complete at over 4000 rpm. In the case of Fig. 12, one pulse which was transfereed from a provisional optical sensor corresponds to one revolution.

The dynamical unbalanced forces for the upper and lower bearings of the repaired circulator were reproduced with the tape which was recorded as preliminary data at the shop in France and were plotted in Fig. 13.

The vibrational acceleration of the inner case of the failed circulator was detected at the lower and upper journal bearing levels. Using these signals, vibrational spectral maps were drawn as shown in Figs. 14 and 15.

After the repair, the vibrational spectral maps in the whole range of rotating speed were also drawn as shown in Figs. 16 and 17.

The height of the data in the maps of Figs. 14 to 17 indicates vibrational energy in logalithmic scale.

The spectra shown in Fig. 14 for the failed circulator are irregular. In other words, the vibration at a position of lower bearing is irregular. As for the upper bearing of the failed circulator, the irregularity decreases to a certain degree as shown in Fig. 15. On the other hand, the second order harmonics of rotating speed as well as induced noises from the 50 Hz commercial electric line appeared.

As for the maps for the repaired circulator, as shown in Figs. 16 and 17, irregular components of vibration disappeared completely, and the higher harmonics of vibration, however, clearly appeared.

The difference of conditions can be clearly judged by these maps, and the frequency analysis technique gives useful information for diagnosis.

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The measurement of vibrational signals of the circulator proves that the fast Fourier transform of the vibrational time-domain signals carried out. Oscillograms of the vibrational signals and others were shown in Figs. 8 to 10.

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As for frequency domain signals of the repaired circulator, basic modes of vibration appeared more clearly than irregular noises.

It is seen from Figs. 16, 17 and 13 that the resonant spectra of higher order harmonics appear in the maps and the curve of unbalanced forces is not parabolic. This might be because the rotor did not vibrate as a simple rigid body but as a complex structure.

It was concluded that the failure detection method using temperature measurement was not appropriate because the damage developes so fast that time delay of the detection could not follow.

Therefore a more reliable and quick-respondent method was required for the safe operation of gas circulators.

The combined use of a fast Fourier analyzer and a small scale computer is hopeful for this purpose. This method, if used with a time-sharing tequnique, will be applicable for several circulators simultaneously.

In order to develop a more reliable system for safety, further studies on bearing technology and tribology will be needed.

8. DIAGNOSTIC SYSTEM

The conceptual scheme of gas circulator diagnostic system is shown in Fig. 18. Vibrational signals are detected with two acceleration probes on the outer surface of the casing at levels of the bearings.

The pulse signals transmitted from the electro-magnetic or optical pickup are used for finding rotating speed of the circulator as well as the force vector. They are also used for synchronizing the vibrational signals to the revolution periods in order to average the data by an analyzer.

The amplified vibrational signals are transferred to a dual-channel fast Fourier analyzer, being transformed into a frequency-domain spectra. The transformation for one channel is carried out in 50 milliseconds at the maximum speed. This procedure is repeated continuously by the commands sent from a computer.

Then the spectral data at both of the upper and lower positions are transferred from a circulator to a computer through a GP-IB cable.

The standard spectral data of a circulator are always stored in a is a great help to the judgement of the circulator cindition.

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The standard spectral data of a circulator are always stored in a

high speed magnetic disk or bubble memories as a "data base" over the whole range of revolution.

The basic process of diagnosis in computer software is as follows:

(1) Detecting of rotating speed of a circulator by the data obtained with a counter

(2) Sending commands to an analyzer in order to transform and average the data

(3) Receiving spectral data arrays of a circulator

(4) Chosing standard spectral data arrays from the "data base" corresponding to a circulator and its rotating speed

(5) Comparing and analyzing of the measured spectral data with the standard "data base"

(6) Output of operator's guiding messages, alarm and control signals to an instrumentation system

(7) Switching of obtaining data among several circulators, if any, and repeating the process.

The above process from (1) to (7) is repeated continuously several ten times a second. Then the safety of the operation of the circulators could possively to be ascertained.

The system described above is now under development.

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REFERENCES

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Table 1 Specifications of Gas Circulators for HENDEL

CIRCULATORS	B_1	B_{21}, B_{22}, B_{23}, B_{24}
(1) BLOWER:		
type	1 stage regenerative	1 stage centrifugal
Fluid	Helium gas	Helium gas
Rotation Speed	3000 to 12000 rpm	3000 to 12000 rpm
Max. Gas Pressure	4.5 MPa	4.5 MPa
Max. Gas Temp.	400°C	400°C
Nominal Flow Rate (at 400 deg, 4 MPa)	0.4 kg/sec (9.4 cub-m/min)	4.0 kg/sec (94 cub-m/min)
Nominal head (same as above)	2kg/cm^2 (6780 m)	1 kg/cm^2 (3390 m)
Journal Bearing (upper & lower)	3 segments, tilting pad	3 segments, tilting pad
Thrust Bearing	6 segments, tilting pad	6 segments, tilting pad
Lubricant	Helium gas	Helium gas
(2) MOTOR:		
type	2 poles, 3 phases	2 poles, 3 phases
Voltage	100 to 440 Volt	100 to 440 Volt
Frequency	50 to 220 Hz	50 to 220 Hz
Rated Power	119 kW	238 kW
Rotor Weight	∿140 kg	∿140 kg
Total Weight	∿1390 kg	∿1400 kg

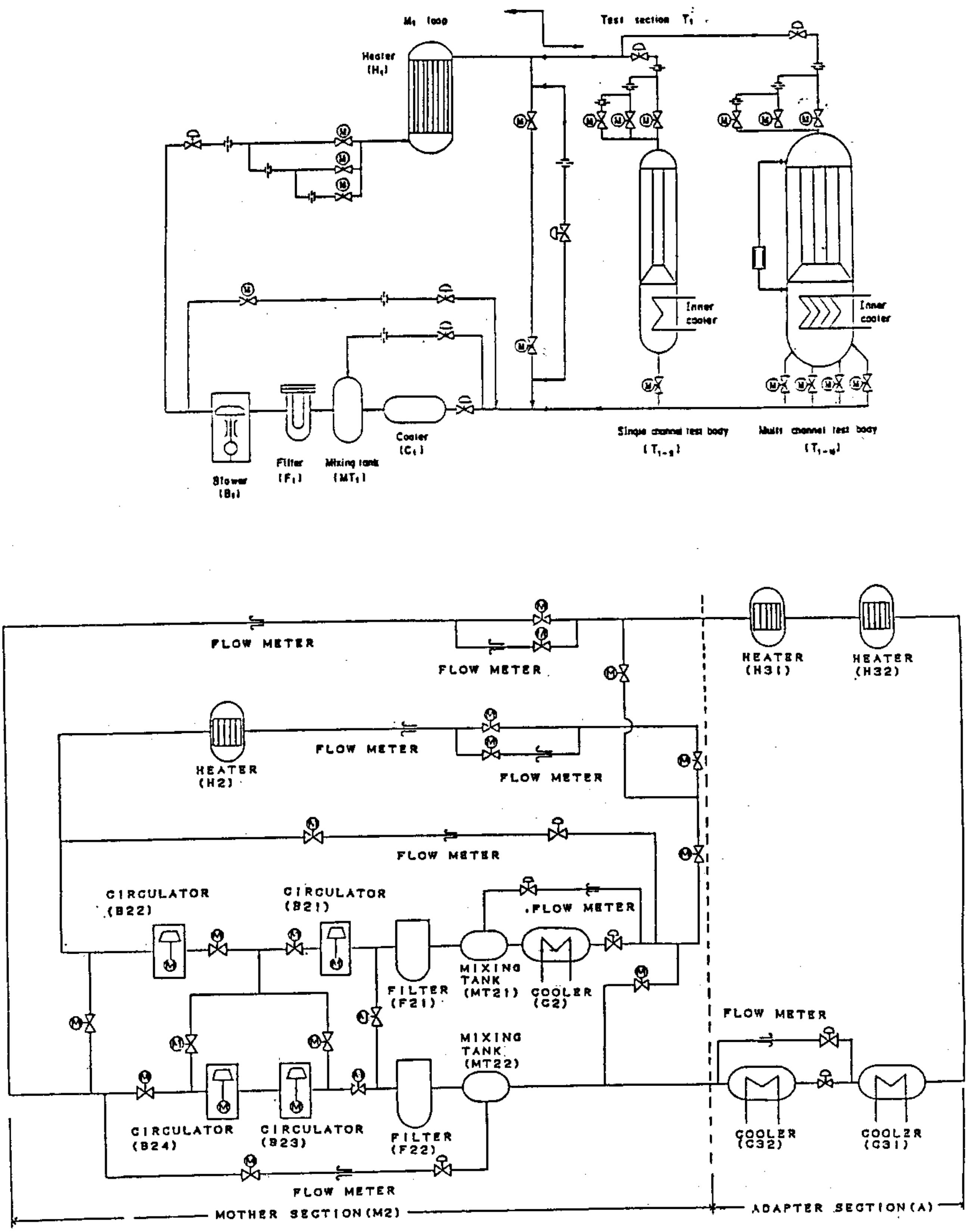

Fig.1 Flow Diagram of HENDEL

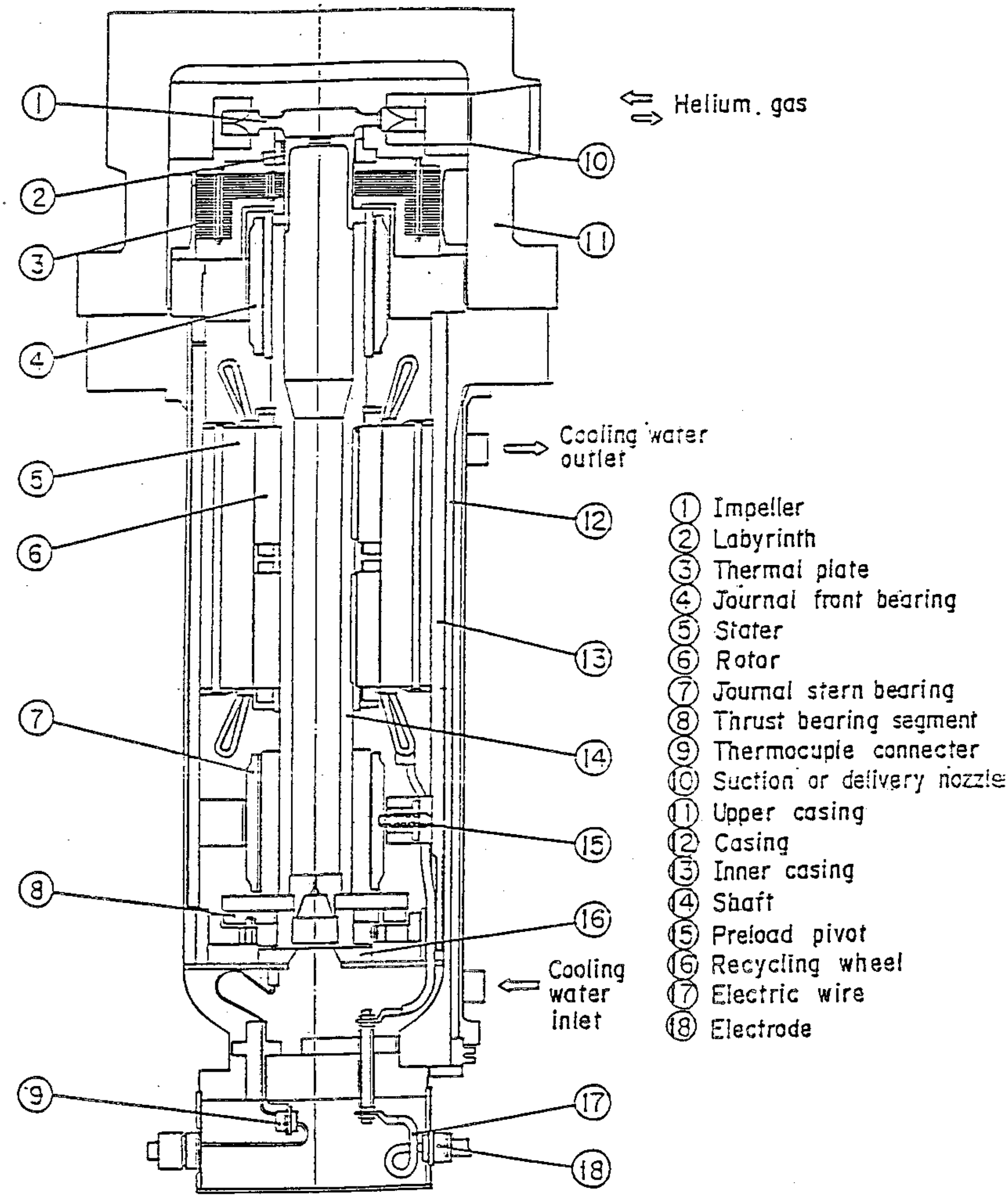

Fig. 2 Sectional View of Gas Circulator (B_1)

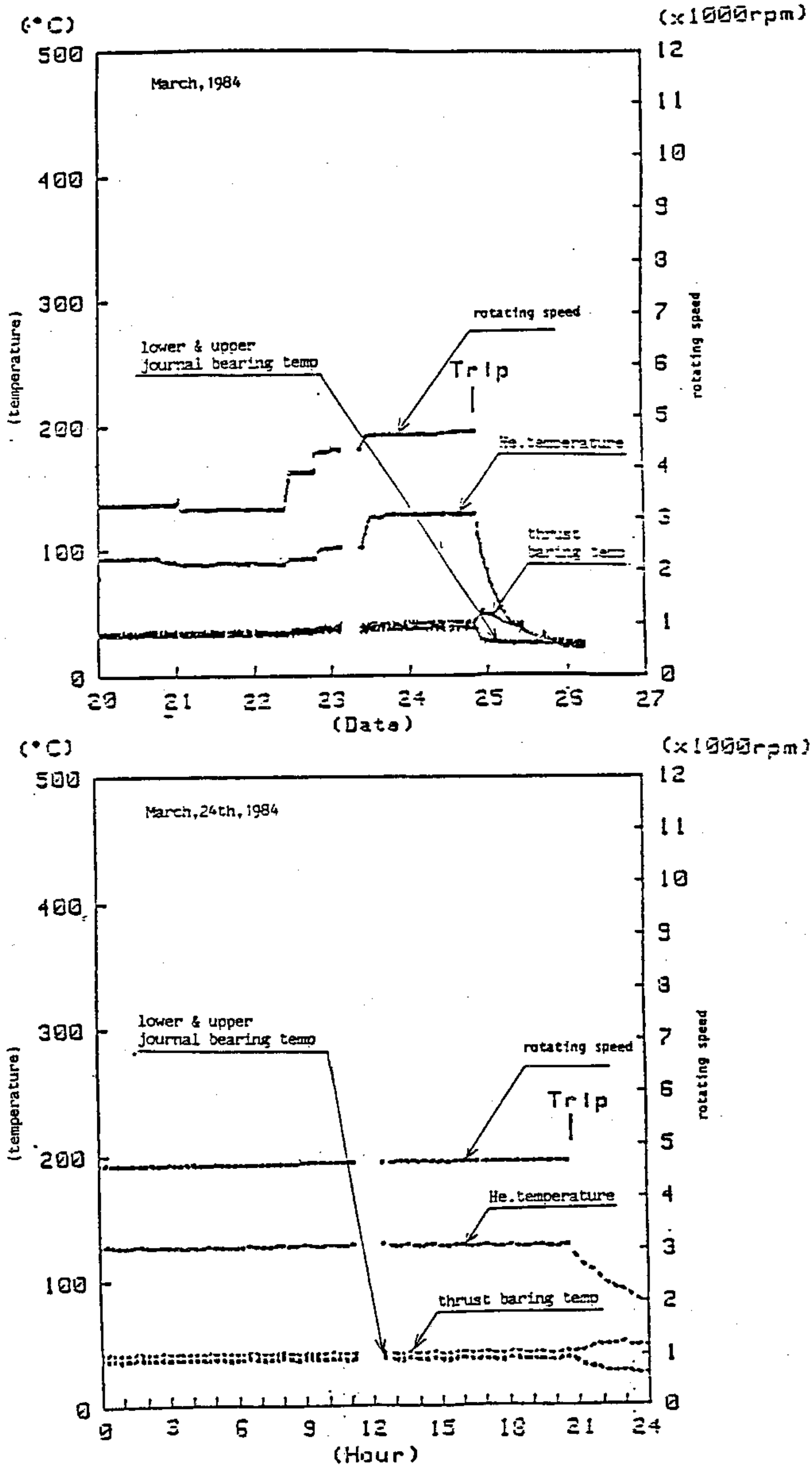

Fig. 3 Operating History of Gas Circulator (B_1)

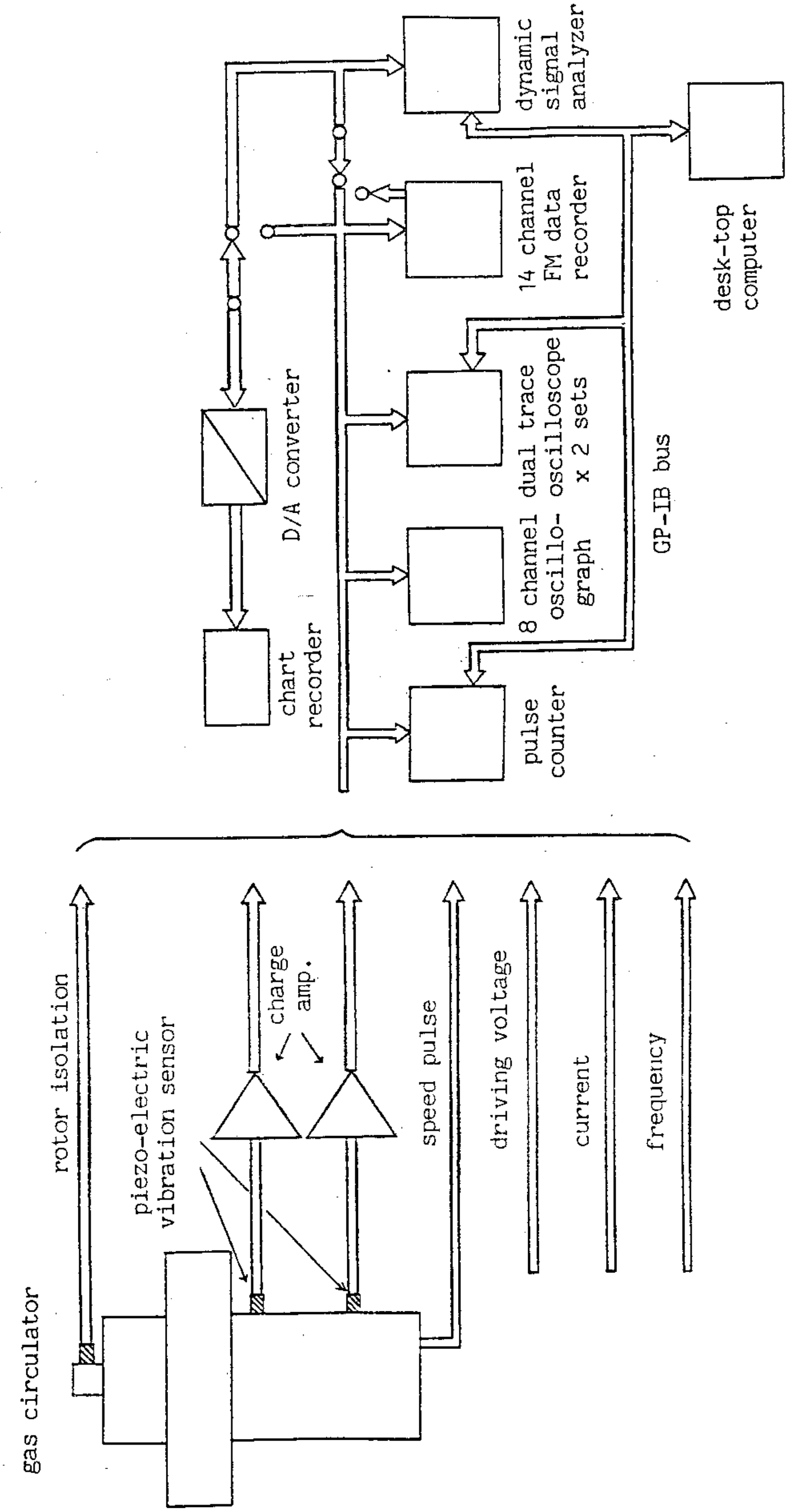

Fig. 4 Measuring Arrangement for Gas Circulator B_1

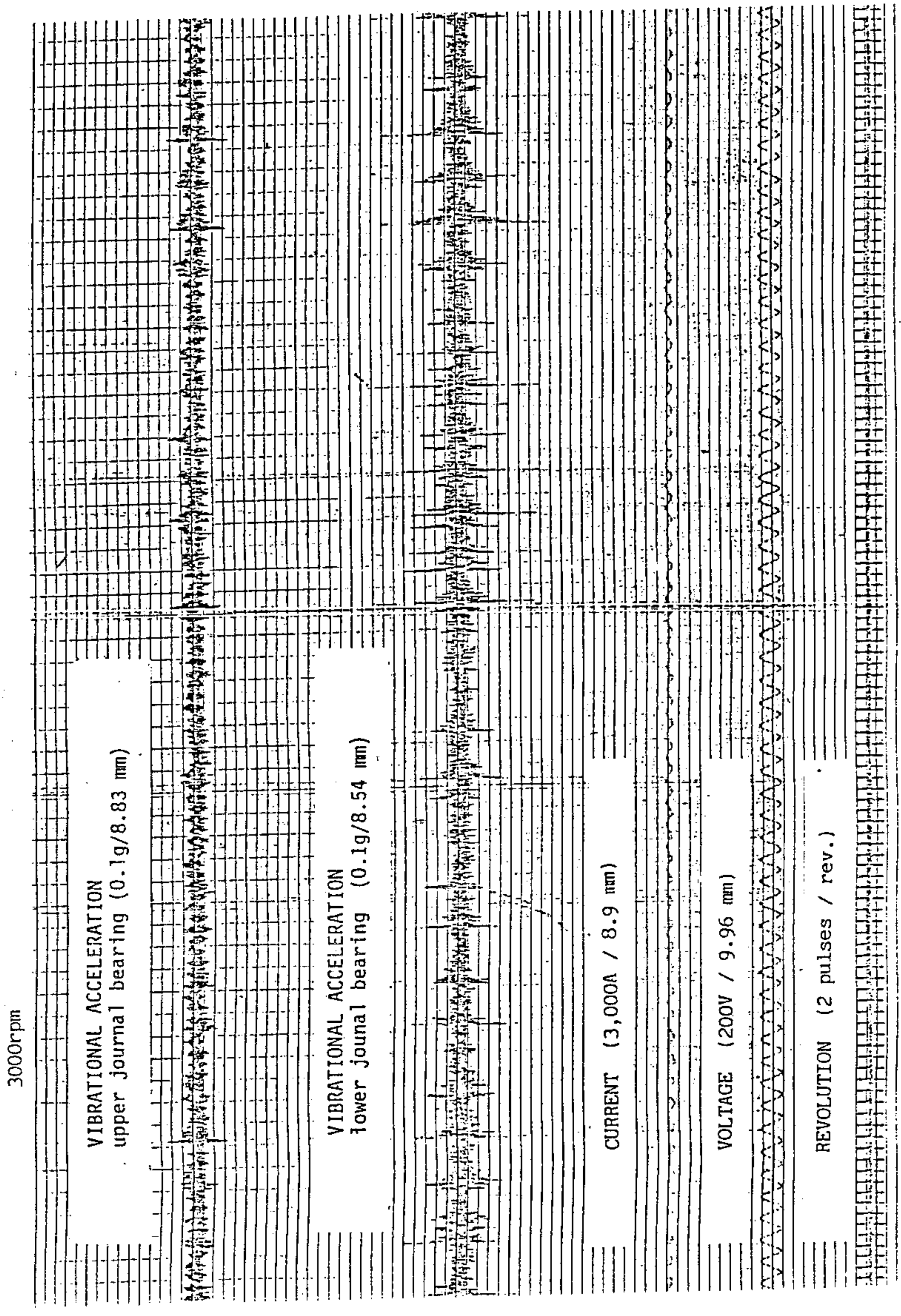

Fig. 5 Vibrational Acceleration, Current, Voltage and Revolution Pulses of Failed Gas Circulator at 3000 rpm

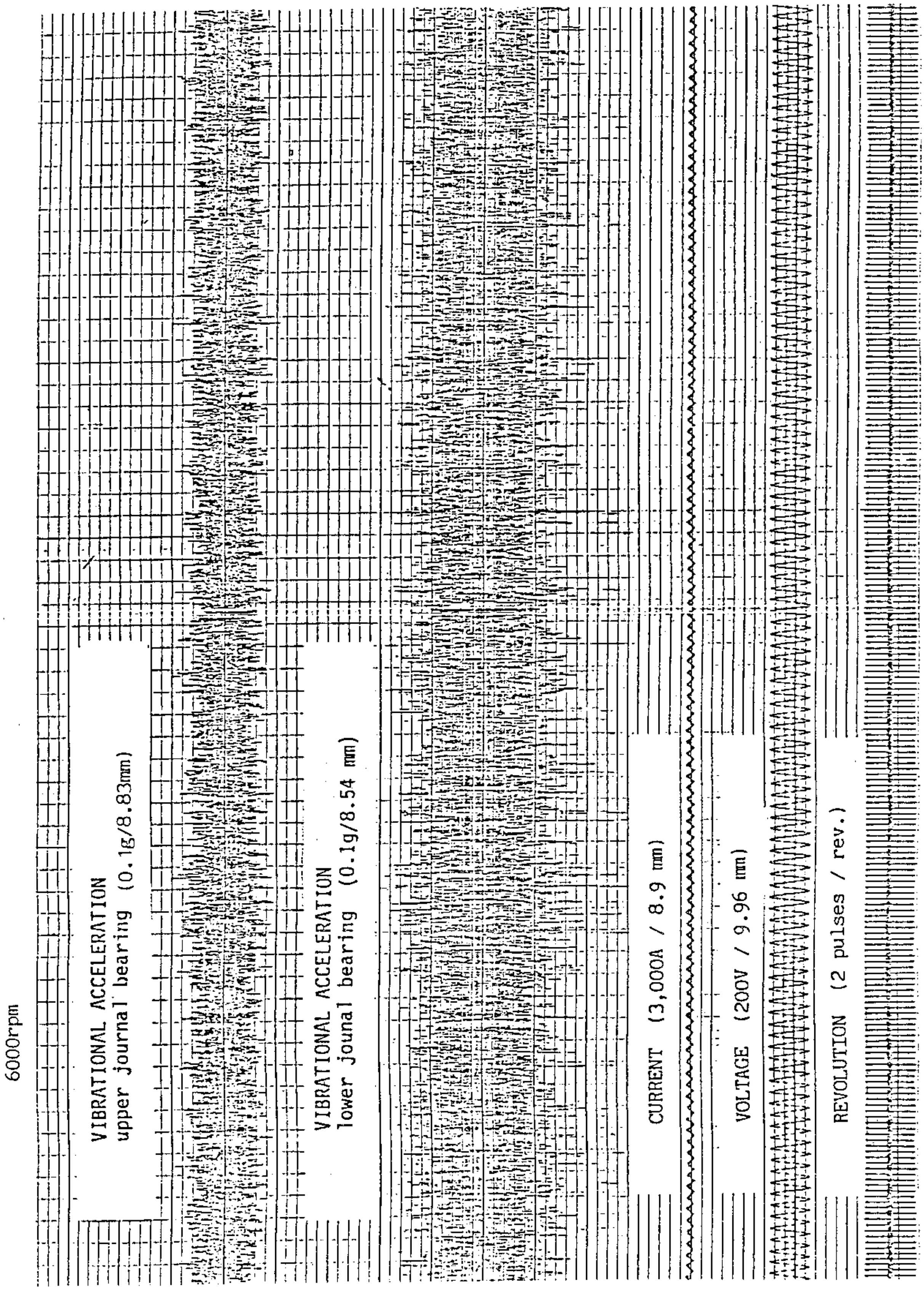

Fig. 6 Vibrational Acceleration, Current, Voltage and Revolution Pulses of Failed Gas Circulator at 6000 rpm

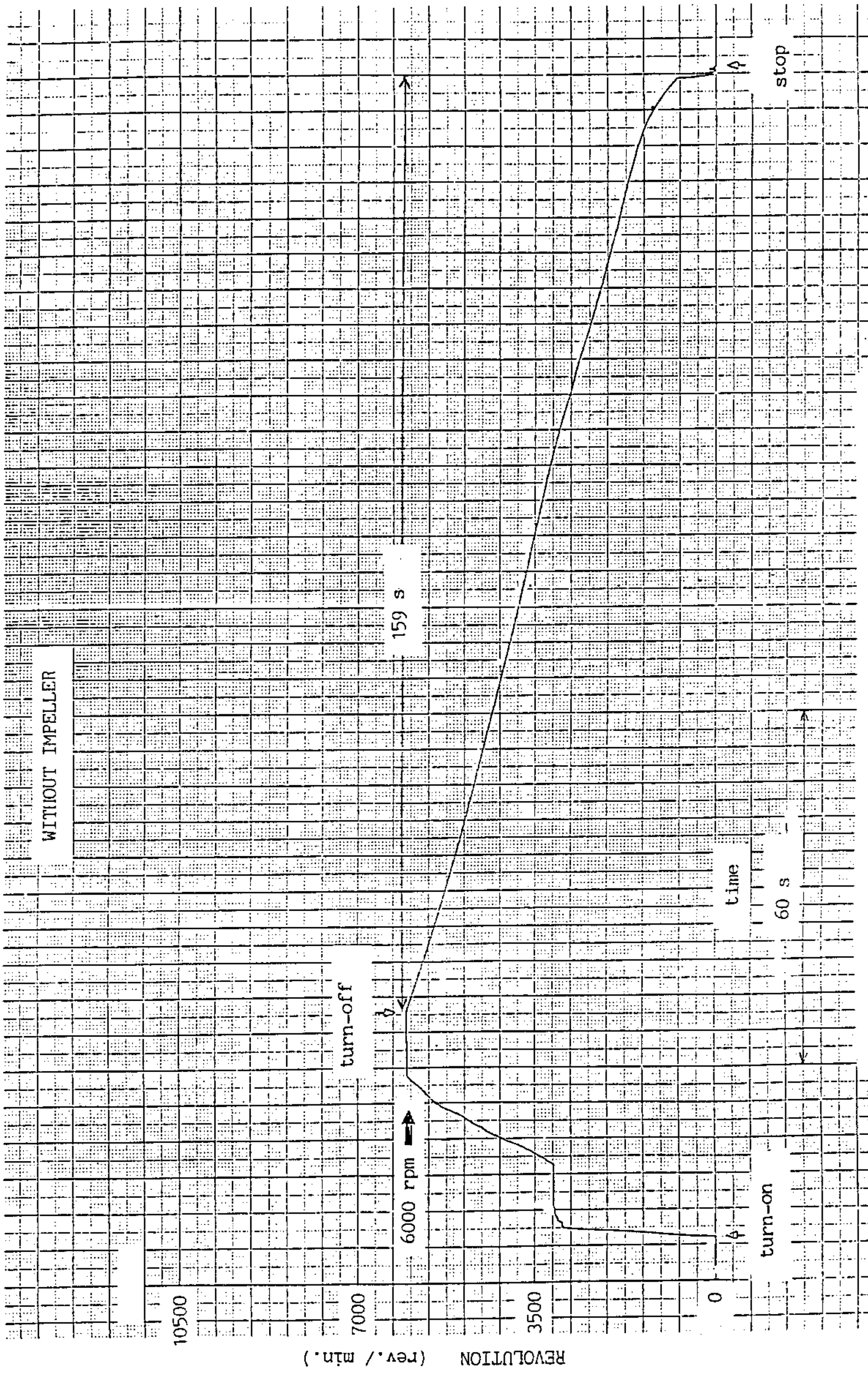

Fig. 7 Run Down Curve of Failed Gas Circulator without Impeller

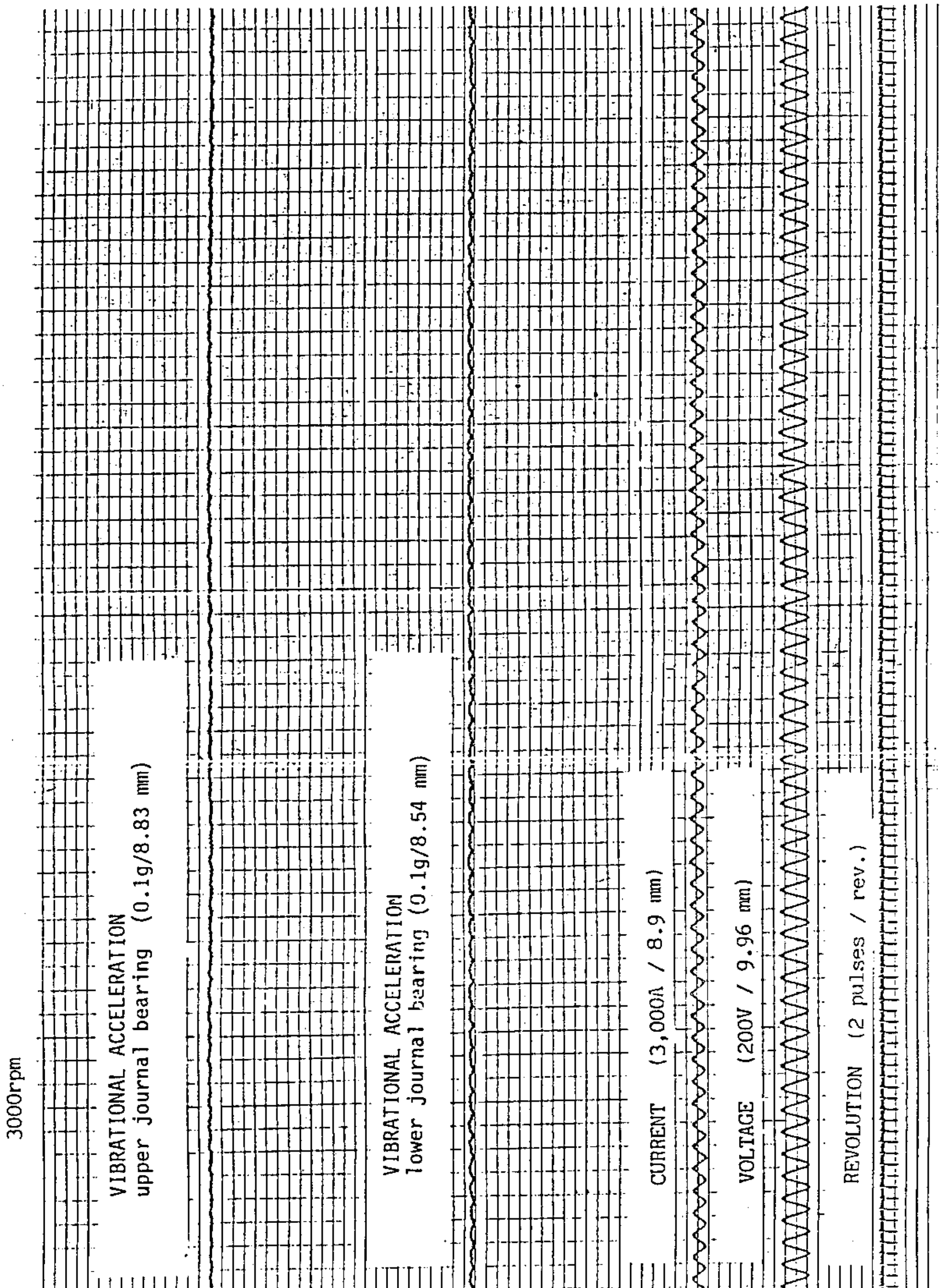

Fig. 8 Vibrational Acceleration, Current, Voltage and Revolution Pulses of Recovered Gas Circulator at 3000 rpm

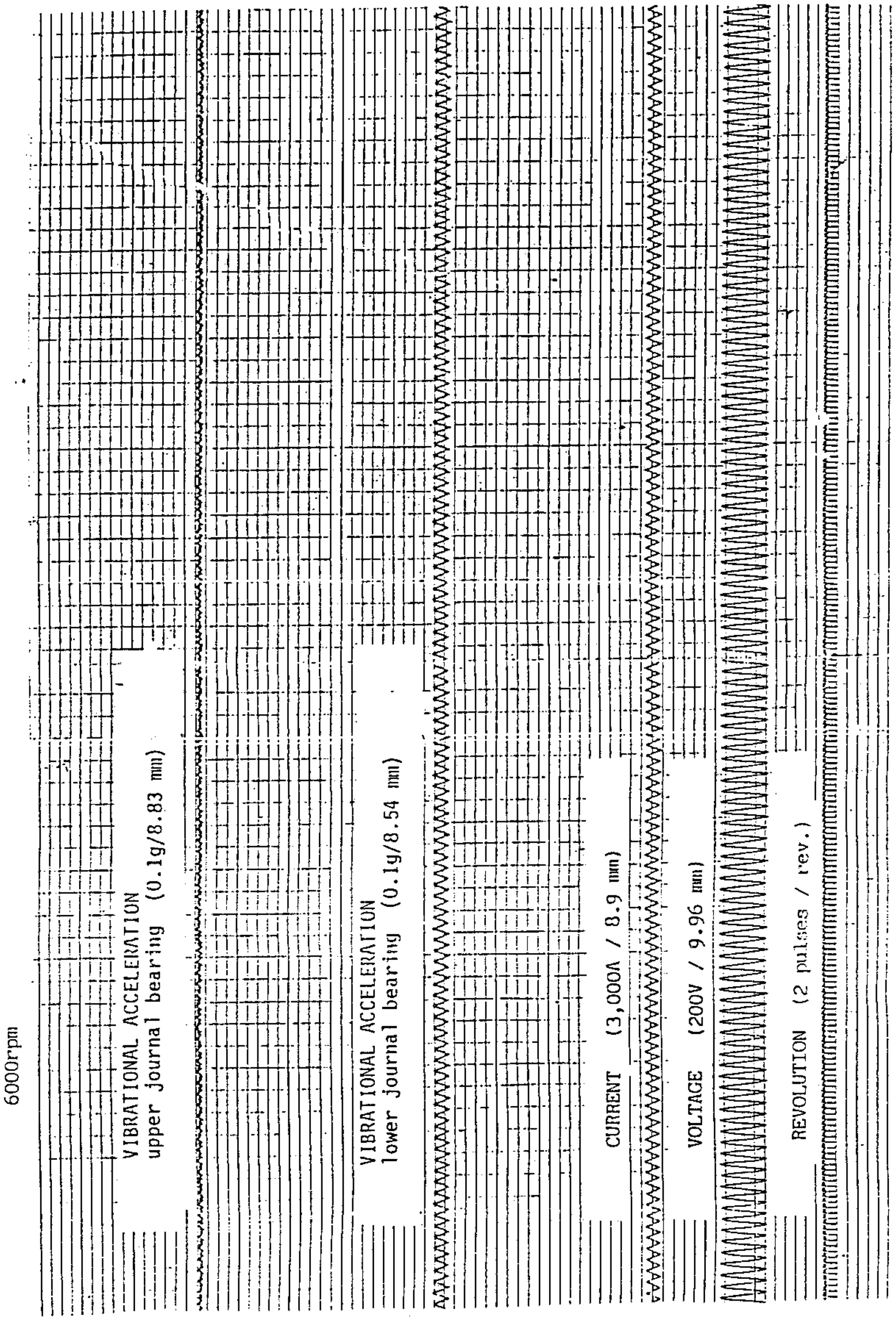

Fig. 9 Vibrational Acceleration, Current, Voltage and Revolution Pulses of Repaired Gas Circulator at 6000 rpm

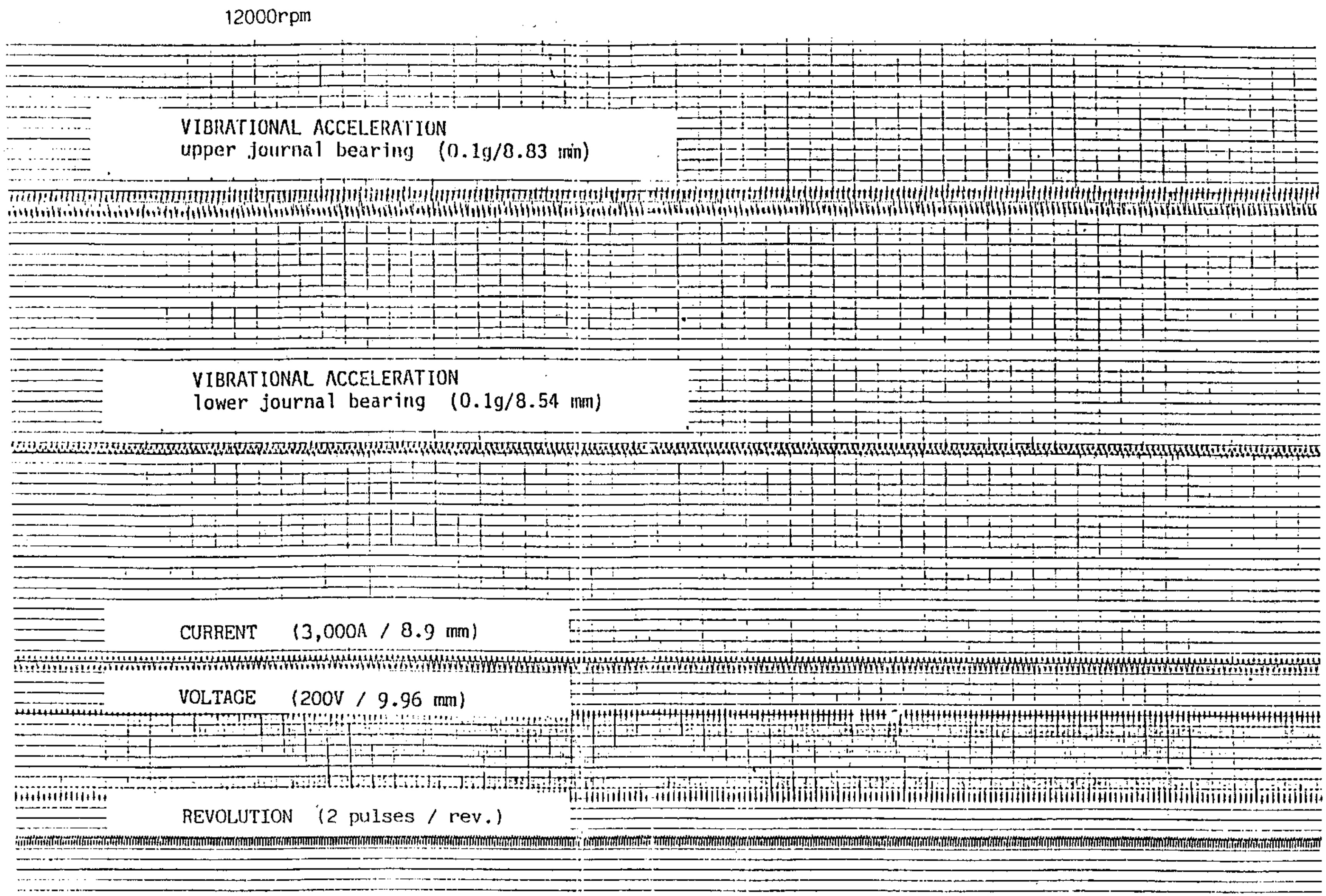

Fig. 10 Vibratory Acceleration, Current, Voltage and Revolution Pulses of Repaired Gas Circulator at 12000 rpm

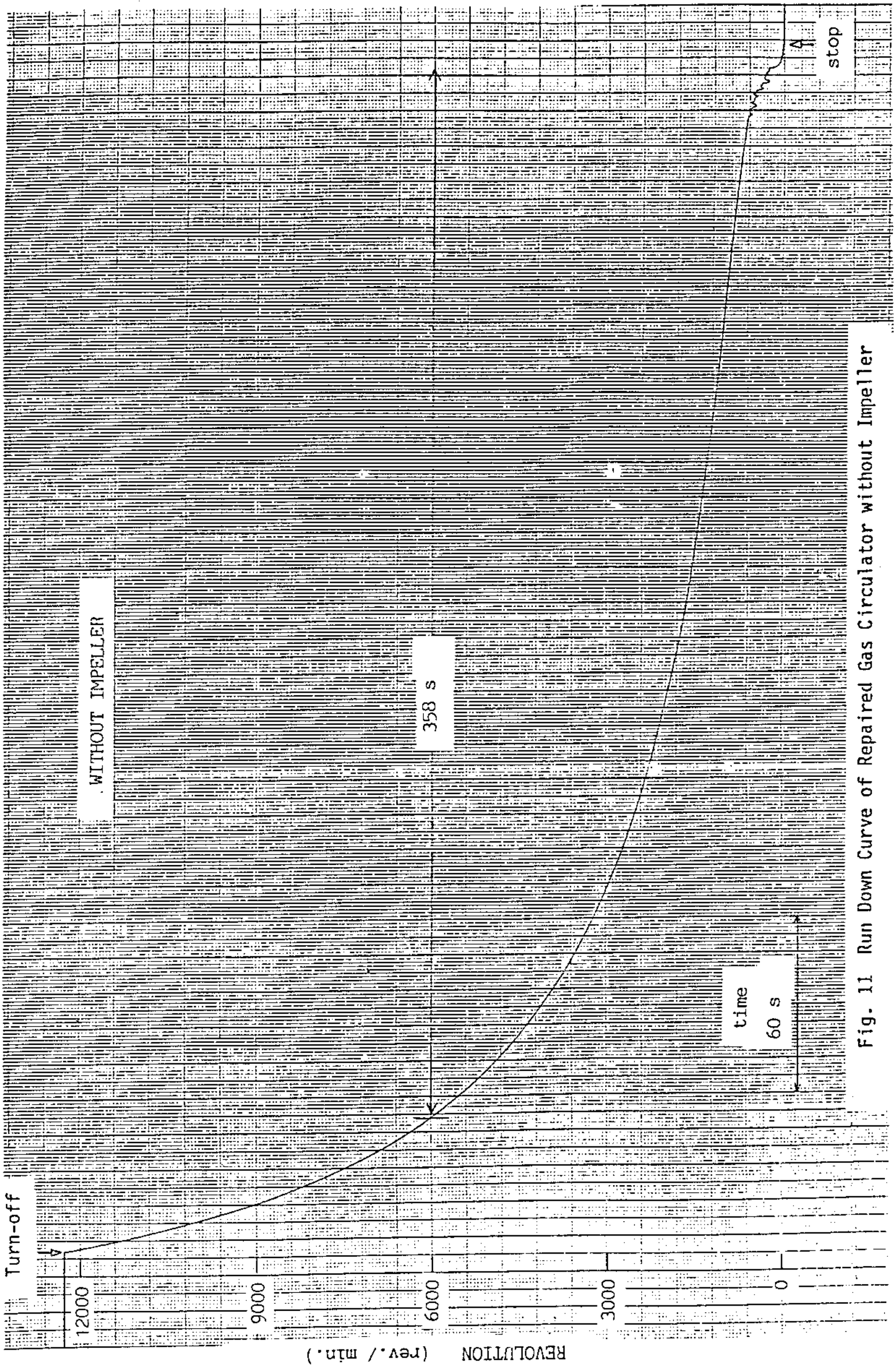

Fig. 11 Run Down Curve of Repaired Gas Circulator without Impeller

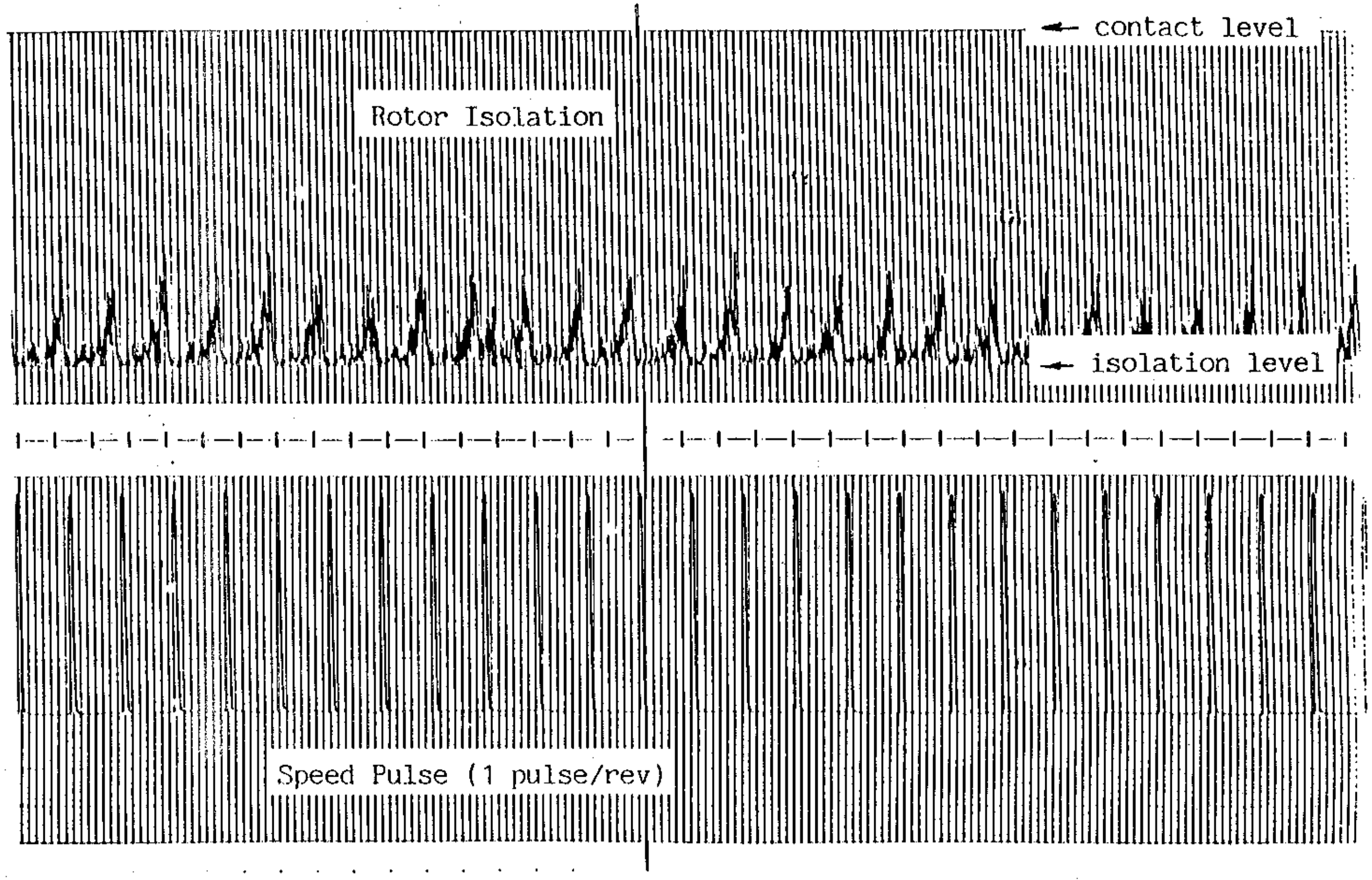

Fig. 12 Electrical Isolation between Rotor and Stator of Repaired Gas Circulator at 3000 rpm

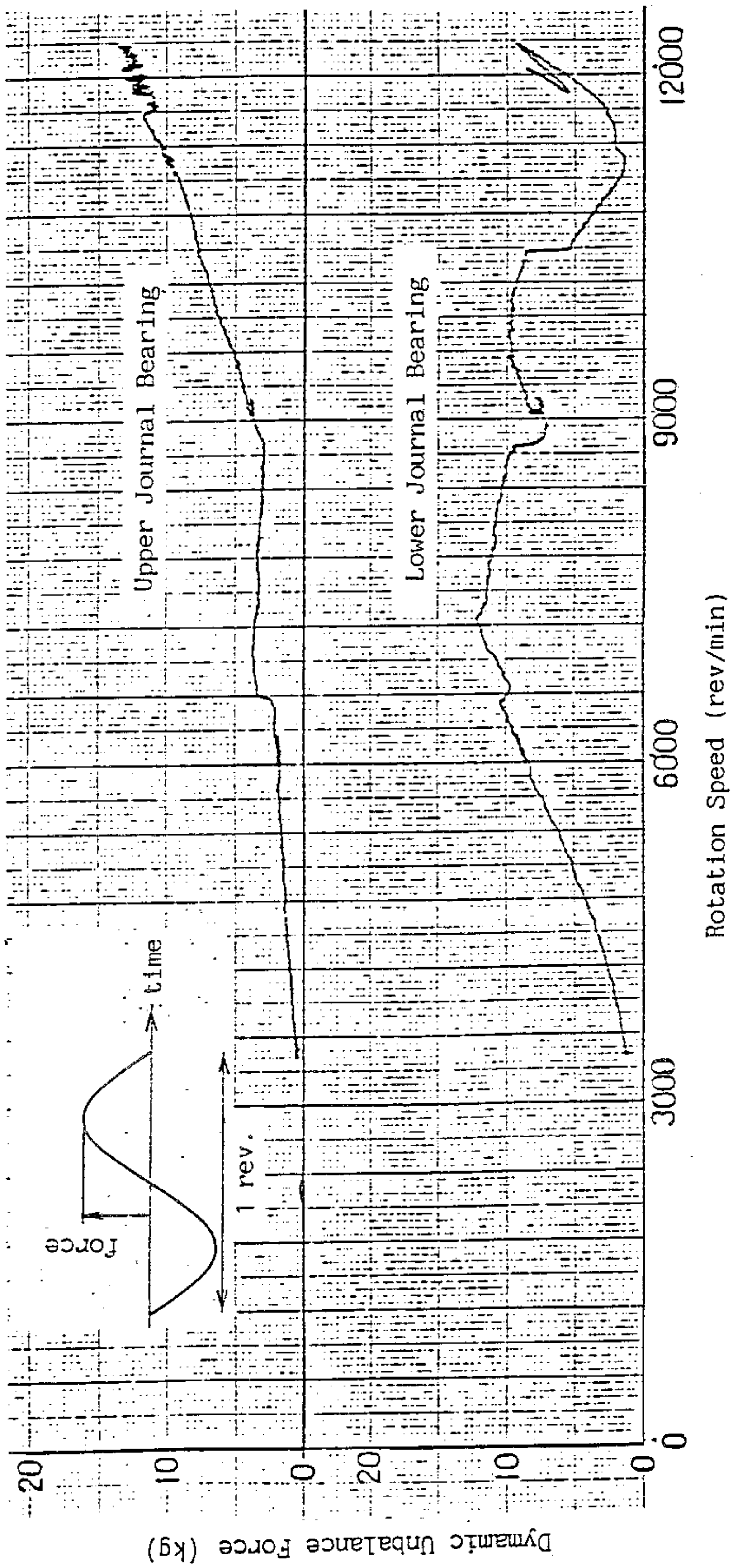

Fig. 13 Dynamic Unbalanced Forces of Repaired Gas Circulator

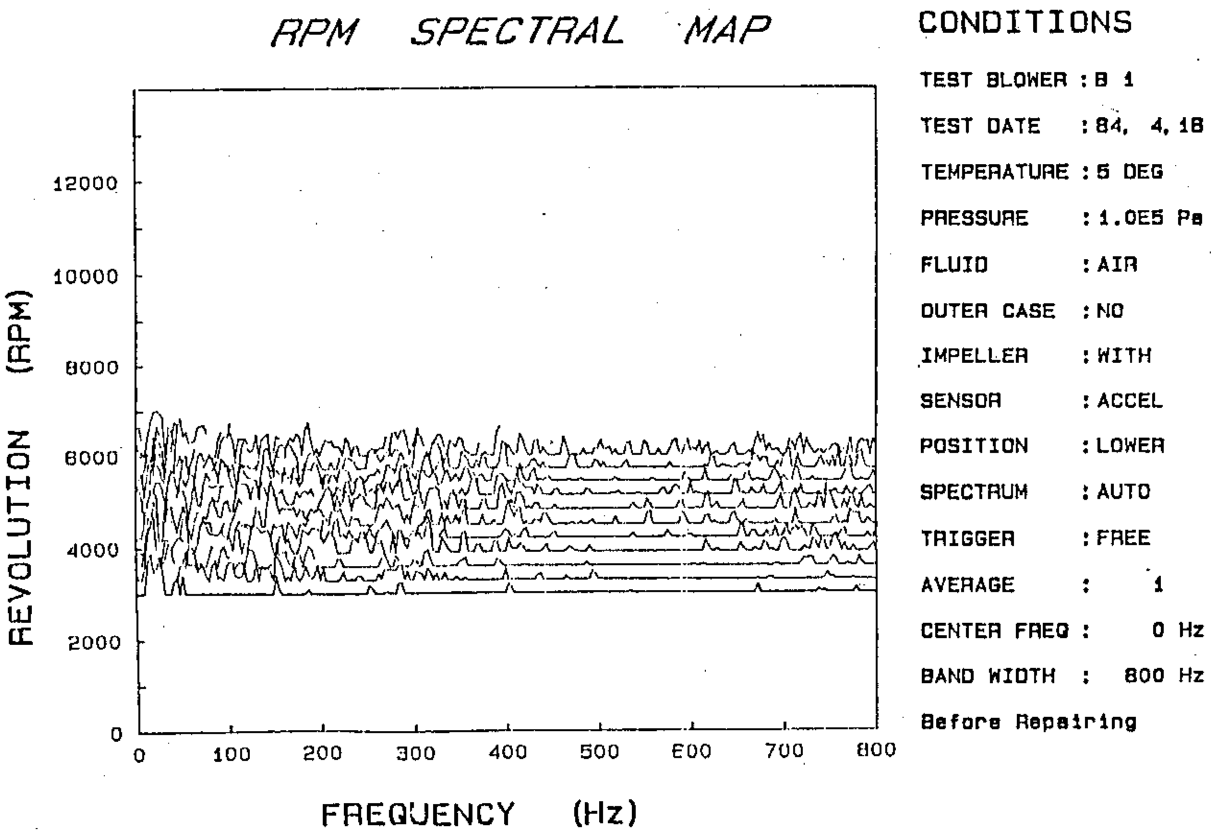

Fig. 14 Spectral Map of Failed Gas Circulator at Lower Journal Position

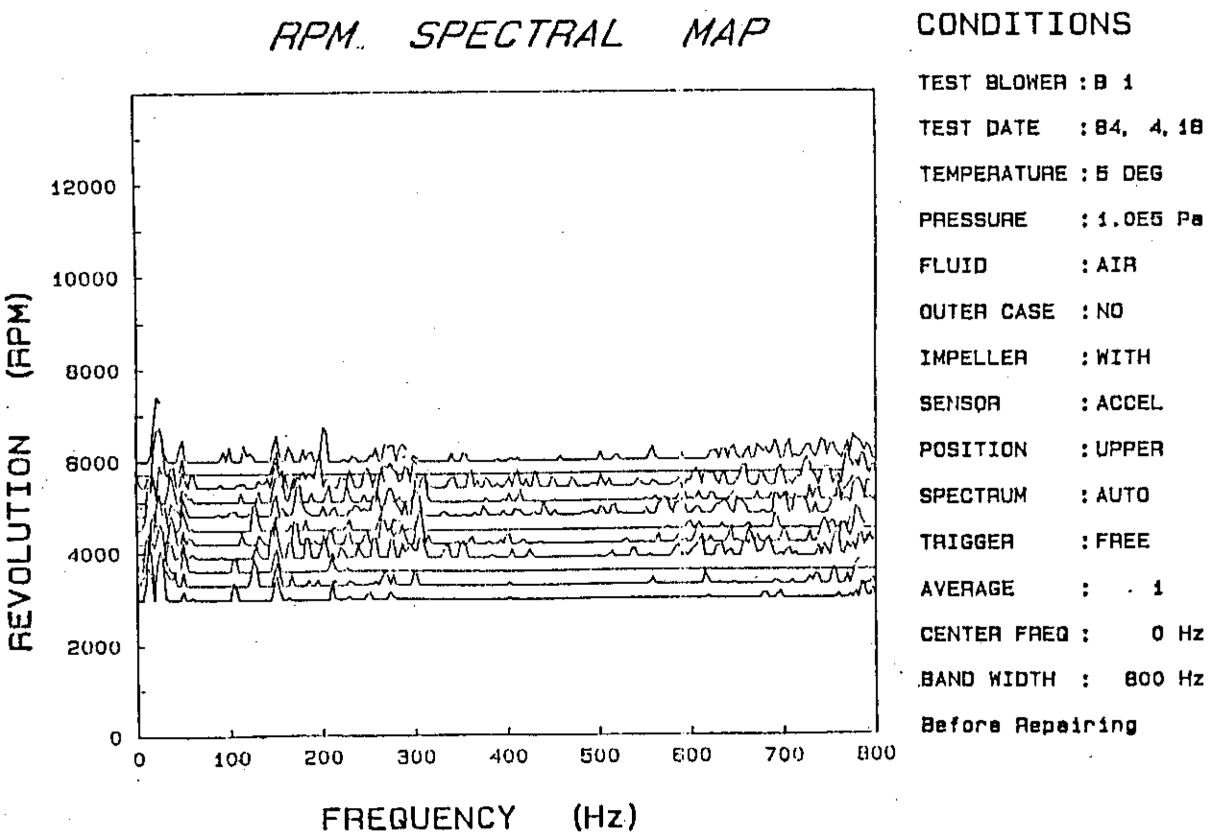

Fig. 15 Spectral Map of Failed Gas Circulator at Upper Journal Position

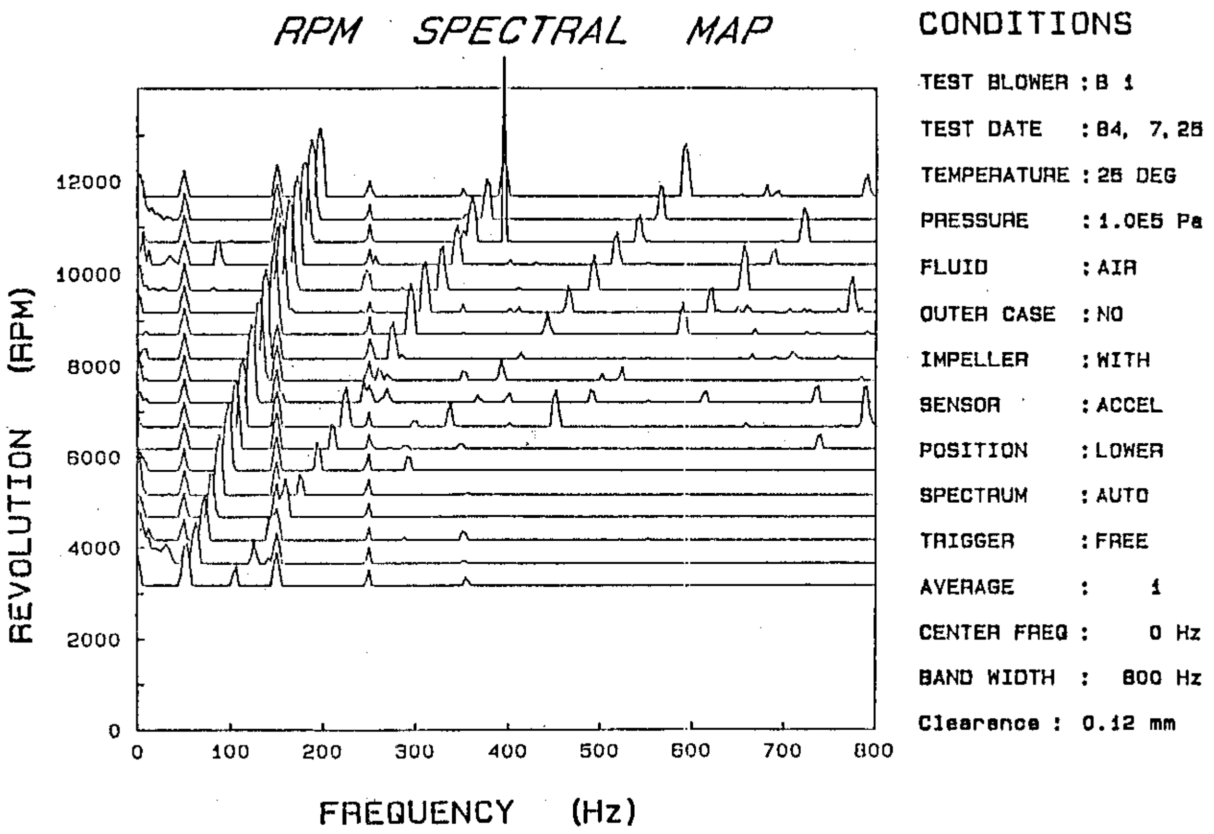

Fig. 16 Spectral Map of Repaired Gas Circulator at Lower Journal Position

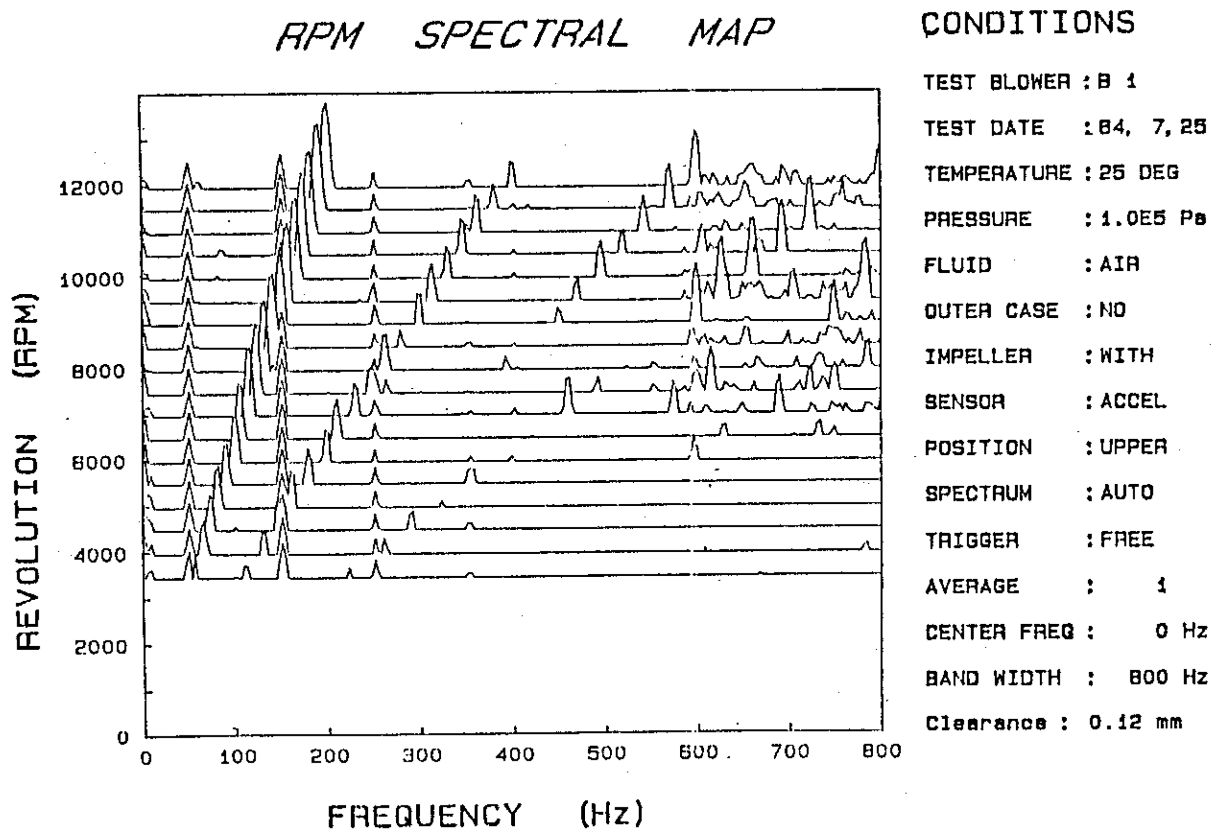

Fig. 17 Spectral Map of Repaired Gas Circulator at Upper Journal Position

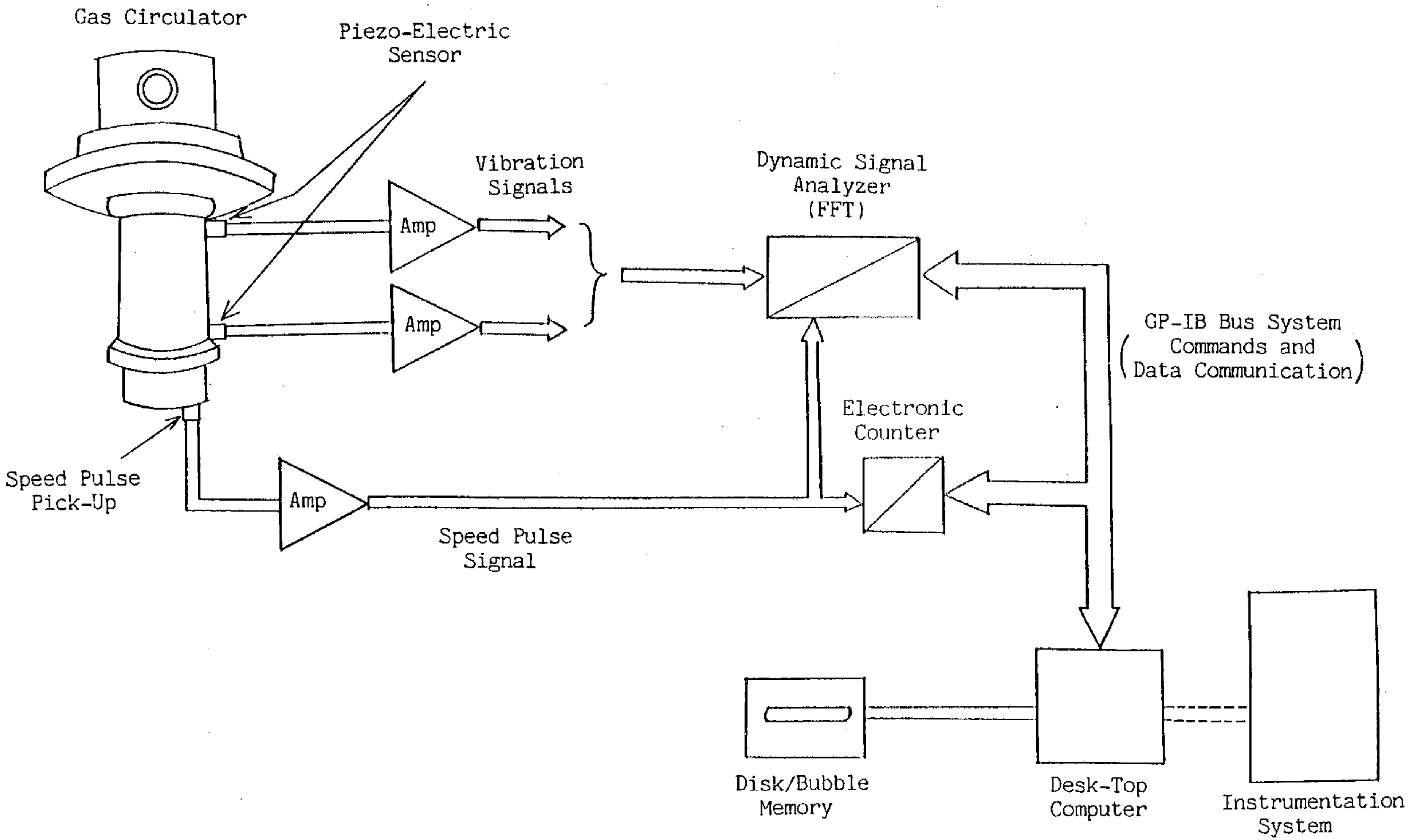

Fig. 18 Diagnostic System for Gas Circulator

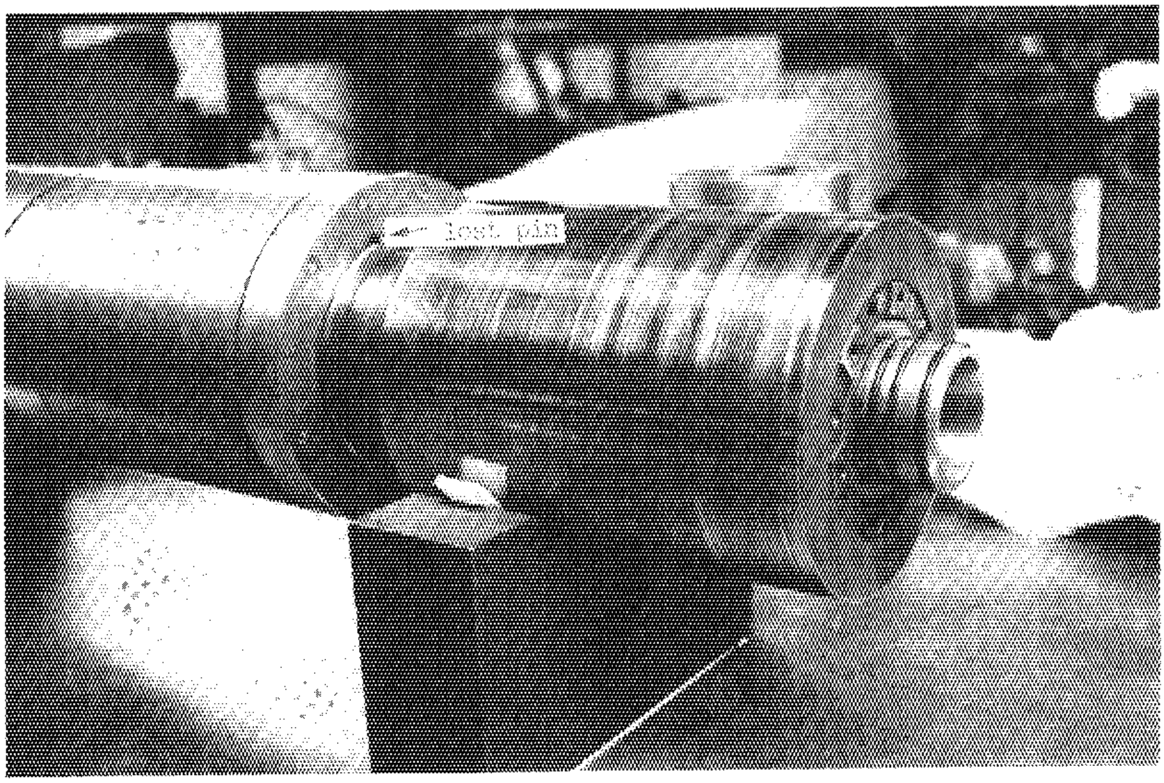

Photo. 1 Scratched Lower Journal Shaft and Motor Rotor of B_1

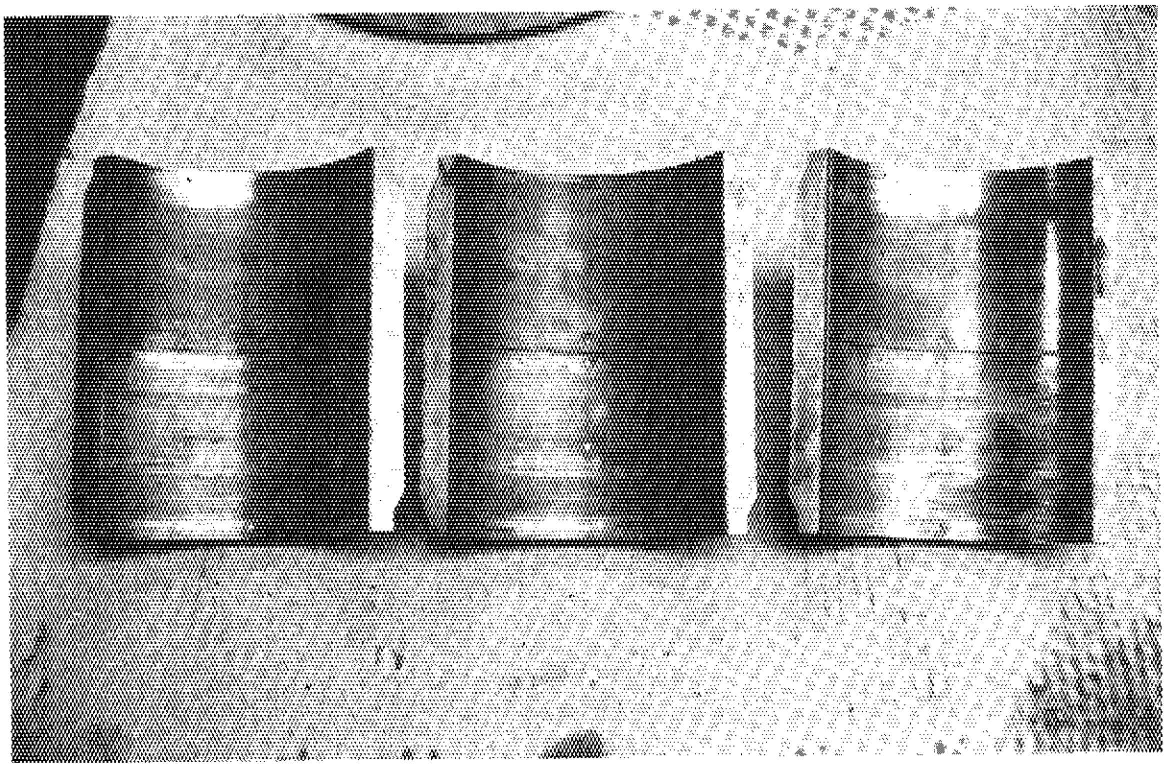

Photo. 2 Scratched Lower Journal Bearing Pads of B_1