THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

DYNAMIC CHARACTERISTICS OF ELECTRO-MAGNETIC COMPRESSORS

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Part of the work reported was initiated at the Tecumseh Products Research Laboratory, Ann Arbor while the first author was associated with the laboratory as a consultant. He wishes to express his appreciation for providing the opportunity.

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NOMENCLATURE

A	Area of the flux cross section of air gap effective in producing tractive force, in.^{2}; A_1 , for inner yoke, A_2 , for outer yoke.
A_b	Cross-sectional area of buffer space, in.^{2}
A_p	Cross-sectional area of piston, in.^{2}
B	Flux density of the magnetic field for the "moving-coil" type, maxwell/in.^{2}
C	Capacitance, μf .
d	Diameter of coil turn, in.
E	Root-mean-square coil voltage, volt.
Em	Maximum coil voltage, volt.
F	Instantaneous mechanical force for the "moving-coil" type or instantaneous magnetic-tractive force for the "moving-iron" type, lbf.
g	Gravitational acceleration, in./sec.^{2}
i	Instantaneous coil current, ampere.
I	Root-mean-square coil current, ampere.
J	Integer used for numerical computation.
k	Spring constant, lbf/in., k_I , for spring I ; k_{II} , for spring II.
ℓ	Piston position measured from the cylinder head for zero spring force, in.; ℓ_I , for spring I; ℓ_{II} , for spring II .
M	Mass of the moving parts including the piston, end frame and part of springs, lbm (or divided by 386.088, lbf-sec.^{2}/in.)
N	Number of coil turns, turns.
n	Ratio of specific heats.
P_b	Gas pressure in buffer space, psia.
P_c	Gas pressure inside cylinder, psia.

NOMENCLATURE (Continued)

P_d	Discharge pressure, psia.
P_s	Suction pressure, psia.
R	Resistance of coil, ohms.
t	Time, sec.
Δt	Time interval used for numerical computation, sec.
x	Instantaneous piston position measured from the cylinder head, in.; x_o at the beginning of compression stroke, x_1 , at the end of compression stroke; x_2 , at the beginning of expansion stroke; x_3 , at the end of expansion stroke; x_a , for zero buffer space; x_b , for maximum buffer space.
σ	Compression ratio.
ϕ	Instantaneous magnetic flux per gap, maxwell.
ω	Angular frequency of imposed voltage, rad./sec., = 2π (cps).

Superscript

$\dot{\ }$, $\ddot{\ }$	Time derivatives.

INTRODUCTION

In the design and control of a compressor, the knowledge of dynamic performance is of prime importance. This paper is devoted to an examination of the transient behavior of electromagnetic compressors, specifically for small horsepower.

A comprehensive review of various types of compressors for refrigeration and compressed air and gases has appeared in references 1 and 2.

In this paper, attention is focused on two different types of electromagnetic compressors: "moving-coil" type or the so called "swing motor" and "moving-iron" type. The former is analogous to the common electromagnetic speaker found in radios and high-fidelity equipment, while the latter operates on the same principle as a high-speed magnet which is designed to move an external load having mass against the action of a constant load force, friction, and a spring.(3) The resonance phenomenon is used to advantage in both types.

In a reciprocating-type compressor, the rotary motion of an induction motor is converted mechanically to reciprocating motion to compress the gas. However an electromagnetic compressor produces this reciprocating motion directly. Therefore the electromagnetic compressors have the following major advantages. (i) Low friction losses: In a conventional compressor converting the rotary motion to reciprocating motion involves friction at several contacting parts, while in the electromagnetic compressor the only point of contact is between piston and cylinder. (ii) Small size, light weight and low cost: The mechanism of the electromagnetic compressor is basically simple and has few parts. (iii) High efficiency and low power consumption: Because the resonance phenomenon is used to advantage in the electromagnetic compressor, the power factor is higher than that for the induction motor. Due to the high efficiency of the electromagnetic system and the low friction losses, these electromagnetic compressors have, in general, a low power consumption.

The dynamic behavior of the electromagnetic compressors is simulated by means of a digital computer in the present paper. The results for the "moving-coil" and "moving-iron" types are obtained and compared.

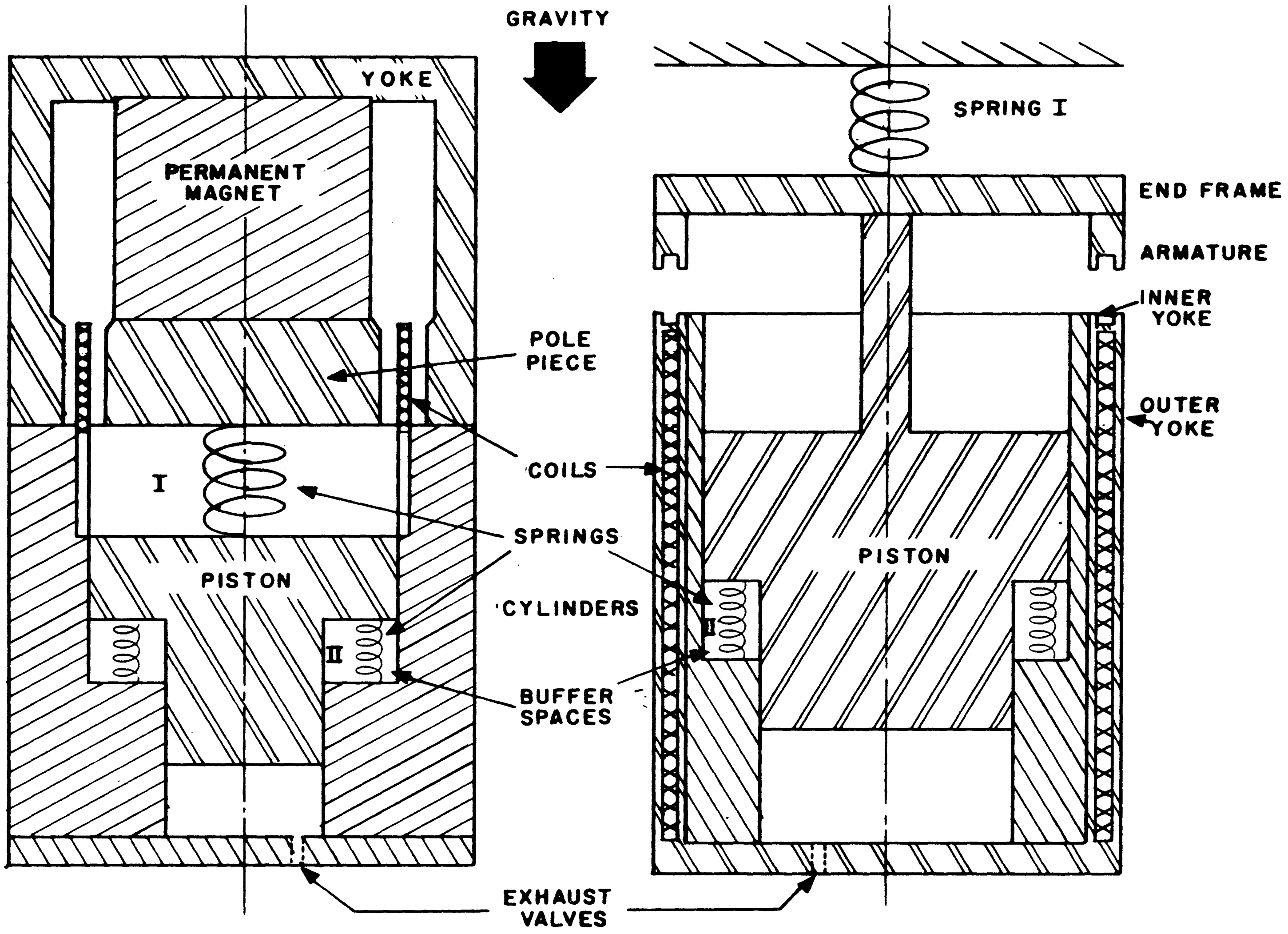
ANALYSIS

The electromagnetic compressors to be investigated are shown in Figure 1.

A schematic view of the "moving-coil" type is illustrated in Figure 1-a. The coil is suspended by two springs in the ring gap formed between the yoke, pole piece and the permanent magnet. A piston is connected to the coil. This piston is inserted in a cylinder which allows the piston and coil to move back and forth without contacting the yoke and pole piece. When the coil is connected to an AC power line, the compressor experiences a starting transient for a certain period of time. But as soon as the starting transient period is elapsed the piston and coil will move back and forth at the given power frequency (50 cps or 60 cps, and so forth).

The "moving-iron" type compressor is schematically shown in Figure 1-b. The coil is wound between the stationary inner and outer yokes. The piston is connected to the end frame with a concentric-ring shape, flat-faced armature. The piston and end frame are suspended by two springs. This piston is inserted in a cylinder which allows the piston and end frame to move back and forth. When the coil is connected to an AC power line, an instantaneous magnetic force is generated across the air gaps to move the end frame and piston. Under a steady periodic operation, the end frame and piston will vibrate at twice the power frequency.

For both type compressors, an intake valve and an exhaust valve permit the cylinder and piston to act as a simple pump to compress the gas. By utilizing the principle of resonance, it is possible to



(a) MOVING-COIL TYPE

(b) MOVING- IRON TYPE

Figure 1. Schematic Diagram of Electromagnetic Compressors.

produce a vibration with a large amplitude at the given power frequency for the "moving-coil" type or at twice the given power frequency for the "moving-iron" type. The mass of the vibrating parts and the strength of the springs maybe calculated to place the mechanical resonance of the system at a certain frequency to achieve high efficiency.

The following assumptions are made in the formulation of the problem:

(i) Friction, part and valve losses are negligible.

(ii) The gas leakage from the cylinder and buffer space is negligible.

(iii) The gas behaves ideally and undergoes reversible polytropic processes in the cylinder and buffer space.

(iv) The resistance voltage (IR) in the magnet is negligible. This means that the reactance voltage is equal to the supplied voltage.

(v) There exists a linear relationship between the magnetic flux ϕ (or flux-linkage $N\phi$) and the current i .

(vi) The piston is subjected to the forces exerted by the gas on both front and rear surfaces of the piston and by the gas in the buffer space.

With these assumptions, the application of force balance produces

$$M(\ddot{x}-g) + k_I(x-\ell_I) + A_p\, P_c(x) + A_b\, P_b(x) = F + A_p\, P_s + A_b\, P_s + k_{II}(x-\ell_{II}) \qquad (1)$$

where $x(t)$ represents the instantaneous location of the piston measured from the cylinder head. The initial conditions are $x(o) = x_o$ and $\dot{x}(o) = 0$. For an ideal gas undergoing a reversible polytropic process, the gas pressure in the cylinder space $P_c(x)$ may be related to the suction pressure P_s as follows.

During compression stroke when $x_1 \leq x \leq x_o$

$$P_c(x) = P_s\left(\frac{x_o}{x}\right)^n \quad . \tag{2-a}$$

During discharge stroke when $x_2 \leq x \leq x_1$

$$P_c(x) = \left(\frac{x_o}{x_1}\right)^n P_s = \text{discharge pressure} \quad . \tag{2-b}$$

During reexpansion stroke when $x_2 \leq x \leq x_3$

$$P_c(x) = \frac{x_o}{x_1}\left(\frac{x_2}{x}\right)^n P_s \quad . \tag{2-c}$$

During suction stroke when $x_3 \leq x \leq x_o$

$$P_c(x) = P_s \quad . \tag{2-d}$$

Similarly, for the gas inside the buffer space, one can write

$$P_b(x) = 0 \quad . \quad \text{when} \quad x > x_b \tag{3-a}$$

and

$$P_b(x) = \left(\frac{x_b - x_a}{x - x_a}\right)^n P_s \quad \text{when} \quad x < x_b \quad . \tag{3-b}$$

For the "moving-coil" type compressor, the instantaneous mechanical force on the conductor in the direction of motion is$^{(1)}$

$$F = 8.86 \times 10^{-2} \, \pi dNB(E_m/R)\sin\omega t \tag{4}$$

where B is the flux density of the magnetic field. For the "moving-iron" type compressor, the instantaneous magnetic-tractive force is$^{(1)}$

$$F = \frac{[\phi(t)/\nu]^2}{72 \times 10^6 \, A_1} \left(1 + \frac{A_1}{A_2} \right) \qquad (5)$$

where ν is the leakage coefficient which is a function of the air gap length.

Figure 2 shows the displacement-time characteristics of the compressors during starting transient. It is easy to realize that the locations x_o, x_1, x_2 and x_3 are all time-dependent. x_b is the location of the piston for the maximum buffer space and is predetermined by design. x_o and x_2 indicate the ends of the suction and discharge strokes of the compressor cycle, respectively. They correspond to the location of the piston at the moment $\dot{x}$ becomes zero during the suction and discharge strokes, respectively. The current values of x_1 and x_3 are determined by $x_1 = x_o/\sigma^{1/n}$ and $x_3 = x_2 \, \sigma^{1/n}$, respectively. Only after the steady-periodic operation of the compressor is established, then the locations x_o, x_1, x_2 and x_3 would become time-independent.

The compression stroke of the compressor cycle may consist of processes 1 and 2. Process 1 represents the interval $x_o \geq x > x_b$, while process 2 is for $x_b \geq x > x_3$. Process 1R or 2R takes place only when the compression stroke fails to yield the specified discharge pressure, that is, when the current value of $(x_o/x_1)^n$ is less than the specified compression ratio σ . The resulting return stroke may be either process 2R or 1R or 2R followed by 1R depending upon the current position of the piston x . If the return stroke begins at $x > x_b$, the process is called 1R, while if it begins at $x < x_b$, the process is called 2R. During process 1R if $\dot{x} = 0$ occurs before the piston

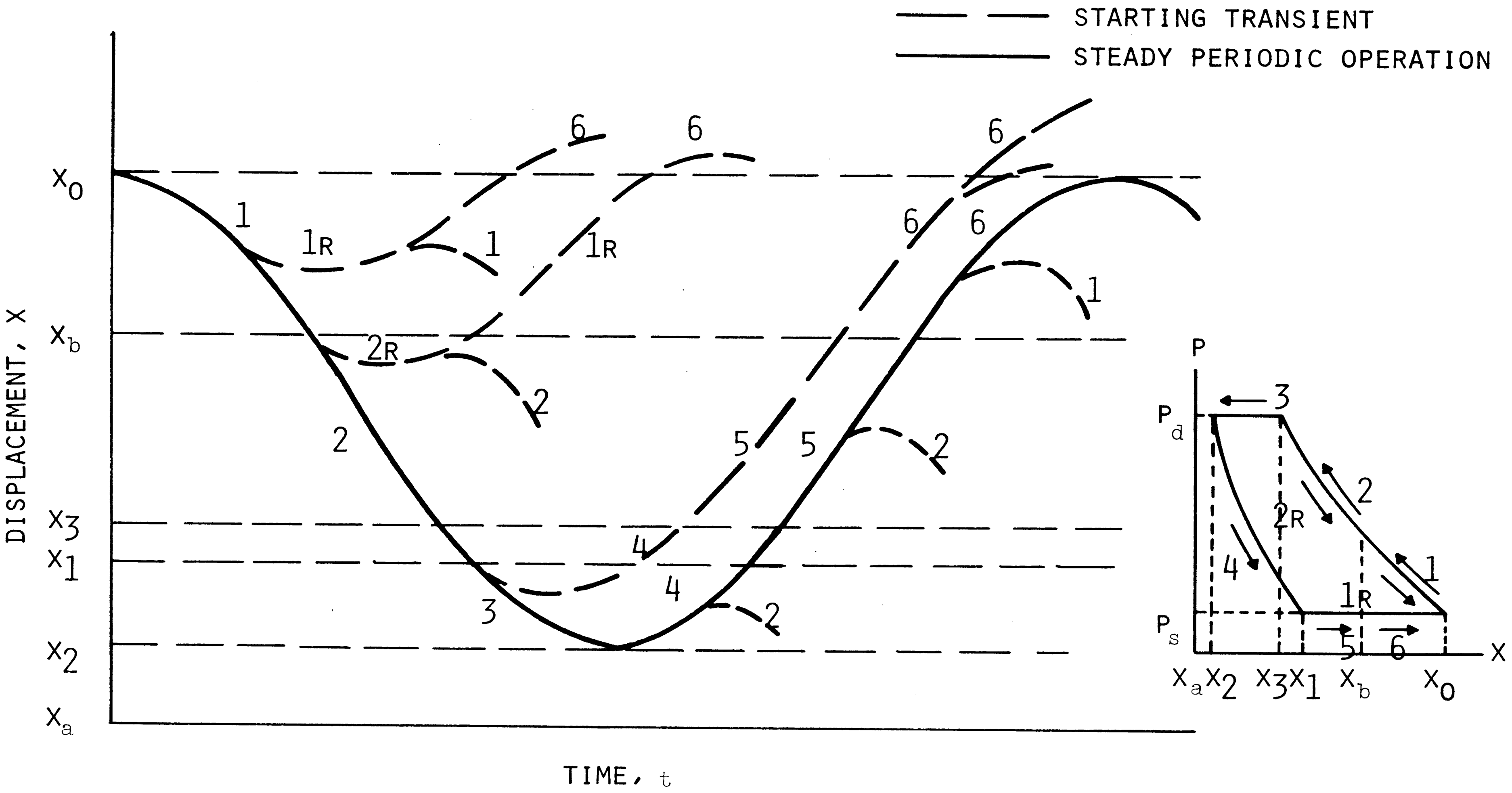


Figure 2. Displacement-Time and Pressure-Displacement Diagrams.

reaches the current x_o, the location x becomes a new x_o. However, process 1R may continue beyond the current x_o. For such cases, process 1R ends at the current x_o and is then followed by process 6 until the piston turns back at the location where $\dot{x} = 0$. That location becomes a new x_o. Process 2R may be followed by process 1R when the piston moves beyond x_b. Or, it may be succeeded by process 2 when the piston turns back before it reaches the location x_b.

Process 3 refers to the discharge stroke which begins at $x = x_3$ and ends at $x = x_2$. It is then followed by process 4 which represents the reexpansion process of the residual gas in the compressor cylinder after the discharge stroke is completed. Process 4 begins at $x = x_2$ and ends at $x = x_1$ when $P \leq P_s$ and the suction valve is forced to open. The suction stroke is represented by process 5 for $x_1 \leq x < x_b$ and by process 6 for $x \geq x_b$.

The location $x = x_b$ has a physical significance. When the piston moves beyond x_b, the gas in the buffer space would exert no net force on the piston. However, when the piston moves within $x < x_b$, the gas in the buffer space becomes under compression and thus would exert a pressure force on the piston.

In summary, Equation (1) may be rewritten for the eight processes as follows. Process 1, from $x = x_o$ (or $\dot{x} = 0$ following process 1R or 6) to $x = x_b$:

$$M(\ddot{x}-g) = k(\ell-x) + A_p P_s \left[\left(\frac{x_o}{x}\right)^n - 1\right] - F \,, \qquad (6\text{-a})$$

subject to the initial conditions $x(0) = x_o$ and $\dot{x}(0) = 0$. Process 2, for $x < x_b$ and $x > 0$ following process 1:

$$M(\ddot{x}-g) = k(\ell-x) + \left[A_p\ P_s \left(\frac{x_o}{x}\right)^n - 1\right] - F \qquad \text{(6-b)}$$

Process 2, from $x = x_b$ (or $\dot{x} = 0$ following process 2R, 4 or 5) to $x = x_1 = x_o/\sigma^{1/n}$:

$$M(\ddot{x}-g) = k(\ell-x) + A_p\ P_s\left[\left(\frac{x_o}{x}\right)^n - 1\right] + A_b\ P_s\left[\left(\frac{x_b-x_a}{x-x_a}\right)^n - 1\right] - F \qquad \text{(6-c)}$$

Process 2R, for $x_1 < x < x_b$ and $\dot{x} > 0$ following process 2 :

$$M(\ddot{x}-g) = k(\ell-x) + A_p\ P_s\left[\left(\frac{x_o}{x}\right)^n - 1\right] + A_b\ P_s\left[\left(\frac{x_b-x_a}{x-x_a}\right)^n - 1\right] - F \qquad \text{(6-d)}$$

Process 3, from $x = x_1$ to $\dot{x} = 0$ at which $x = x_2 = x_3/\sigma^{1/n}$:

$$M(\ddot{x}-g) = k(\ell-x) + A_p\ P_s\left[\left(\frac{x_o}{x_1}\right)^n - 1\right] + A_b\ P_s\left[\left(\frac{x_b-x_a}{x-x_a}\right)^n - 1\right] - F \qquad \text{(6-e)}$$

Process 4, from $x = x_2$ or $\dot{x} = 0$ following process 3 to $x = x_3 = x_2\sigma^{1/n}$

$$M(\ddot{x}-g) = k(\ell-x) + A_p\ P_s\left[\left(\frac{x_o x_2}{x\ x_1}\right)^n - 1\right] + A_b\ P_s\left[\left(\frac{x_b-x_a}{x-x_a}\right)^n - 1\right] - F \qquad \text{(6-f)}$$

Process 5, from $x = x_3$ to $x = x_b$:

$$M(\ddot{x}-g) = k(\ell-x) + A_b\ P_s\left[\left(\frac{x_b-x_a}{x-x_a}\right)^n - 1\right] - F \qquad \text{(6-g)}$$

Process 6, from $x = x_b$ to $\dot{x} = 0$ at which $x = x_o$:

$$M(\ddot{x}-g) = k(\ell-x) - F \qquad \text{(6-h)}$$

For the "moving-coil" type compressor, the impressed voltage is known as $E = E_m \sin\omega t$. However, for the "moving-iron" type compressor, the impressed voltage equation for a magnet circuit shunted by a condensor is

$$E = N\dot{\phi} + IR + \frac{1}{C}\int_o^t I dt$$

or

$$E \quad \sin\omega t = 10^{-8} N\dot{\phi} + iR + \frac{10^6}{C} \int_0^t i \, dt \qquad (7)$$

where C is the capacitance in microfarads. When the force required to establish the flux in the iron part of the circuit is ignored, the total magnetic force across the air gaps can be written as

$$Ni = \frac{2\phi x}{\mu A_1} \left(1 + \frac{A_1}{A_2}\right) . \qquad (8)$$

where μ is the permeability of air (= 3.192 maxwell/amp.-turn in an inch cube). Equations (7) and (8) are combined to yield the magnetic flux equation

$$E_m \sin\omega t = 10^{-8} N\dot{\phi} + 0.628 \frac{\phi x R}{NA_1} \left(1 + \frac{A_1}{A_2}\right) + \frac{0.628 \times 10^6}{CNA_1} \left(1 + \frac{A_1}{A_2}\right) \int_0^t \phi x dt \qquad (9)$$

Its apprорriate initial condition is $\phi(0) = 0$. $E_m \sin\omega t$ in Equation (9) is the impressed voltage or the forcing function of the physical system.

In case of the "moving-coil" type compressor, the nonlinear differential Equation (1) together with its appropriate initial conditions provide a complete statement of the problem. However, for the "moving-iron" type compressor, Equation (1) is coupled with the integro-differential Equations (9). They have to be solved simultaneously for $x(t)$ and $\phi(t)$. Numerical reductions for both cases are performed by means of the finite difference technique. Equation (1) may be re-written in finite difference form as

$$x(J) = \Big\{Mg + k[\ell - x(J-1)] + A_P\,P_C(J-1) - A_P\,P_S + A_b\,P_b(J-1) - A_b\,P_S - \frac{[\phi(J)/\nu]^2}{72\times 10^6 A_1}\left(1 + \frac{A_1}{A_2}\right)\Big\} \div M(\Delta t)^2 \tag{10}$$

where $J = 1$ corresponds to $t = 0$, $t = (J-1)\Delta t$, and Δt is the time interval used in numerical reduction. Equation (9) is first reduced to the differential equation by a differentiation. The resulting equation may then be expressed in finite difference form as

$$\phi(J) = \Big\{E_m\,\omega\cos[\omega(J-1)\Delta t] + \left[\frac{2\times 10^{-8}N}{(\Delta t)^2} + 0.628\,\frac{R}{NA_1}\left(1 + \frac{A_1}{A_2}\right)\frac{x(J-2)}{\Delta t} - \frac{0.628\times 10^6}{NCA_1}\left(1 + \frac{A_1}{A_2}\right)x(J-1)\right]\phi(J-1) - \frac{10^{-8}N}{(\Delta t)^2}\,\phi(J-2)\Big\} \div \left[\frac{10^{-8}N}{(\Delta t)^2} + \frac{0.628R}{NA_1}\left(1 + \frac{A_1}{A_2}\right)\frac{x(J-1)}{\Delta t}\right] \tag{11}$$

The appropriate initial conditions for the last two equations are $x(1) = x(2) = x_o$ and $\phi(1) = \phi(2) = 0$.

RESULTS AND DISCUSSION

An examination of Equation (1) reveals that the displacement-time characteristics of the compressor is functions of the mass of the vibrating parts M, the spring constants k_I and k_{II}, the initial spring forces as represented by ℓ_I and ℓ_{II}, the geometrical configuration of the piston as described by A_p and A_b, the initial location of the piston x_o, the suction pressure P_S, the polytropic exponent n, the piston position at the maximum buffer space x_b, and the magnetic force F. As shown by Equation (4), the magnetic force for the "moving-coil" type compressor depends upon the number of coil turns N, the diameter of coil turns d, the flux density of the magnetic field B, the resistance of the coil R and the impressed voltage E_m and frequency ω. On the other hand the magnetic force of the "moving-iron" type compressor depends upon the magnetic flux ϕ and the areas of the flux cross section of the inner and outer air gaps A_1 and A_2. This magnetic flux is coupled with the displacement governed by Equation (9). Therefore, the magnetic flux as well as the displacement are functions of the impressed voltage E_m and frequency ω, the number of coil turns N, the coil resistance R, the capacity of the condensor C and the areas of the flux cross section of the air gaps.

The numerical computation was performed by means of an IBM 7090 digital computer for both compressors. A set of input data were selected: $A_p = 1.0$ in.^{2}, $A_b = 0.25$ in.^{2}, $P_S = 19.2$ psia, $P_d = 192$ psia, $k_{II} = 0$ lbf/in., $x_a = 0$ in., $x_b = 0.05$ in., $x_o = 0.05$ in., $\ell_I = 0.0454$ in., $R = 40$ ohms, $\omega = 60$ cycles/sec. $N = 725$ turns, $C = 0\,\mu f$,

E_m = 110 volts, d = 1 in. , B = 80,000 maxwell/in.^{2} , $A_1 = A_2 = 1.4$ in.^{2} and $\nu = 1.41$. Two values each of the important quantities M, k_I and n were selected to investigate the role they play in the dynamic characteristics of the compressors: M = 0.696 and 0.812 lbm, k_I = 300 and 550 lbf/in., and n = 1.0 for isothermal process and 1.4 for isentropic process (in case of air). The results are presented in graphical form in Figure 3 for the "moving-coil" type compressor and in Figures 4 through 8 for the "moving-iron" type compressor.

It is seen in Figure 3 that the magnetic force of the "moving-coil" type varies sinusoidally like the impressed voltage or current. Immediately following the starting, the piston moves toward the cylinder head. The compression stroke fails because it yields a low compression ratio. A full force cycle following the first positive maximum value of the force results in the first full compressor cycle. Only the compressor having M = 0.812 lbm (0.0021 lbf-sec.^{2}/in.) and k_I = 300 lbf/in. gives the desired compression ratio of ten. More importantly, this compressor has almost attained the steady periodic operation after the second force cycle. The period of each compressor cycle is identical with that of the impressed voltage. The other two compressors having M = 0.812 lbm, k_I = 500 lbf/in. and M = 0.696 lbm, k_I = 550 lbf/in. produce the compression ratio of less than ten with irregular vibrating periods. In addition, the piston undergoes two compression strokes with entirely different compression ratios in every compressor cycle. One of these compression ratios is too small to be of any use. Therefore the compressor having M = 0.812 lbm and k_I = 300 lbf/in. is better than the other two.

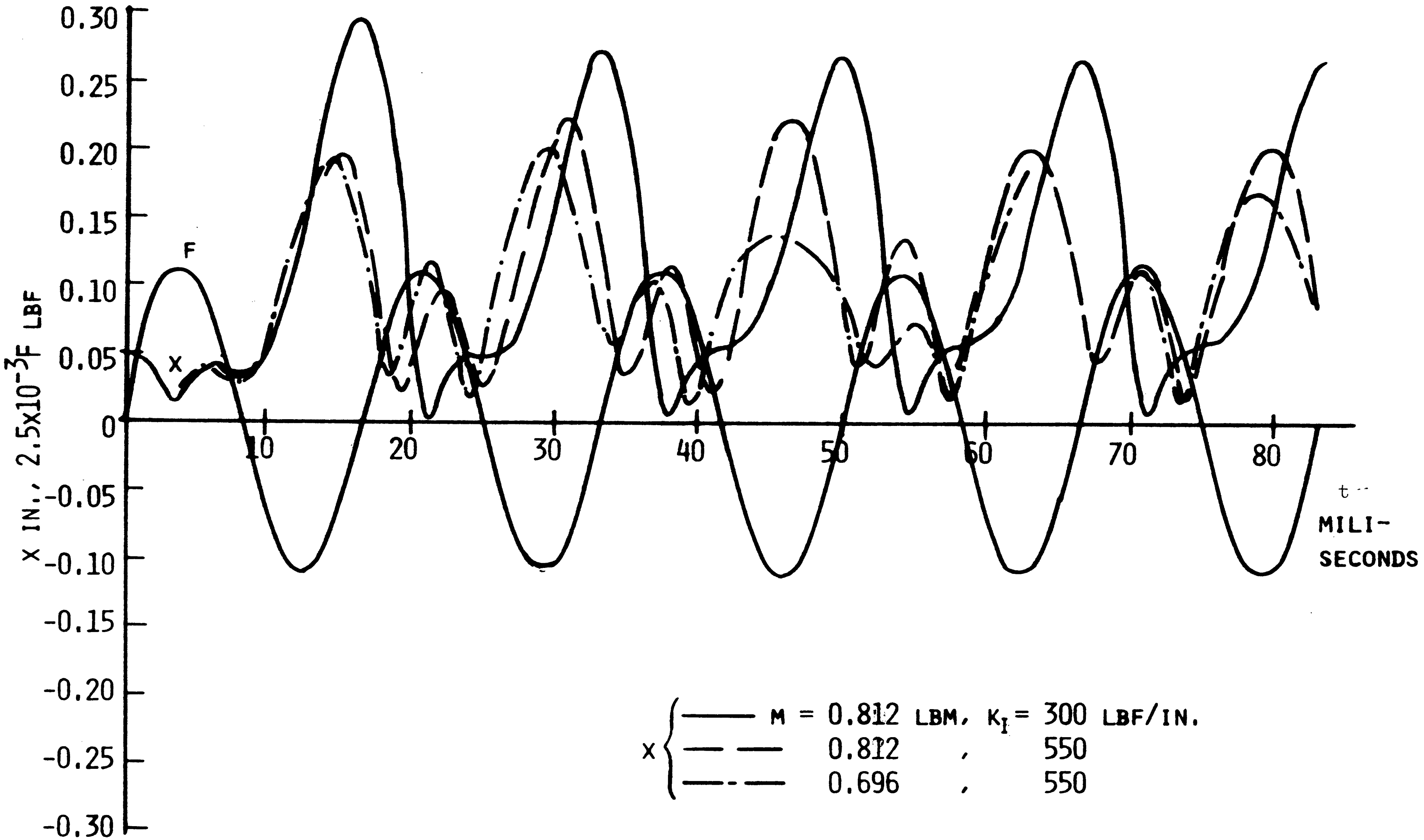


Figure 3. Dynamic Characteristics of "Moving-Coil" Type Electromagnetic Compressor for n = 1.41.

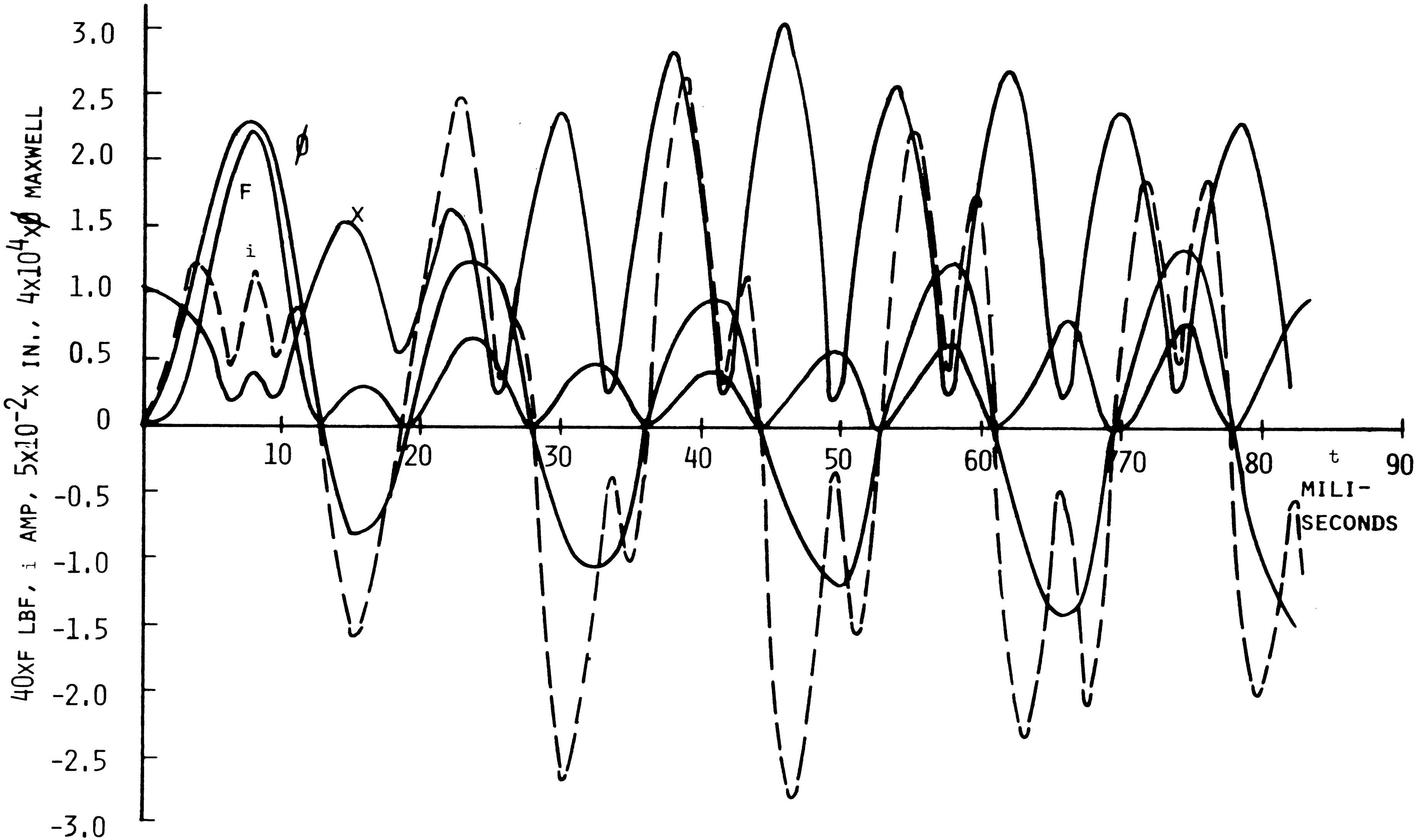


Figure 4. Dynamic Characteristics of Moving-Iron Type Electromagnetic Compressor for $M = 0.812$ lbm, $k_I = 550$ lbf/in., $k_{II} = 0$, and $n = 1.0$.

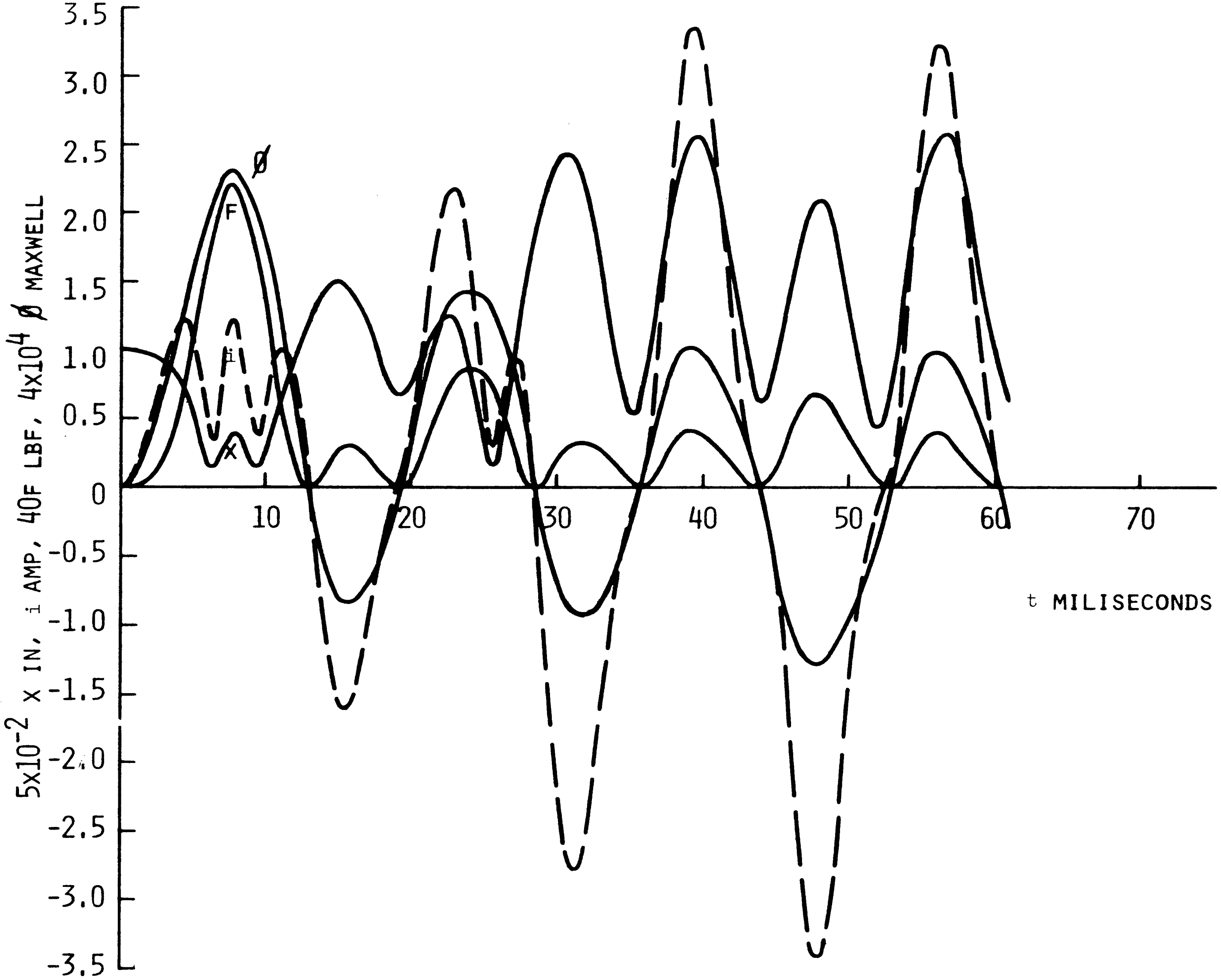


Figure 5. Dynamic Characteristics of "Moving-Iron" Type Electromagnetic Compressor with $M = 0.812$ lbm, $k_I = 300$ lbf/in., $k_{II} = 0$, and $n = 1.0$.

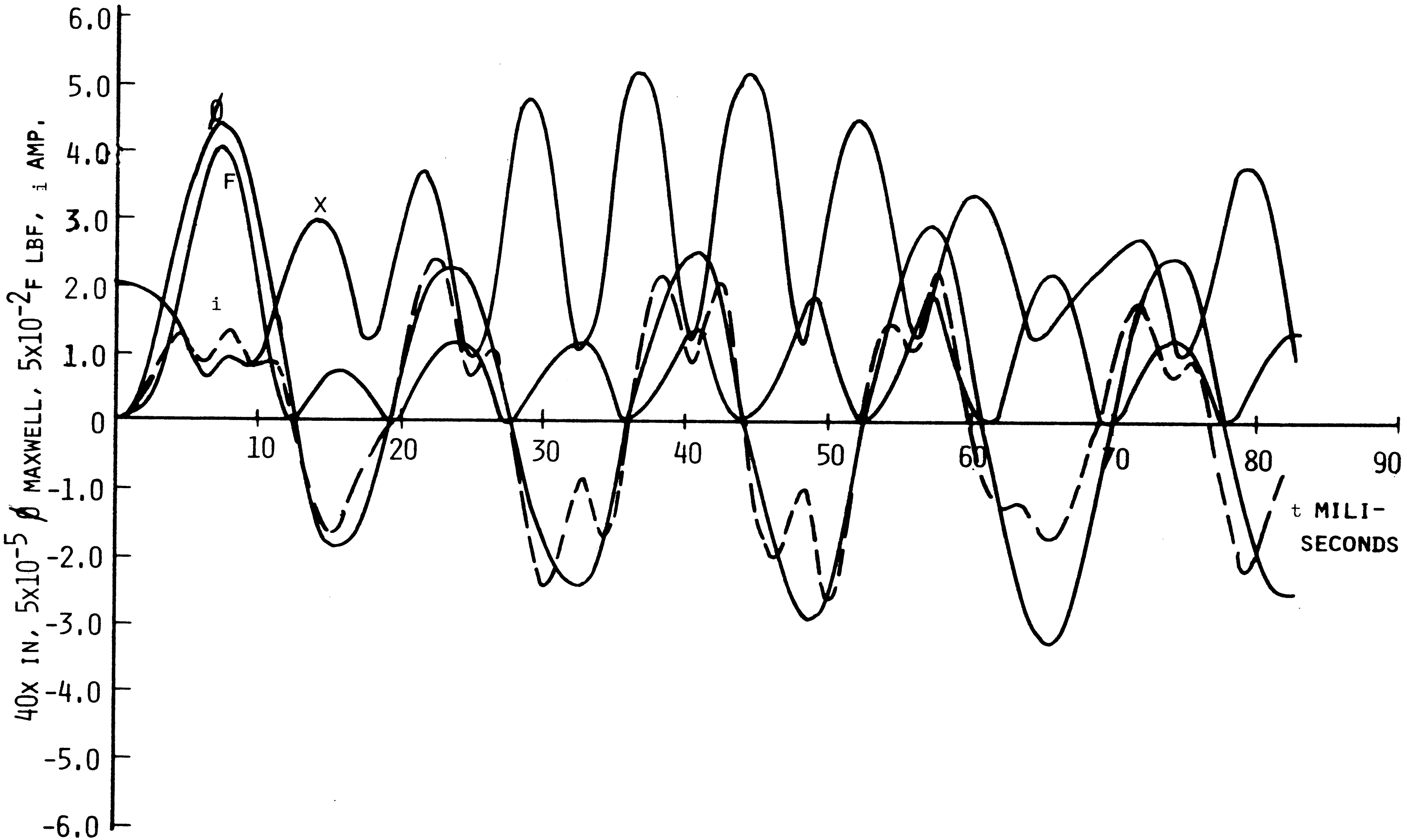


Figure 6. Dynamic Characteristics of "Moving-Iron" Type Electromagnetic Compressor with $M = 0.812$ lbm, $k_I = 550$ lbf/in., $k_{II} = 0$ and $n = 1.41$.

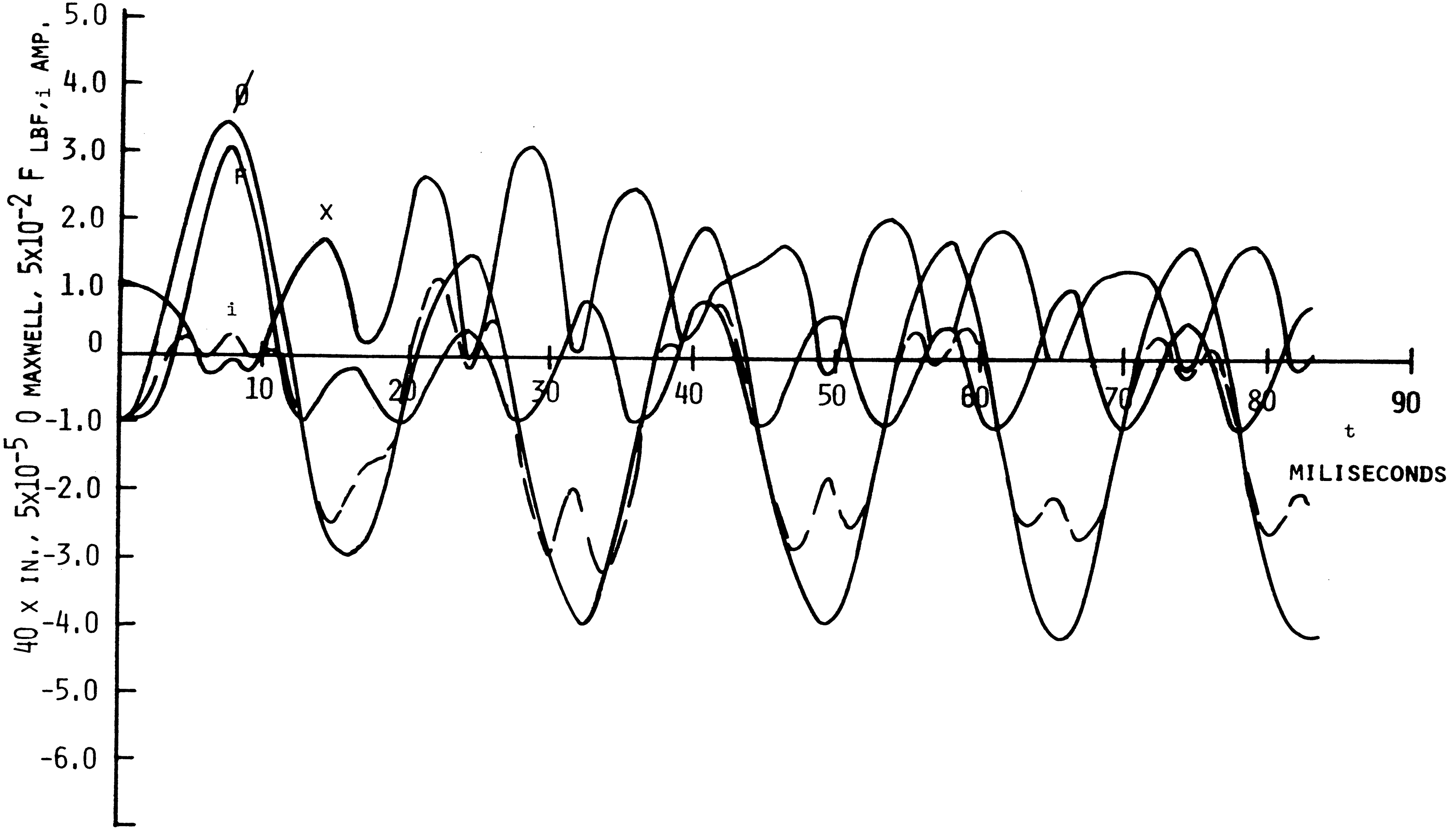


Figure 7. Dynamic Characteristics of "Moving-Iron" Type Electromagnetic Compressor with $M = 0.696$ lbm, $k_I = 550$ lbf/in., $k_{II} = 0$ and $n = 1.41$.

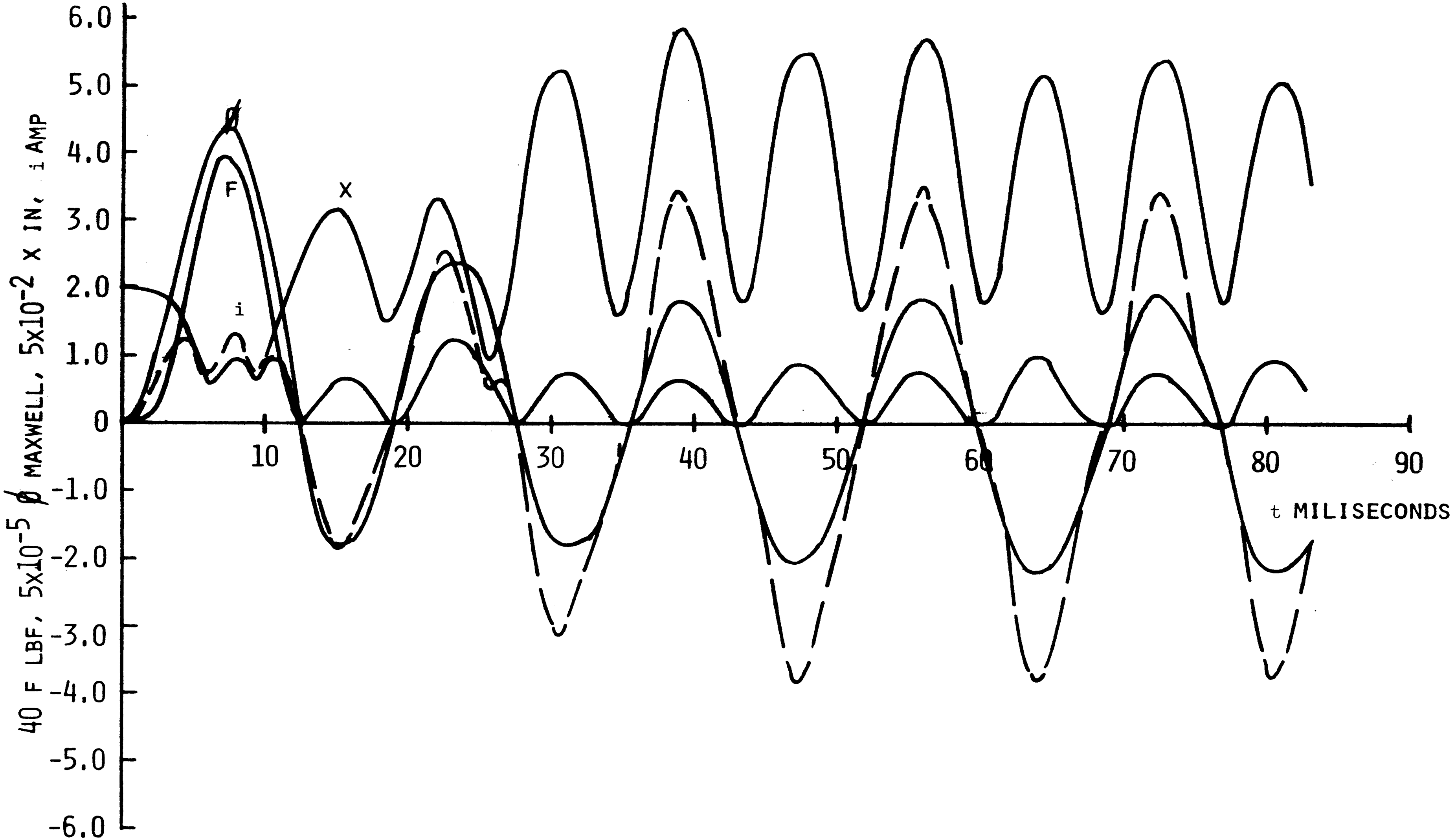


Figure 8. Dynamic Characteristics of "Moving-Iron" Type Electromagnetic Compressor with $M = 0.812$ lbm, $k_I = 300$ lbf/in., $k_{II} = 0$ and $n = 1.41$.

The displacement-time, force-time, current-time and magnetic flux-time characteristics of the "moving-iron" type compressor are graphically illustrated in Figures 4 through 8. It is disclosed by examining these figures that in the same time interval of 83.3 miliseconds, this compressor may perform twice as many compression cycles as the previous type since two cycles of the magnetic force are generated in each cycle of the impressed voltage. This is the principal advantage of the "moving-iron" type compressor. However it is rather difficult or time consuming to find out an appropriate set of the system variables for a desired performance of the compressor.

Only five sets of the system variables are studied in the text. The results are presented in Figures 4 through 8. It is disclosed that the patterns and magnitudes of the variations in the magnetic flux, magnetic force, current and displacement in the first 10 miliseconds are about the same for the five cases. During the 10 milisecond time interval, both the magnetic flux and force have attained their highest maxima, while the current vibrates twice and the piston performs two compression strokes.

The effect of the polytropic exponent n may be found by comparing Figures 4 and 6. After 50 miliseconds has elapsed, the compressor undergoing an isothermal process has come closer to an almost steady-periodic operation than the compressor undergoing an adiabatic process, although in practice an adiabatic process is more likely to occur. It is interesting to note that the current-time variations in Figures 4 and 6 are of the "M" shape for positive current and of the "W" shape for negative current.

As was revealed by comparing Figures 6 and 7, the increase in the mass of the moving part from 0.696 lbm to 0.812 lbm results in an increase in the swing displacement of the piston and consequently the compression ratio. A comparison of Figures 6 and 8 for adiabatic processes shows that the reduction in the spring constant k_I from 550 lbf/in. to 300 lbf/in. results in a higher compression ratio and a smoother operating condition. However, a comparison of Figures 4 and 5 for isothermal processes indicated that the effect of the spring constant on the compression ratio is insignificant.

CONCLUDING REMARKS

It is rather hard to draw a conclusion on the effects of each system variable on the dynamic characteristics of the compressors from the limited numerical results. However, it is obviously feasible to find out an appropriate set of the system variables to design a compressor with the desired performance. The "moving-iron" type compressor has an undefeatable advantage over the "moving-coil" type, that is, twice the pumping rates. The penalty the former type has to pay is more computations.

PROGRAM FOR UNSTEADY BEHAVIORS OF MOVING-COIL TYPE COMPRESSOR

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$COMPILE FASTRAN,EXECUTE,I/O DUMP,PRINT OBJECT,PUNCH OBJECT
C PROGRAM FOR UNSTEADY BEHAVIORS OF MOVING-COIL TYPE COMPRESSOR
      DIMENSION X(5),PHI(5)
      READ INPUT TAPE 7,2003,A,B,SO,XL,XK,AP,AB,PD,PS,XMASS,W,V
60    READ INPUT TAPE 7,2005,CAPAC,RESIST,WINDS,DELTIM,LIMIT,DIA, GFX,
     1VOLT
      WRITE OUTPUT TAPE 6,3002
      WRITE OUTPUT TAPE 6,3003,A,B,SO,XL,XK,AP,AB,PD,PS,V
      WRITE OUTPUT TAPE 6,3004,CAPAC,RESIST,WINDS,DELTIM,LIMIT,XMASS,W
      WRITE OUT PUT TAPE 6,3005 ,DIA, GFX,VOLT
      SIG=PD/PS
      S1=SO/SIG   **(1./V)
      ABPS=AB*PS
      APPSSO=AP*PS*SO **V
      APPSS1=APPSSO/S1**V
      ABPSBA=AB*PS*(B-A)**V
      APPS=AP*PS
      DELTSQ=DELTIM**2
      SO1=SO
      PC1=170.0*W
      PC2=1.0E-8*WINDS
      PC3=.468*RESIST/WINDS
      PC4=0.0
      PC5=DELTSQ
      EMFCON=1.04E-8
100   DM=DELTSQ/XMASS
      X(1)=SO
      T=DELTIM
      EMF=0
      X(2)=.5*((XK*(XL-X(1))-EMF)*DM+2.*X(1))
      L=3
C ----PHASE 2 OF CYCLE----
      IAB=3
700   DO 808 I=IAB,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      EMF=.278*WINDS*DIA* GFX*VOLT/RESIST*SIN(W*T)*1.0E-6
      X(L)=(XK*(XL- X(L-1))+ABPSBA/(X(L-1)-A)**V+APPSSO/X(L-1)**V-ABPS-
     1  APPS-EM  F)*DM+2.*X(L-1)-X(L-2)
      WRITE OUTPUT TAPE 6,5002,X(L),T,EMF
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      SO2=SO1/SIG**(1./V)
      IF (X(3)-SO2) 151,800,800
800   RATE=X(3)-X(1)
      IF (RATE) 808,802,803
808   CONTINUE
      GO TO 60
803   RATEN=X(3)-X(1)
      IF (RATE+RATEN) 802,805,805
805   IKEEP=IKEEP-1
802   XIM=IKEEP
      TOTAL=XIM*DELTIM
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,EMF
C ----PHASE 2R OF CYCLE-----
801   IAA=IKEEP
      IAAP=IAA+1
```

```
      DO 806 I=IAAP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      EMF=.278*WINDS*DIA* GFX*VOLT/RESIST*SIN(W*T)*1.0E-6
      X(L)=(XK*(XL-X(L-1))+ABPSBA/(X(L-1)-A)**V+APPSSO/X(L-1)**V-ABPS-AP
     1PS-EMF)*DM+2.*X(L-1)-X(L-2)
      WRITE OUTPUT TAPE 6,5002,X(L),T,EMF
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      IF (X(3)-B) 807,807,810
807   RATE=X(3)-X(1)
      IF (RATE) 809,806,806
809   IAB=IKEEP
      XIM=IKEEP
      TOTAL=XIM*DELTIM
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,EMF
      GO TO 700
806   CONTINUE
      GO TO 60
C ----PHASE 1R OF CYCLE----
810   IAC=IKEEP
      IACP=IAC+1
      DO 811 I=IACP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      EMF=.278*WINDS*DIA* GFX*VOLT/RESIST*SIN(W*T)*1.0E-6
      X(L)=(XK*(XL-X(L-1))+APPSSO/X(L-1)**V-APPS-EMF)*DM+2.*X(L-1)-X(L-
     1     2)
      WRITE OUTPUT TAPE 6,5002,X(L),T,EMF
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      IF (X(3)-S01) 814,814,812
814   RATE=X(3)-X(1)
      IF (RATE) 840,840,811
840   IABP=IKEEP
      IAB=IABP+1
      XIM=IKEEP
      TOTAL=XIM*DELTIM
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,EMF
      IF (X(3)-B) 700,700,1001
1001  S01R=X(3)
      S01=S01R
      IEND=IKEEP
      GO TO 1002
811   CONTINUE
      GO TO 60
C ----PHASE 6 OF CYCLE-----
812   IAE=IKEEP
      IAEP=IAE+1
      DO 813 I=IAEP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      EMF=.278*WINDS*DIA* GFX*VOLT/RESIST*SIN(W*T)*1.0E-6
      X(L)=(XK*(XL-X(L-1))-EMF)*DM+2.*X(L-1)-X(L-2)
```

```
      WRITE OUTPUT TAPE 6,5002,X(L),T,EMF
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      RATE=X(3)-X(1)
      IF (RATE) 816,815,813
 813  CONTINUE
      GO TO 60
 816  RATEN=X(3)-X(1)
      IF (RATE+RATEN) 815,817,817
 817  IKEEP=IKEEP-1
 815  IEND=IKEEP
      XIM=IKEEP
      TOTAL=XIM*DELTIM
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,EMF
C ----PHASE 1 OF CYCLE-----
      SOLAST=X(3)
      S01=SOLAST
1002  APPSS0=AP*PS*S01**V
      IAF=IEND
      IAFP=IAF+1
      DO 830 I=IAFP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      EMF=.278*WINDS*DIA* GFX*VOLT/RESIST*SIN(W*T)*1.0E-6
      X(L)=(XK*(XL-X(L-1))+APPSS0/X(L-1)**V-APPS-EMF)*DM+2.*X(L-1)-X(L-
     1    2)
      WRITE OUTPUT TAPE 6,5002,X(L),T,EMF
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      IF (X(3)-B) 831,832,832
 832  RATE=X(3)-X(1)
      IF (RATE) 830,835,835
 835  XIM=IKEEP
      TOTAL=XIM*DELTIM
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,EMF
      GO TO 810
 830  CONTINUE
      GO TO 60
 831  IAB=IKEEP+1
      GO TO 700
C ----PHASE 3 OF CYCLE----
 151  IC=IKEEP
      ICP=IC+1
      S02=S01/SIG  **(1./V)
      APPSS0=AP*PS*S01**V
      APPSS1=APPSS0/S02**V
      DO 170 I=ICP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      EMF=.278*WINDS*DIA* GFX*VOLT/RESIST*SIN(W*T)*1.0E-6
      X(L)=(XK*(XL-X(L-1))+ABPSBA/(X(L-1)-A)**V+APPSS1-ABPS-APPS-EMF)*DM
     1+2. *X(L-1)-X(L-2)
      WRITE OUTPUT TAPE 6,5002,X(L),T,EMF
      X(1)=X(L-2)
```

```
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      RATE=X(3)-X(1)
      IF (RATE) 170,185,180
  170 CONTINUE
      GO TO 60
  180 RATEN=X(3)-X(1)
      IF (RATE+RATEN) 185,181,181
  181 IKEEP=IKEEP-1
  185 ID=IKEEP
      S2=X(2)-(X(2)-X(1))*RATE/(RATE-RATEN)
      S3=S2*SIG **(1./V)
      XIM=ID
      APPSS0=AP*PS*S3**V
      TOTAL=XIM*DELTIM
      S01=S3
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,EMF
      IKEEP=IKEEP+1
      IF (B-S3)801,801,900
C ----PHASE 4 OF CYCLE----
  900 IKEEP=IKEEP-1
      IAQ=IKEEP
      IAQP=IAQ+1
      DO 902 I=IAQP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      EMF=.278*WINDS*DIA* GFX*VOLT/RESIST*SIN(W*T)*1.0E-6
      X(L)=(XK*(XL-X(L-1))+ABPSBA/(X(L-1)-A)**V+APPSS0/X(L-1)**V-ABPS-AP
     1 PS-EMF   )*DM+2.*X(L-1)-X(L-2)
      WRITE OUTPUT TAPE 6,5002,X(L),T,EMF
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      IF (X(3)-S3) 904,904,906
  904 RATE=X(3)-X(1)
      IF (RATE) 908,908,902
  902 CONTINUE
      GO TO 60
  908 IAB=IKEEP
      XIM=IKEEP
      TOTAL=XIM*DELTIM
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,EMF
      GO TO 700
C ----PHASE 5 OF CYCLE----
  906 IAP=IKEEP
      IAPP=IAP+1
      DO 910 I=IAPP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      EMF=.278*WINDS*DIA* GFX*VOLT/RESIST*SIN(W*T)*1.0E-6
      X(L)=(XK*(XL-X(L-1))+ABPSBA/(X(L-1)-A)**V-ABPS-EMF)*DM+2.*X(L-1)-X
     1     (L-2)
      WRITE OUTPUT TAPE 6,5002,X(L),T,EMF
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
```

```
      L=4
      IKEEP=I
      IF (X(3)-B) 912,912,812
912   RATE=X(3)-X(1)
      IF (RATE) 914,914,910
910   CONTINUE
      GO TO 60
914   XIM=IKEEP
      TOTAL=XIM*DELTIM
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,EMF
      S01=X(3)
      APPSS0=AP*PS*S01**V
      IAB=IKEEP+1
      GO TO 700
2003  FORMAT (10F6.0,F10.0,F10.1)
2005  FORMAT (3F6.1,F8.6,I4,3F10.2)
3002  FORMAT (52H1UNSTEADY-STATE DYNAMIC ANALYSIS OF AXIAL COMPRESSOR)
3003  FORMAT (3H A=,F10.5, 3H B=,F10.5,4H S0=,F10.5,4H XL=,F10.5,
     14H XK=,F10.5,4H AP=,F10.5,4H AB=,F10.5,4H PD=,F10.5,4H PS=,F10.5,
     23H V=,F5.1)
3004  FORMAT (7H CAPAC=,F6.1,8H RESIST=,F6.1,7H WINDS=,F6.1,8H DELTIM=,
     1F8.6,7H LIMIT=,I4,7H XMASS=,F10.5,3H W=,F10.6)
3005  FORMAT (5H DIA=,F10.2,6H MGFX=,F10.2,6H VOLT=,F10.2)
5001  FORMAT (6H XEND=,F9.5,6H TIME=,F7.5           ,7H FORCE=,
     1F10.5)
5002  FORMAT (3H X=,     F9.5,6H TIME=,F7.5           ,7H FORCE=,
     1F10.5)
      END
$DATA
```

PROGRAM FOR UNSTEADY BEHAVIORS OF MOVING-IRON TYPE COMPRESSOR

```
      DIMENSION X(5),PHI(5)
      READ INPUT TAPE 7,2003,A,B,S0,XL,XK,AP,AB,PD,PS,XMASS,W,V
60    READ INPUT TAPE 7,2005,CAPAC,RESIST,WINDS,DELTIM,LIMIT
      WRITE OUTPUT TAPE 6,3002
      WRITE OUTPUT TAPE 6,3003,A,B,S0,XL,XK,AP,AB,PD,PS,V
      WRITE OUTPUT TAPE 6,3004,CAPAC,RESIST,WINDS,DELTIM,LIMIT,XMASS,W
      SIG=PD/PS
      S1=S0/SIG    **(1./V)
      ABPS=AB*PS
      APPSS0=AP*PS*S0 **V
      APPSS1=APPSS0/S1**V
      ABPSBA=AB*PS*(B-A)**V
      APPS=AP*PS
      DELTSQ=DELTIM**2
      S01=S0
      PC1=170.0*W
      PC2=1.0E-8*WINDS
      PC3=.468*RESIST/WINDS
      PC4=0.0
      PC5=DELTSQ
      EMFCON=1.04E-8
100   DM=DELTSQ/XMASS
      X(1)=S0
      T=DELTIM
      PHI(1)=0.
      PHI(2)=PHI(1)
      EMF=EMFCON*PHI(2)**2
      X(2)=.5*((XK*(XL-X(1))-EMF)*DM+2.*X(1))
      L=3
C ----PHASE 2 OF CYCLE----
      IAB=3
700   DO 808 I=IAB,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      PHIA=PC1*COS(W*T)+(2.*PC2/PC5+PC3*X(L-2)/DELTIM
     1    -PC4*X(L-1))*PHI(L-1)-PC2*PHI(L-2)/PC5
      PHIB=PC2/PC5+PC3*X(L-1)/DELTIM
      PHI(L)=PHIA/PHIB
      EMF=EMFCON*PHI(L)**2
      PHI(1)=PHI(L-2)
      PHI(2)=PHI(L-1)
      PHI(3)=PHI(L)
      X(L)=(XK*(XL- X(L-1))+ABPSBA/(X(L-1)-A)**V+APPSS0/X(L-1)**V-ABPS-
     1 APPS-EM  F)*DM+2.*X(L-1)-X(L-2)
      CURT=.468*X(L)*PHI(L)/WINDS
      WRITE OUTPUT TAPE 6,5002,X(L),T,PHI(L),EMF,CURT
      X(1)=X(L-2)
      X(2)=X(L-1)
```

```
      X(3)=X(L)
      L=4
      IKEEP=I
      SO2=SO1/SIG**(1./V)
      IF (X(3)-SO2) 151,800,800
800   RATE=X(3)-X(1)
      IF (RATE) 808,802,803
808   CONTINUE
      GO TO 60
803   RATEN=X(3)-X(1)
      IF (RATE+RATEN) 802,805,805
805   IKEEP=IKEEP-1
802   XIM=IKEEP
      TOTAL=XIM*DELTIM
      CURT=.468*X(3)*PHI(3)/WINDS
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,PHI(3),EMF,CURT
C ----PHASE 2R OF CYCLE-----
801   IAA=IKEEP
      IAAP=IAA+1
      DO 806 I=IAAP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      PHIA=PC1*COS(W*T)+(2.*PC2/PC5+PC3*X(L-2)/DELTIM-PC4*X(L-1))*PHI(L-
     1     1)-PC2*PHI(L-2)/PC5
      PHIB=PC2/PC5+PC3*X(L-1)/DELTIM
      PHI(L)=PHIA/PHIB
      EMF=EMFCON*PHI(L)**2
      PHI(1)=PHI(L-2)
      PHI(2)=PHI(L-1)
      PHI(3)=PHI(L)
      X(L)=(XK*(XL-X(L-1))+ABPSBA/(X(L-1)-A)**V+APPSSO/X(L-1)**V-ABPS-AP
     1PS-EMF)*DM+2.*X(L-1)-X(L-2)
      CURT=.468*X(L)*PHI(L)/WINDS
      WRITE OUTPUT TAPE 6,5002,X(L),T,PHI(L),EMF,CURT
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      IF (X(3)-B) 807,807,810
807   RATE=X(3)-X(1)
      IF (RATE) 809,806,806
809   IAB=IKEEP
      XIM=IKEEP
      TOTAL=XIM*DELTIM
      CURT=.468*X(3)*PHI(3)/WINDS
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,PHI(3),EMF,CURT
      GO TO 700
806   CONTINUE
      GO TO 60
C ----PHASE 1R OF CYCLE----
810   IAC=IKEEP
      IACP=IAC+1
      DO 811 I=IACP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      PHIA=PC1*COS(W*T)+(2.*PC2/PC5+PC3*X(L-2)/DELTIM
```

```
     1   -PC4*X(L-1))*PHI(L-1)-PC2*PHI(L-2)/PC5
      PHIB=PC2/PC5+PC3*X(L-1)/DELTIM
      PHI(L)=PHIA/PHIB
      EMF=EMFCON*PHI(L)**2
      PHI(1)=PHI(L-2)
      PHI(2)=PHI(L-1)
      PHI(3)=PHI(L)
      X(L)=(XK*(XL-X(L-1))+APPSSO/X(L-1)**V-APPS-EMF)*DM+2.*X(L-1)-X(L-
     1    2)
      CURT=.468*X(L)*PHI(L)/WINDS
      WRITE OUTPUT TAPE 6,5002,X(L),T,PHI(L),EMF,CURT
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      IF (X(3)-S01) 814,814,812
814   RATE=X(3)-X(1)
      IF (RATE) 840,840,811
840   IABP=IKEEP
      IAB=IABP+1
      XIM=IKEEP
      TOTAL=XIM*DELTIM
      CURT=.468*X(3)*PHI(3)/WINDS
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,PHI(3),EMF,CURT
      IF (X(3)-B) 700,700,1001
1001  S01R=X(3)
      S01=S01R
      IEND=IKEEP
      GO TO 1002
811   CONTINUE
      GO TO 60
C ----PHASE 6 OF CYCLE-----
812   IAE=IKEEP
      IAEP=IAE+1
      DO 813 I=IAEP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      PHIA=PC1*COS(W*T)+(2.*PC2/PC5+PC3*X(L-2)/DELTIM-PC4*X(L-1))*PHI(L-
     1   1)-PC2*PHI(L-2)/PC5
      PHIB=PC2/PC5+PC3*X(L-1)/DELTIM
      PHI(L)=PHIA/PHIB
      EMF=EMFCON*PHI(L)**2
      PHI(1)=PHI(L-2)
      PHI(2)=PHI(L-1)
      PHI(3)=PHI(L)
      X(L)=(XK*(XL-X(L-1))-EMF)*DM+2.*X(L-1)-X(L-2)
      CURT=.468*X(L)*PHI(L)/WINDS
      WRITE OUTPUT TAPE 6,5002,X(L),T,PHI(L),EMF,CURT
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      RATE=X(3)-X(1)
      IF (RATE) 816,815,813
813   CONTINUE
```

```
      GO TO 60
816   RATEN=X(3)-X(1)
      IF (RATE+RATEN) 815,817,817
817   IKEEP=IKEEP-1
815   IEND=IKEEP
      XIM=IKEEP
      TOTAL=XIM*DELTIM
      CURT=.468*X(3)*PHI(3)/WINDS
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,PHI(3),EMF,CURT
C ----PHASE 1 OF CYCLE-----
      SOLAST=X(3)
      S01=SOLAST
1002  APPSS0=AP*PS*S01**V
      IAF=IEND
      IAFP=IAF+1
      DO 830 I=IAFP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      PHIA=PC1*COS(W*T)+(2.*PC2/PC5+PC3*X(L-2)/DELTIM-PC4*X(L-1))*PHI(L-
     1 1)-PC2*PHI(L-2)/PC5
      PHIB=PC2/PC5+PC3*X(L-1)/DELTIM
      PHI(L)=PHIA/PHIB
      EMF=EMFCON*PHI(L)**2
      PHI(1)=PHI(L-2)
      PHI(2)=PHI(L-1)
      PHI(3)=PHI(L)
      X(L)=(XK*(XL-X(L-1))+APPSS0/X(L-1)**V-APPS-EMF)*DM+2.*X(L-1)-X(L-
     1    2)
      CURT=.468*X(L)*PHI(L)/WINDS
      WRITE OUTPUT TAPE 6,5002,X(L),T,PHI(L),EMF,CURT
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      IF (X(3)-B) 831,832,832
832   RATE=X(3)-X(1)
      IF (RATE) 830,835,835
835   XIM=IKEEP
      TOTAL=XIM*DELTIM
      CURT=.468*X(3)*PHI(3)/WINDS
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,PHI(3),EMF,CURT
      GO TO 810
830   CONTINUE
      GO TO 60
831   IAB=IKEEP+1
      GO TO 700
C ----PHASE 3 OF CYCLE----
151   IC=IKEEP
      ICP=IC+1
      S02=S01/SIG    **(1./V)
      APPSS0=AP*PS*S01**V
      APPSS1=APPSS0/S02**V
      DO 170 I=ICP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      PHIA=PC1*COS(W*T)+(2.*PC2/PC5+PC3*X(L-2)/DELTIM-PC4*X(L-1))*PHI(L-
```

```
     1     1)-PC2*PHI(L-2)/PC5
      PHIB=PC2/PC5+PC3*X(L-1)/DELTIM
      PHI(L)=PHIA/PHIB
      EMF=EMFCON*PHI(L)**2
      PHI(1)=PHI(L-2)
      PHI(2)=PHI(L-1)
      PHI(3)=PHI(L)
      X(L)=(XK*(XL-X(L-1))+ABPSBA/(X(L-1)-A)**V+APPSS1-ABPS-APPS-EMF)*DM
     1+2. *X(L-1)-X(L-2)
      CURT=.468*X(L)*PHI(L)/WINDS
      WRITE OUTPUT TAPE 6,5002,X(L),T,PHI(L),EMF,CURT
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      RATE=X(3)-X(1)
      IF (RATE) 170,185,180
 170  CONTINUE
      GO TO 60
 180  RATEN=X(3)-X(1)
      IF (RATE+RATEN) 185,181,181
 181  IKEEP=IKEEP-1
 185  ID=IKEEP
      S2=X(2)-(X(2)-X(1))*RATE/(RATE-RATEN)
      S3=S2*SIG **(1./V)
      XIM=ID
      APPSSO=AP*PS*S3**V
      TOTAL=XIM*DELTIM
      S01=S3
      CURT=.468*X(3)*PHI(3)/WINDS
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,PHI(3),EMF,CURT
      IKEEP=IKEEP+1
      IF (B-S3) 801,801,900
C ----PHASE 4 OF CYCLE----
 900  IKEEP=IKEEP-1
      IAQ=IKEEP
      IAQP=IAQ+1
      DO 902 I=IAQP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      PHIA=PC1*COS(W*T)+(2.*PC2/PC5+PC3*X(L-2)/DELTIM-PC4*X(L-1))*PHI(L-
     1    1)-PC2*PHI(L-2)/PC5
      PHIB=PC2/PC5+PC3*X(L-1)/DELTIM
      PHI(L)=PHIA/PHIB
      EMF=EMFCON*PHI(L)**2
      PHI(1)=PHI(L-2)
      PHI(2)=PHI(L-1)
      PHI(3)=PHI(L)
      X(L)=(XK*(XL-X(L-1))+ABPSBA/(X(L-1)-A)**V+APPSSO/X(L-1)**V-ABPS-AP
     1 PS-EMF  )*DM+2.*X(L-1)-X(L-2)
      CURT=.468*X(L)*PHI(L)/WINDS
      WRITE OUTPUT TAPE 6,5002,X(L),T,PHI(L),EMF,CURT
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
```

```
      IKEEP=I
      IF (X(3)-S3) 904,904,906
904   RATE=X(3)-X(1)
      IF (RATE) 908,908,902
902   CONTINUE
      GO TO 60
908   IAB=IKEEP
      XIM=IKEEP
      TOTAL=XIM*DELTIM
      CURT=.468*X(3)*PHI(3)/WINDS
      WRITE OUT PUT TAPE 6,5001,X(3),TOTAL,PHI(3),EMF,CURT
      GO TO 700
C ----PHASE 5 OF CYCLE----
906   IAP=IKEEP
      IAPP=IAP+1
      DO 910 I=IAPP,LIMIT
      XIM=I-1
      T=XIM*DELTIM
      PHIA=PC1*COS(W*T)+(2.*PC2/PC5+PC3*X(L-2)/DELTIM-PC4*X(L-1))*PHI(L-
     1   1)-PC2*PHI(L-2)/PC5
      PHIB=PC2/PC5+PC3*X(L-1)/DELTIM
      PHI(L)=PHIA/PHIB
      EMF=EMFCON*PHI(L)**2
      PHI(1)=PHI(L-2)
      PHI(2)=PHI(L-1)
      PHI(3)=PHI(L)
      X(L)=(XK*(XL-X(L-1))+ABPSBA/(X(L-1)-A)**V-ABPS-EMF)*DM+2.*X(L-1)-X
     1    (L-2)
      CURT=.468*X(L)*PHI(L)/WINDS
      WRITE OUTPUT TAPE 6,5002,X(L),T,PHI(L),EMF,CURT
      X(1)=X(L-2)
      X(2)=X(L-1)
      X(3)=X(L)
      L=4
      IKEEP=I
      IF (X(3)-B) 912,912,812
912   RATE=X(3)-X(1)
      IF (RATE) 914,914,910
910   CONTINUE
      GO TO 60
914   XIM=IKEEP
      TOTAL=XIM*DELTIM
      CURT=.468*X(3)*PHI(3)/WINDS
      WRITE OUTPUT TAPE 6,5001,X(3),TOTAL,PHI(3),EMF,CURT
      S01=X(3)
      APPSS0=AP*PS*S01**V
      IAB=IKEEP+1
      GO TO 700
2003  FORMAT (10F6.0,F10.0,F10.1)
2005  FORMAT (3F6.1,F8.6,I4)
3002  FORMAT (52H1UNSTEADY-STATE DYNAMIC ANALYSIS OF AXIAL COMPRESSOR)
3003  FORMAT (3H A=,F10.5, 3H B=,F10.5,4H S0=,F10.5,4H XL=,F10.5,
     14H XK=,F10.5,4H AP=,F10.5,4H AB=,F10.5,4H PD=,F10.5,4H PS=,F10.5,
     23H V=,F5.1)
3004  FORMAT (7H CAPAC=,F6.1,8H RESIST=,F6.1,7H WINDS=,F6.1,8H DELTIM=,
     1F8.6,7H LIMIT=,I4,7H XMASS=,F10.5,3H W=,F10.6)
5001  FORMAT (6H XEND=,F9.5,6H TIME=,F7.5,5H PHI=,F15.5-7H FORCE=,
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