MORE ELECTRIC COMMERCIAL AIRCRAFT ENGINES
(Integral Starter/ Generator & Magnetic Bearings)

A. F. Kascak, G. V. Brown, and G. L. Stefko
NASA Lewis Research Center
Cleveland, Ohio

Background: The first figure shows a typical small gas turbine engine. This engine has a tower shaft to drive the accessories, a starter, and a generator. One of the accessories is an oil pump which lubricates the rolling element bearings on both the gas generator shaft and power turbine shaft. If we removed the tower shaft and had all the accessories electrically driven by an integral starter/ generator on the gas generator shaft and replaced the rolling element bearings with magnetic bearings; then this engine would become a "more electric engine". The advantage of doing this is that we eliminate the lubrication system and use less secondary air flow to the bearing compartments.

A magnetic bearing is shown as an insert in figure 1. A magnetic bearing is similar to a electric motor. It has laminated stator with coils raped around poles to form electro magnets and a laminated rotor. The magnetic bearing is a active control device which levitates the rotor in the center of the stator cavity. The magnetic bearing works by sensing the position of the rotor, (shaft), with a proximity probe. A controller uses this position to send a corrective command to an amplifier to power the electro magnets. The electro magnets pull the shaft to the commanded position.

Magnetic bearings are radial or thrust magnetic actuators composed of a rotor, stator, and coils. These actuators are part of a control system which need displacement probes, power amplifiers, and a controller. For high loads transience and power loss conditions an auxiliary bearing is included to prevent the high speed rotor laminations from contacting the stationary stator laminations.

The rotor and stator laminations are made of cobalt steel and the coils are made of nickel plated copper wire with a ceramic insulation. The displacement probes can be either eddy current, inductive, capacitance, or self sensing. (Self sensing probes uses the change in the inductance of the electro magnets as an inductive probe.) The capacitance probes seem to be the most stable at high temperature but require the rotating shaft to be grounded. The power amplifiers can be either linear or pulse width modulated (PWM). The PWM amplifiers are smaller and more efficient but more noisy.

Al Kasack

What we get when we remove oil from the system; this is a conventional lubrication system you can't even read all the little parts but there's pumps and reservoirs and stuff to pump the fluid through the bearing cavities if you look at the exterior outlay of the engine that is around the outside of the case you look at how many winds there are on there and you map it out this is what it kind of looks like and if you use magnetic bearings this complicated systems will reduce to this system so there's considerable simplification in the magnetic bearing in the lubrication system and in fact there is none the other thing you can do with magnetic bearing is you're not limited by the DN level anymore that's the diameter times the RPM of the bearing you have a limit that is higher than the three million DN that normal oil lubricated bearings are limited to, the gas generator shaft is over here and the power tubing shaft goes through the inside of this gas generator shaft, the gas generators bearings are usually designed to the DN limits so in this particular case these would be the gas generators bearings and then this is the small power turbine shaft that goes through there this shaft tends to be very thin and very flexible so you're going to need more than two bearings to support it. You go to the magnetic bearings you can actually support the power turbine shaft on two bearings systems since the diameter can be increased at the same speed you got a higher the DN limit. The other thing you can do with a engine like this is to use active stall control now when in stall control these are the first lower cases of stall the first case is where there is an axial pressure wave traveling up and down the compressors and then the rotating stall is where you have a rotating pressure wave traveling up and down the rotor what you'd like to do in a engine of the air is being compressed as you go in this direction so on the blade tips the air bleeds back around the outside from high to low if you move the rotor back and forth you can reduce axial pressure wave that will remove the lowest mode of stall and if you whirl the rotor into cavity so that the blade tip clearance varied to this side from this side and that was a rotating variance you can produce rotating pressure wave that could actually cancel out the rotating stall. What you'd get if add these things together well these are some of the estimates made by the industry Pratt-Whitney made an estimate with the Air Force so they could save 10 - 15% by ruling the oil coolers and the engine weight by removing the oil coolers and the pumps and the plumbing that can be translated into a SFC savings of 2-4%. You also get a safe more reliable engine there's no oil leak you can do a health monitoring with the system and you can do vibration control, in addition to that you can increase the efficiency by cutting down the secondary air flow that you need for cooling the bearings you won't need and that's a 1-2% savings. The blade tips you can, if you have a conical compressor you can move this compressors back towards and cut down the blade tips actively so you can increase you're cut down you blade tip clearances if you want and that can add another one or two percent and then if you can actually do the stall line management you got a huge savings there 5-11% the other things it does with the higher the DN limits and the shorter stiffer rotor designs you can have and no oil flow you have a new design envelope you can design the engine too ;what are the ramifications for seals in the more electric engines well there are no oil seals so I'm not going to be very popular with the oil seals guys but the secondary seals since we're cutting down less air of bleed air we're going to have to have smaller tighter seals where we do have to bleed air the seals are going to have to go at higher speeds, because the engine is going to turn at higher speeds, and there's going to be a higher pressure in this engine because we're going for a higher efficiencies in terms of the blade tips seals if we use blade tip control then we'll want conical casing so that'll impact the blade tips clearance area and if we do stall line management then we may have to increase the blade tip clearance to get the size of the pressure wave we need in there to operate it beyond the stall limits. The auxiliary bearings are going to running there's going to one running at least a thousand they all run a thousand degrees and depending on the bearings size the seals have not yet been defined. Well who's interested in this program or a program similar to this well each of the engine manufacturers have strong in house programs the government's supported several programs the Navy has retrofitted an existing engine down in Pratt and they ran a magnetic on it and it ran very successfully the Air Force is looking in the IHPTET program the phase three use in the magnetic bearings and the integral starter generator on their phase three program and the Army is trying to design a flight weight controller at GE for a similar program the question we ask here is why do want to do a commercial program that the military seems to be doing well the goals of the military missions are different than commercial area in the military the IHPTET phase three they're open towards the are of ten G's and you never do that on a commercial aircraft. High Mach numbers up to 3 , well you might do that in a commercial aircraft but there really striving to reduce the fuel consumption and the weight, in a commercial engine you large fan moments , you got a larger thrust you need larger in fill starter generators you have different low boom loads on the engine and the cost to bleed air is different than various parts of the engine and the backup bearings are probably the biggest area that would be easier and in a military you make engine you make a single engine airplane and the magnetic bearings go out you got to make sure you can land on the backup bearings then maybe an hour on running on back up barring in a commercial engine all you would have to do is be able to shut down that engine if it is a multi-engine aircraft. What are we doing in house in that area? We have two programs going one is a flight adaptive controller and the second is a high temperatures magnetic bearings program in the area of adaptive controller we're looking at expert systems the first one is the magnetic barring is basically an unstable system so we need a mobile controller to stabilize the system and have the rotor run inside the cavity the next thing we'd like to have it to is to respond to pilot stick commands so that if the pilot is going to turn the engine can anticipate that and move the rotor to a point to where you're not going to have the rub. The third area is unexpected activities and that will be blade loss, bird ingestion, hard rubs from thermal growth or something along those lines then lastly we want to be able to do a health monitoring with magnetic bearings you can pulse the barring and produce a pulse and with the probes you can measure what's coming out and you can get health monitoring information from them. The other area we're working in is a high temperature magnetic bearings program we're trying to develop coils (wire) that'll with stand the thousand degrees, probes that with stand thousand degrees and that thousand degrees can be H curves are nonlinear and then to test this out we want to develop a rig that will verify all these things what we found in there area of the coils there is right now on the market a copper wire that has a nickel clad on the outside and then a vitreous coating on the outside of that we could wind this in the wet ceramic and the wires could for fourteen hundred degrees and the ceramics good for about two thousand degrees we found that the capacitance probe works very well up to twelve hundred degrees and its commercially available the only problem with it is we have to ground the shaft and we'll work around that later we maybe to get around that by using a probe which we're going have to do anyhow we're developing non linear algorithms to handle the VH non linearity then we're in the process of building a high temperature rig. This is a picture of rig that is being designed for us at Texas A&M and will eventually be running, probably towards the beginning of next year. The rotor will run at twenty thousand rpms the heated section is over here right now we have design of radial magnetic bearings to go in there we have the parts built we're winding the coils the chamber's capable of twelve hundred degrees. We have high temperature capacity probes to measure the displacement and that's basically the rig and it is being fabricated - at the present time we have no way of checking out or controller program because we don't have the actual magnetic bearings program that could use blade loss and various other simulation devices, but we do have an active rotor control program but rather than use magnets we use piezoelectric actuators, these are actuators that when you put a voltage on them they expand what they do is they move a conventional bearing around in the cavity or so this so if you want to move this barring up you expand this actuator this way and the barring goes up horizontally you expand this one and we have piezoelectric actuators here on either side of this machine so we are testing our algorithms on this piece of electric active vibration control rig rather than magnetic bearings rig because we don't have them. Some of the interesting things you can find from this are shown on the next grid, on the next diagram. If you look at the critical speeds for this particular rig there are three of them within a few thousands rpm the first one looks like this, the second one looks like this, the third one looks like this and if you're trying to control the vibrations you can possible control this vibrations but you may make this vibration worse or this vibration worse and so the first thing we're trying to do is reduce the vibrations all along the rotor so if you had a seal in this location which is not in the same location as the barring you actually reduce the vibrations there so it won't rub, well we took the eddy current probes and we had them locate up and down the rotor and we took the maximum value of any speed or at any condition and plotted it on the following graph. So at nine thousand rpm, at 9600 rpm we plotted the maximum vibration we found up and down the rotor vertically, and this is where we varied the stiffness of the bearings by changing, actively controlling the damping feedback and the stiffness by controlling the proportional feedback so as you can see you have a plane here and at this speed the optimum value for C and K is right here, now this is the horizontal vibrations this is the vertical vibrations now if you went to a different speed you wind up with a different optimum here and here and this shows you the first thing you have to do with the controller you want gain schedule you want to change the stiffness and damping with speed. The next thing you want to show is on this bearing rig we have a disc on the end here when it's assembled and there's a little numb on here that we can break off with a selenoid, and when we break it off it simulates a blade loss event, and what we did here is we had the computer get the vibrations signals, we broke off the blade at this point the computer started the vibrations collecting data up to here and then determine it was a blade loss event rather than bird ingestion event or rub. And it put a electromagnetic signal into this piece of the actuators so we're electronically re-balance the rotor this is the control voltage that went into these piezoelectric actuators and this is the amplitude of the vibrations that came out at this point can do better than that it change the control, this thing was like and this is the vibration that came out of the signal after that, the last thing you got to be careful of is when you use an active vibrations to control this the system is mechanical here but you have the other components which are electrical and so you have a mechanical electrical system that has to be analyze for instability at this rate normally this turbine can run up to sixty thousand rpm's and first three criticals were down around twelve thousands rpm but we could not run to gain them because the rotor was going unstable so what we did was we model the shaft with finite elements we model the electronics, the amplifiers, the controller, and delaying the signals and low and behold when we calculated the unstable eigenvalue this is the one turned out is was out at two thousand one hundred hertz which is roughly hundred and twenty thousand rpm this is what it look like this is what hung us up in any active control system any mode that can be unstable can be driven because there's always white noise involved, any how that's our program we're looking towards applying it to other areas and those other areas are in the are of space to replace batteries with a fly wheel energy storage system and then the fly wheel can actually be used as a momentum wheel in some instances we're looking at magnetic bearings to be used on the space shuttle main engine in replacing the ball bearings we're looking at auxiliary power units for continuous power and then the Army's interested in magnetic bearings and fly wheels for very efficient batteries for the tanks especially in the sleep mode where most tanks sit they sit on watch and they don't want to run the big turbine engines, that's my program.

QUESTIONS

Q: The electric engine, could you comment on the power generator or the power energy so and the issue of how long range and so forth.

A: Are you talking about ...?

Q: The energy source, the electric energy

A; The more electric engine is really a gas turbine engine with a intregal starter generator is that what you're talking about or our you talking about ...

A: The electric engine

A: It is still a gas turbine ... but there is a battery application that we use in fly wheels to start energy in space there going use the photo electric cells of the space station to drive it.

Q: Could you comment on the size of the bearings required supporting the same box (gearbox) ... magnetic vs oil lubricated

A: Well the bearings are on the order of a thousand pounds they maybe one to two thousands pound. The bearings you saw there that I have a picture we tested in a test cell this particular barring here is about five inches in diameter and about five inches

long and it'll produce about a thousand pounds load. They're talking somewhere between one and two thousands pounds.
Q: How big is the diameter of the shaft versus the one you're going to build at Texas A&M
A: On the rig you mean
Q: What are you going to use to support you shaft
A; Well I'm not sure the shafts, the outer race of the bearings bit determines how much I can fit into that cavity. Its upwards of eight or nine inches I think I know this five inch one is the one we're testing in there now and the one we built for room temperature we made all the conversions we needed to bring it up to a thousand degrees and that one will fit in there and this is roughly five inches across.
Q: And what's the shaft diameter
A; Oh the shaft diameter this is three inches from here to here and on the rotating part of the shaft is, I'm not absolutely sure but I think it's on the order of an inch and a half
Q: From the numbers you quoted for an equivalent performance benefit do they assume that we also replace the gearbox, with electric bearings.
A: The gearbox won't be there, the integral starter generator will be attached directly into the gas generator shaft the gas generator turns into...
Q: How are going to drive the hydraulic pumps
A: It'll be done with motor on the outside all of the pumping of fluids of the hydraulic fluids will be done with electric motors on the outside.
Q: So it'll be one very large generator
A: Yes that's the idea, you have to realize these generators the gas generators on some of this engines could turn as high as forty thousands rpm and two hundred and fifty K W generators is not very large of speeds but switch off these machines
Q: You mention that, that particular barring despite its diameter of five inch long you mentioned a thousand pound load capacity that'll work out to forty PSI a low capacity, industrial bearings are a little higher than that ..does that fall off with speed and temperature you have.
A: Well you see it's five inches from here to here, and from here to here it's three inches in diameter that's where you'll
Q: Both of these ... is three inches, so you got two by five fifteen square inch
A: It's a little over hundred and fifty pounds per square inch
Q: Okay, to get that are you using improved vanadium alloys
A: Yes we are using the cobalt steel the cobalt steel by the way will take a thousand degrees their heat treated by magnetic properties about fifteen to hundred fifty degrees and when you bring up a thousand that's the point which they begin to oxidizes so you have to careful of oxidation and if you get into a real oxidation problem you'll just have to can them in the stainless steel can and evacuate the can if that is a real problem...U of Virginia has done that on a commercial chemical barring already this one is in cans.
Q: So what is the ratio between the magnetic barring and the shaft size, the size of a magnetic barring and a shaft
Q: You mean the ratio?

A: In an actual engine, these bearings were not design for an actual engine and I can quote you some numbers from IHPTET but I'm not sure if I should be at this point, I won't do that right now... any other questions.

High Temperature Magnetic Bearing Applied to Gas Turbine Engine

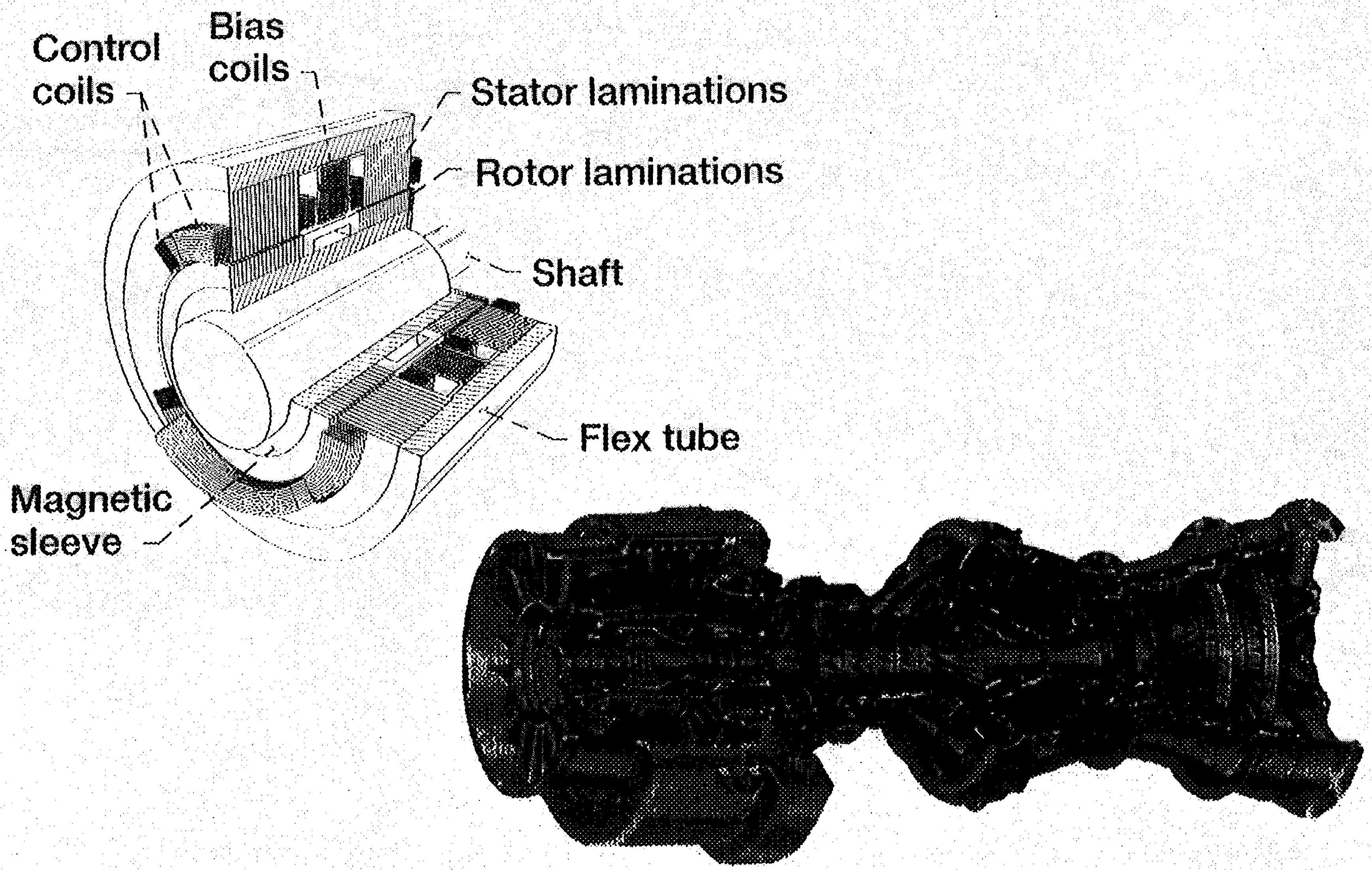


Fig. 1

BACKGROUND
What is a Magnetic Bearing?

- A proximity probe measures the shaft position
- A controller commands an amplifier
- The amplifier powers the electro magnet
- The electro magnet pulls the shaft to the commanded position

Fig. 2

Magnetic Bearing Components

- Radial or Thrust Magnetic Actuator
  (Rotor, Stator, Coil)
- Displacement Probe
  (Eddy Current, Inductive, Capacitance, Self sensing)
- Power Amplifier (Linear or PWM)
- Controller (Analog or Digital)
- Auxiliary Bearing
  (Rub, Ball or Roller, Foil, Air, Powder)

Fig. 3

MAGNETIC BEARINGS
For
GAS TURBINE ENGINES

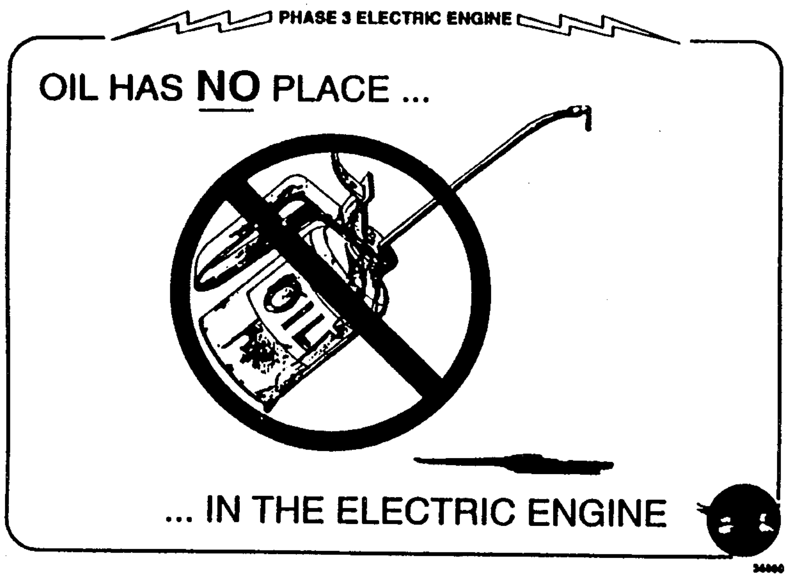
Advantages:

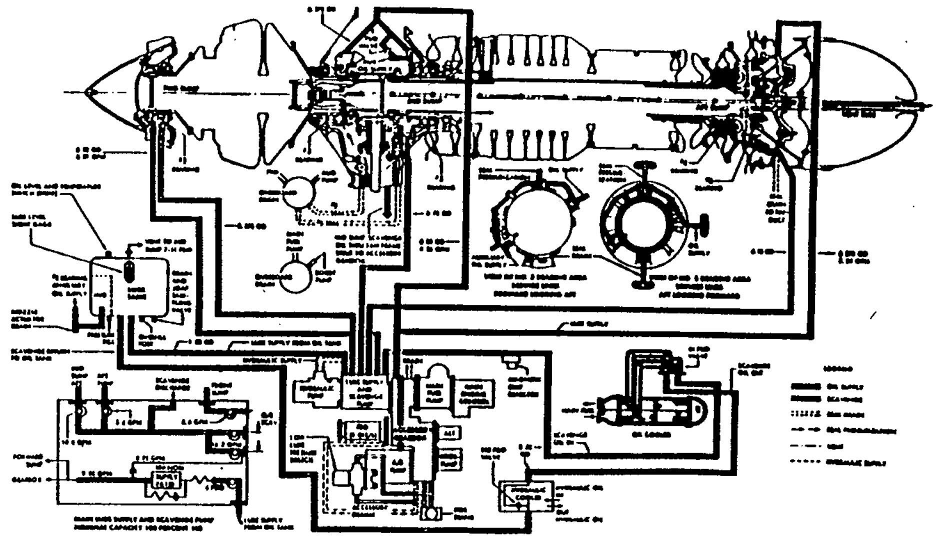
- Oil-less operation
- Higher speed limit
- Stall control
- Adaptive vibration control
- Blade vibration control (HCF)
- Health monitoring

Fig. 4

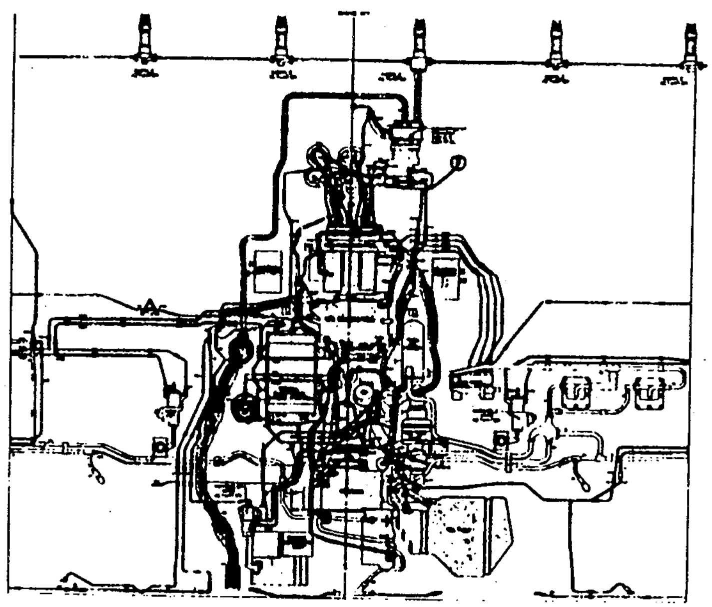
ENGINE EXTERNALS ARE GREATLY REDUCED

Fig. 5

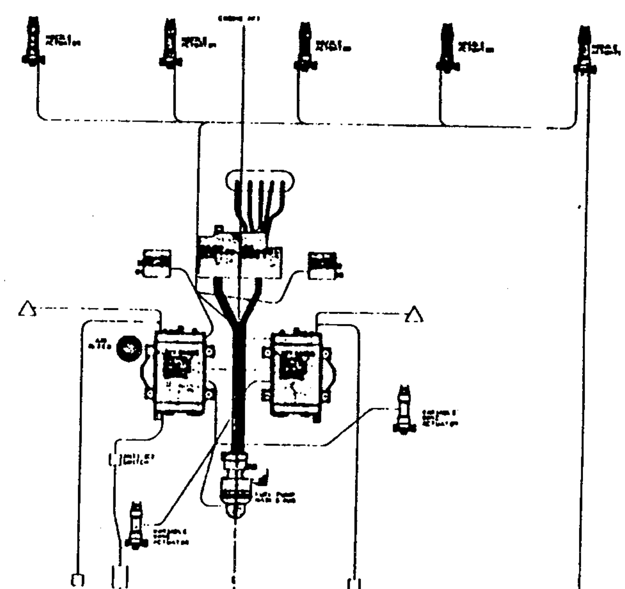




LUBE SYSTEM SCHEMATIC

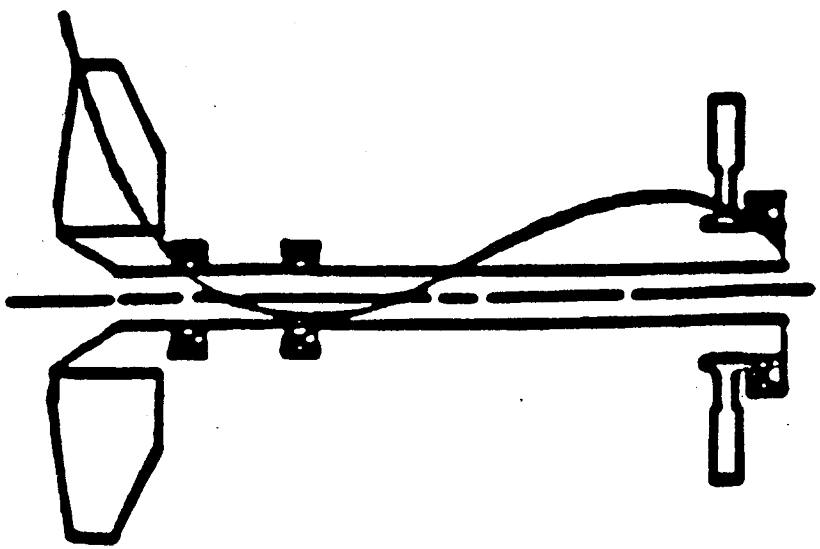


360^0 UNWRAP WITH LUBE SYSTEM

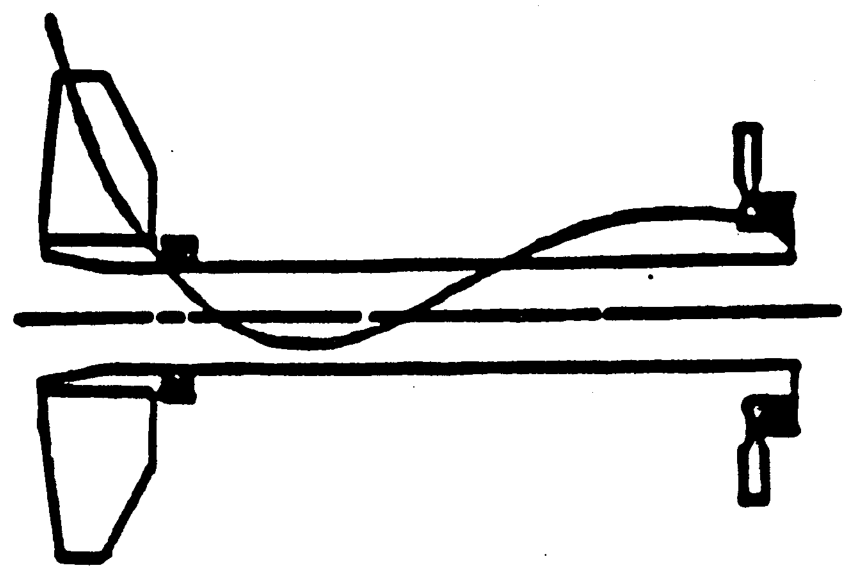


360^0 UNWRAP WITH MAGNETIC BEARINGS

MAGNETIC BEARINGS WILL PERMIT A TWO-BEARING MAIN SHAFT



THREE BEARING SUPPORT:
SUPER ALLOY MAIN SHAFT

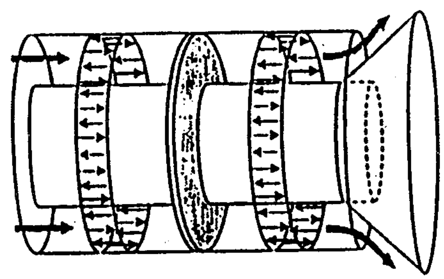


TWO BEARING SUPPORT:
STIFF, LARGER DIAM. MMC
MAIN SHAFT

Fig. 6

STALL SUPRESSION MAY GIVE BIG PERFORMANCE GAINS

Lowest Order



Higher Order

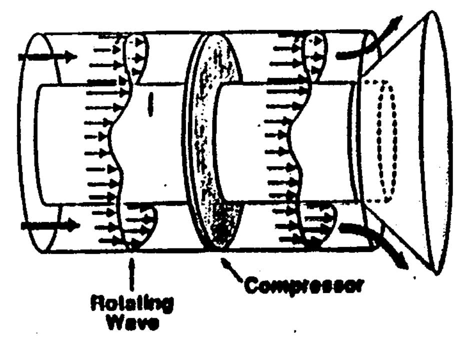


Fig. 7

Benefits of Using More Electric Engines

- Safer and More Reliable
  - No oil cooler, pumps, plumbing, oil seals, & oil leaks
  - Health monitoring and vibration control
- Higher Efficiency—7 to 15% in specific fuel consumption (P&W, Allison)
  - Less secondary air flow and higher temperature limits—1 to 2%
  - Blade tip clearance control—1 to 2%
  - Stall line management—5 to 11%
- Larger Design Envelope & Clean Engine Design
  - Higher rotational speeds & larger diameter stiff rotors

Fig. 8

Seals For More Electric Engines

- No Oil Seals

- Secondary Air Seals
  Higher speed rotors => Higher speed seals
  Less bleed air => Tighter seals
  Higher efficiency => Higher pressure

- Blade Tip Seals
  Blade tip clearance control => Conical casing
  Stall Line Management => Larger tip clearance

- Auxiliary Bearing Seals (1000^{o}F)
  (Depends on bearing type)

Fig. 9

WHO IS INTERESTED?

- Engine Manufactures: (GE, Pratt, Allison, and Allied Signal have in-house programs)

- Government:

  Navy- Magnetic bearing retrofitted on existing engine

  Air Force- IHPTET engine supported on magnetic bearings & integral starter generator (ISG)

  Army- Flight weight controller for magnetic bearings

Fig. 10

MORE ELECTRIC ENGINE

- **Military & Commercial Engines have Different Missions and therefore Different Design Goals: (such as trading engine life for performance)**

-Military IHPTET- Phase III

High Maneuver Loads (10 g's)
High Mach Number (up to Mach 3)
Reduce Fuel Consumption by 50%
Reduce Weight by 50%

- Commercial Aircraft

Higher Fan Moments
Larger Integral Starter/ Generator
Different Cooling Loads
Different Performance Costs of Bleed Air
Different Backup Bearing Requirements

Fig. 11

TECHNICAL CHALLENGES

- Rotordynamics of transition from magnetic to auxiliary bearings
- Can rotating stall be controlled by blade tip leakage?
- Which blade modes can be controlled by shaft motion?
- Flight condition adaptive controller
  - Robust nonlinear controller
  - Blade loss, bird ingestion, seal rub, etc.
  - Pilot commanded maneuver or speed change
  - Pulse Actuators to determine health of system
  - Operation with failures in coils
- Electro mechanical stability
  - Finite element modeling of laminations
  - Skin depth & eddy current predictions
  - VXB terms added to finite element analysis
- High temperature
  - Degraded magnetic & strength properties
  - Coil insulation, expansion, and heat transfer
  - Probe drift and calibration

Fig. 12

MAGNETIC BEARINGS PROGRAMS

High Temperature Magnetic Bearings

- Coils, (Square wire, Insulation, Oxidation)
- Probes, (Inductive, Eddy current, Optical, Capacitance)
- Non linear B vs H effects
- Test rig
  - Rotor dynamics mode
  - Load measurements

Flight Adaptive Controllers- (Expert system based)

- Modal control of rotor bearing system
- Adaptive to pilot stick commands
- Adaptive to blade loss, bird ingestion, etc.
- Health Monitoring

Fig. 13

High Temperature Magnetic Bearing Rig

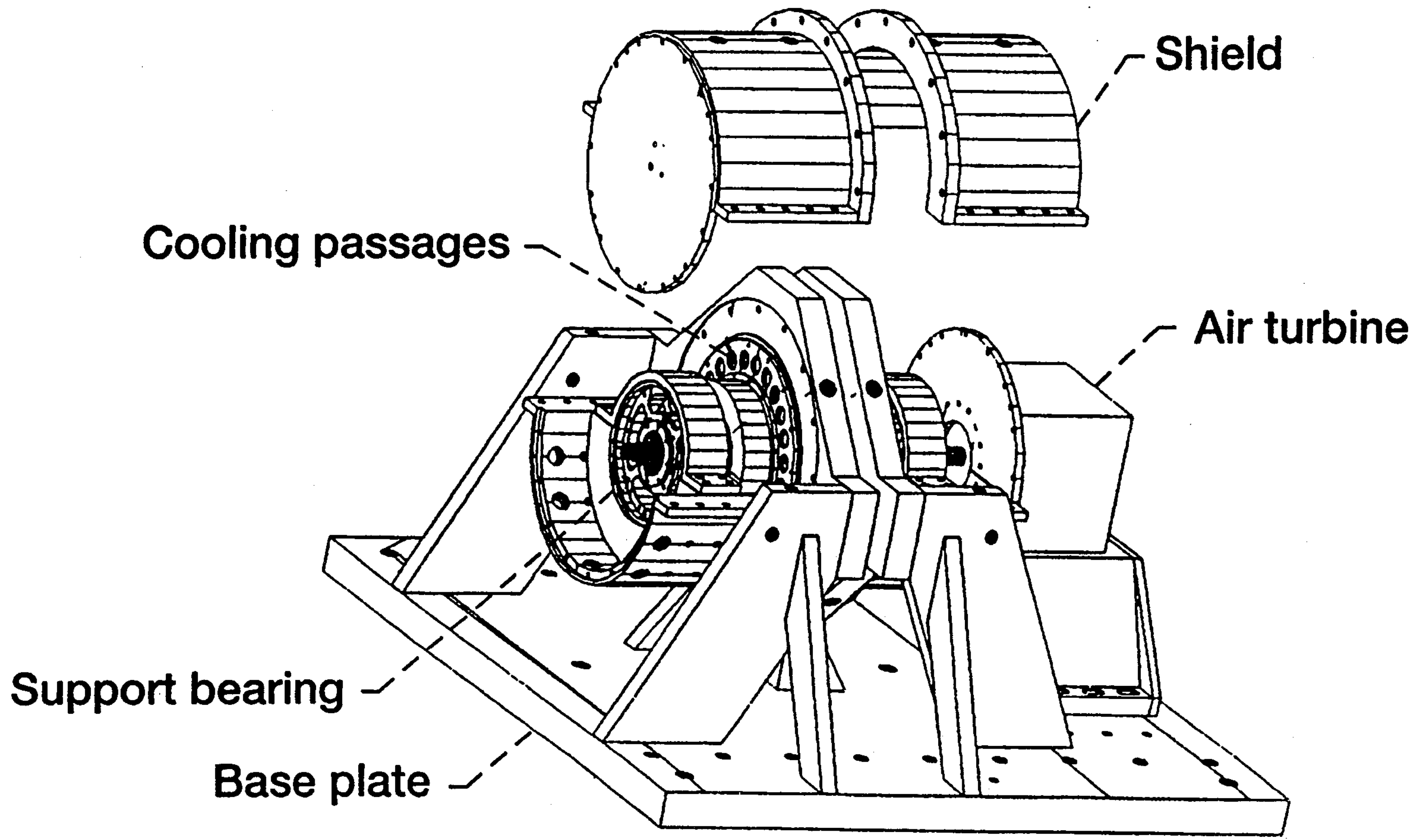


Fig. 14

OBJECTIVE

The objective is to determine the limits in temperature and speed of a magnetic bearing operating in an engine environment

- Design & Build Test Rig (1000°F & 20,000 RPM)
- Design & Build Test Bearing

- Test Various Wire Insulation
- Test Various Displacement probes
- Test Various Lamination Designs

- Measure Bearing Coefficients
- Measure Bearing Stability
- Measure Bearing Controllability

- Rotordynamic Test (Blade Loss, Seal Rub, FOD, & etc)

Fig. 15

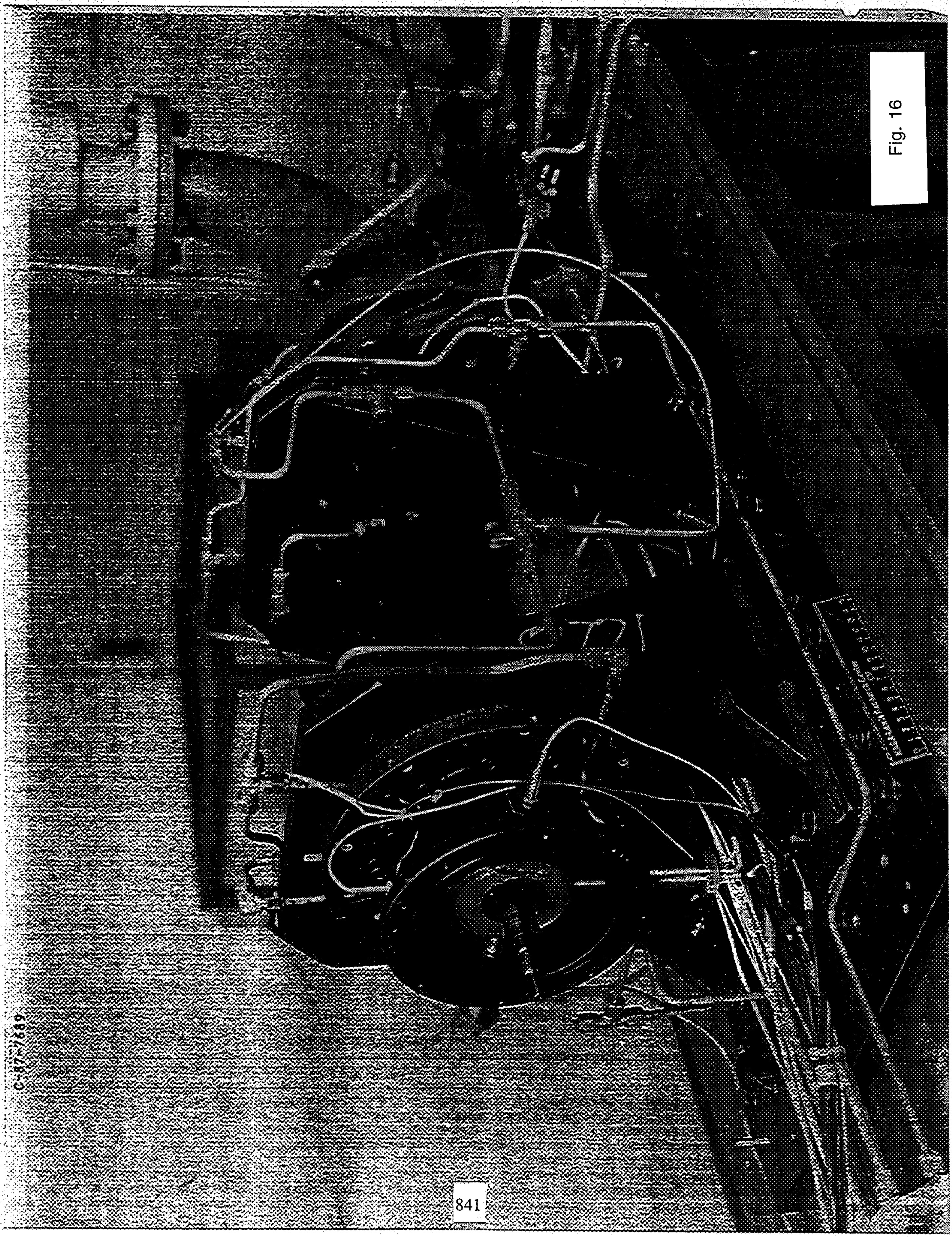
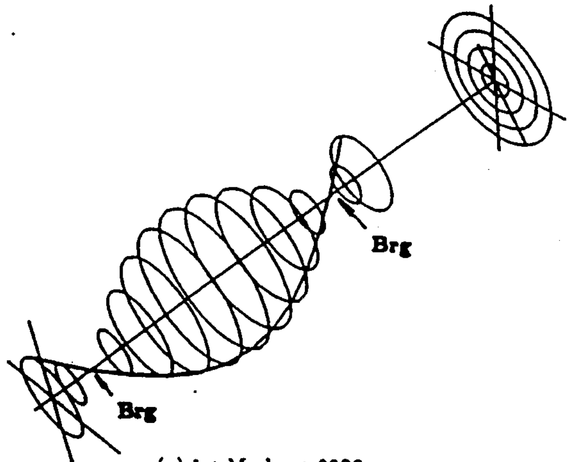
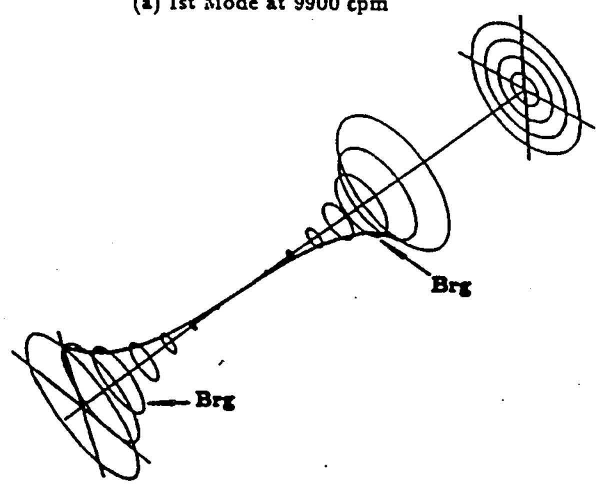


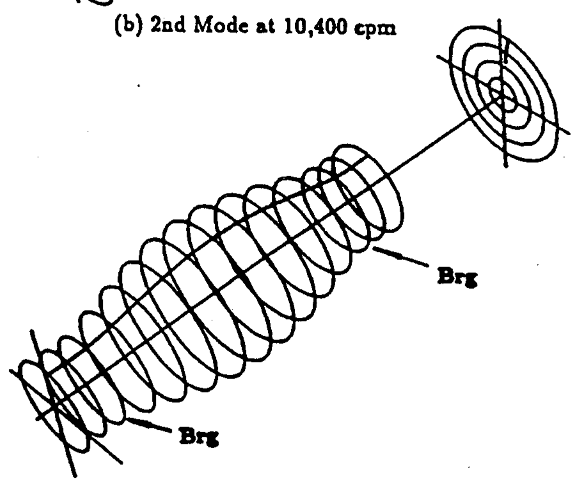
Fig. 16



(a) 1st Mode at 9900 cpm



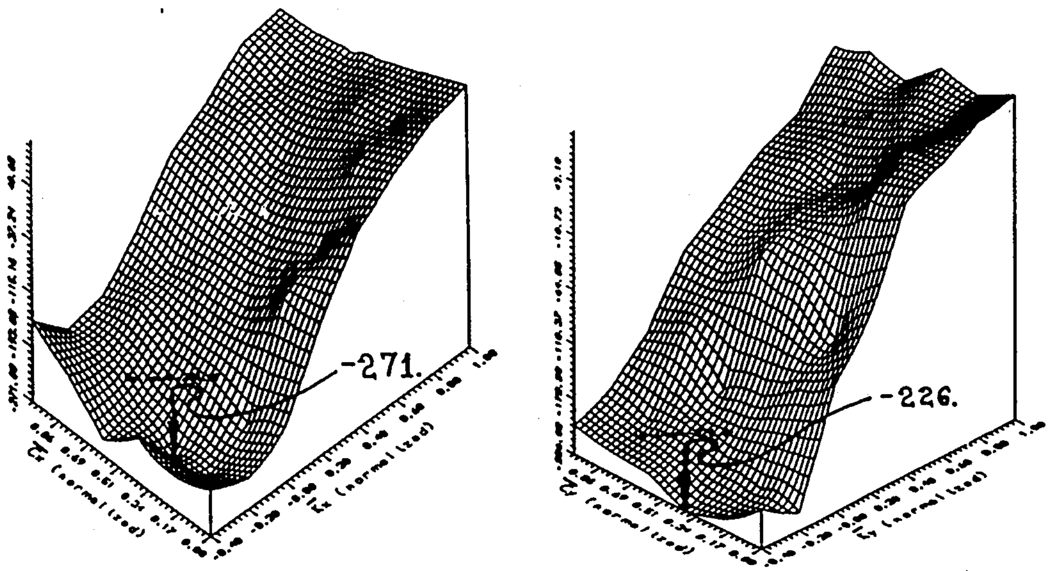
(b) 2nd Mode at 10,400 cpm



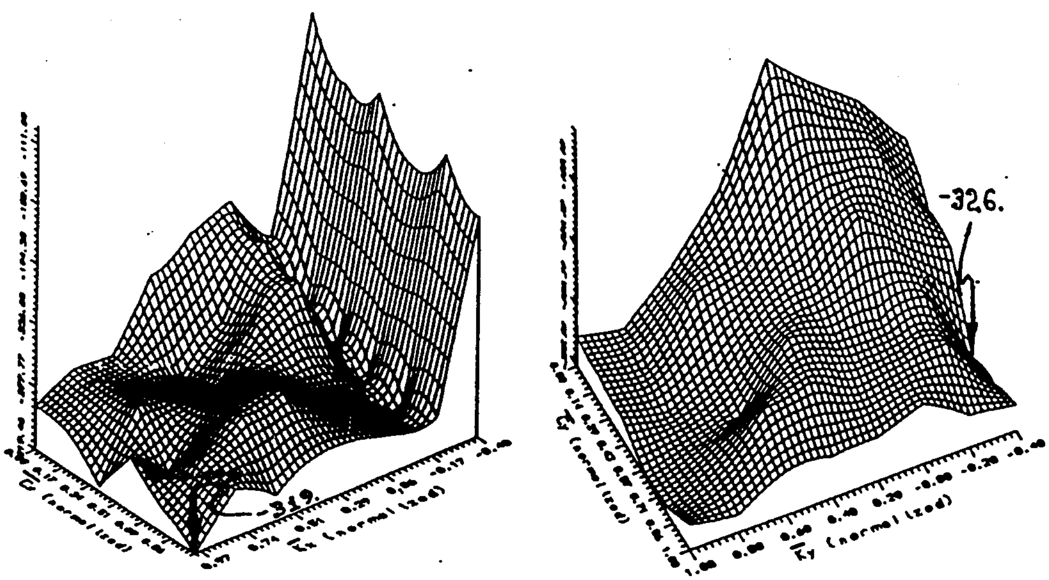
(c) 3rd Mode at 12.000 cpm

Simulated modes at 10,000 rpm

Fig. 17



(a) Norm surface vs. Cx and Kx at 9,600 rpm (b) Norm surface vs. Cy and Ky at 9,600 rpm



(c) Norm surfaces vs. $\overline{C}x$ and $\overline{K}x$ at 11,000 rpm (d) Norm surface vs. $\overline{C}y$ and $\overline{K}y$ at 11,000 rpm

Optimal norm surfaces for the x and y planes at 9,600 and 11,000 rpm

Fig. 18

Active Vibration Control

Controlled Blade Loss; 2.06 g-cm at 8000 rpm

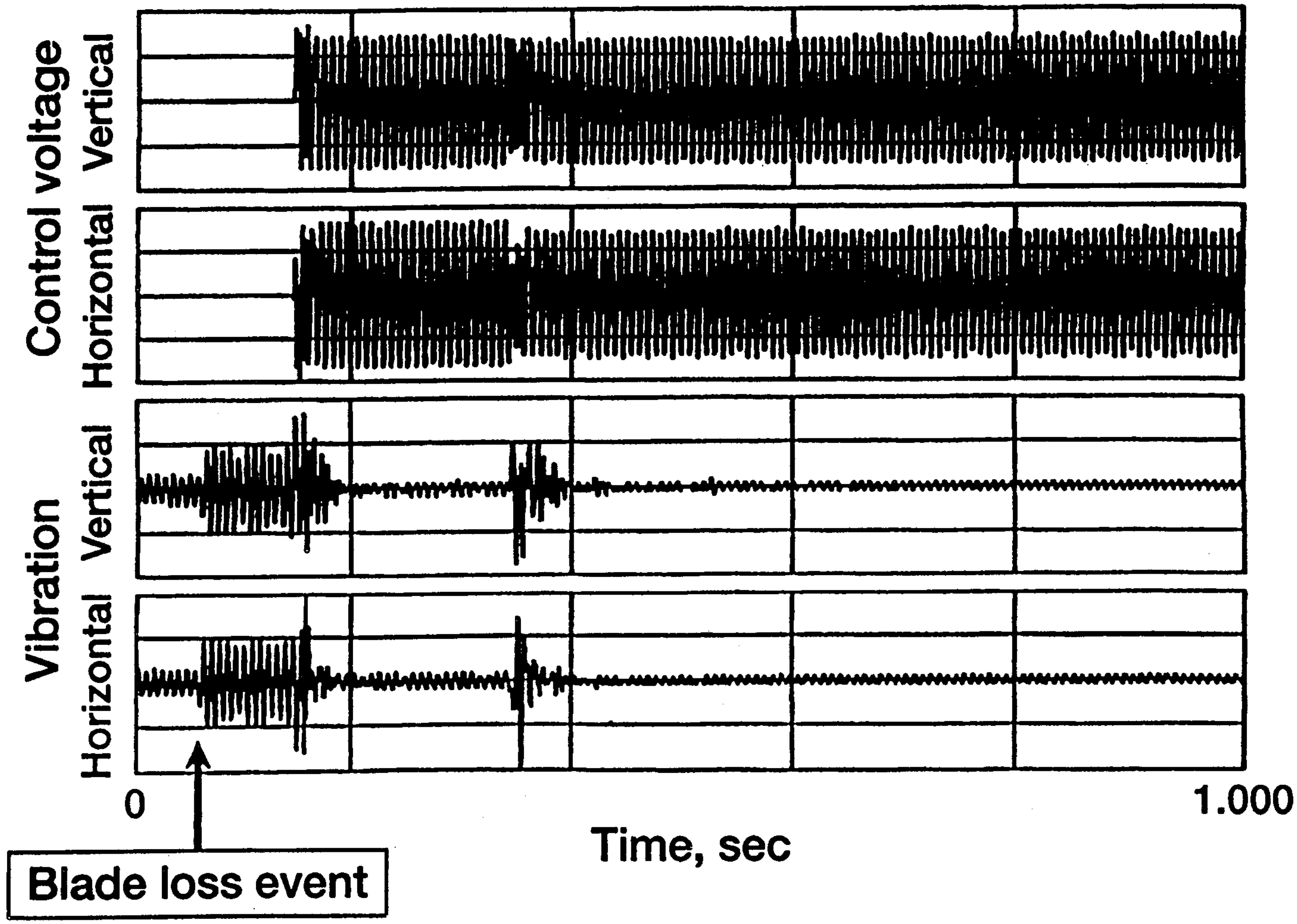
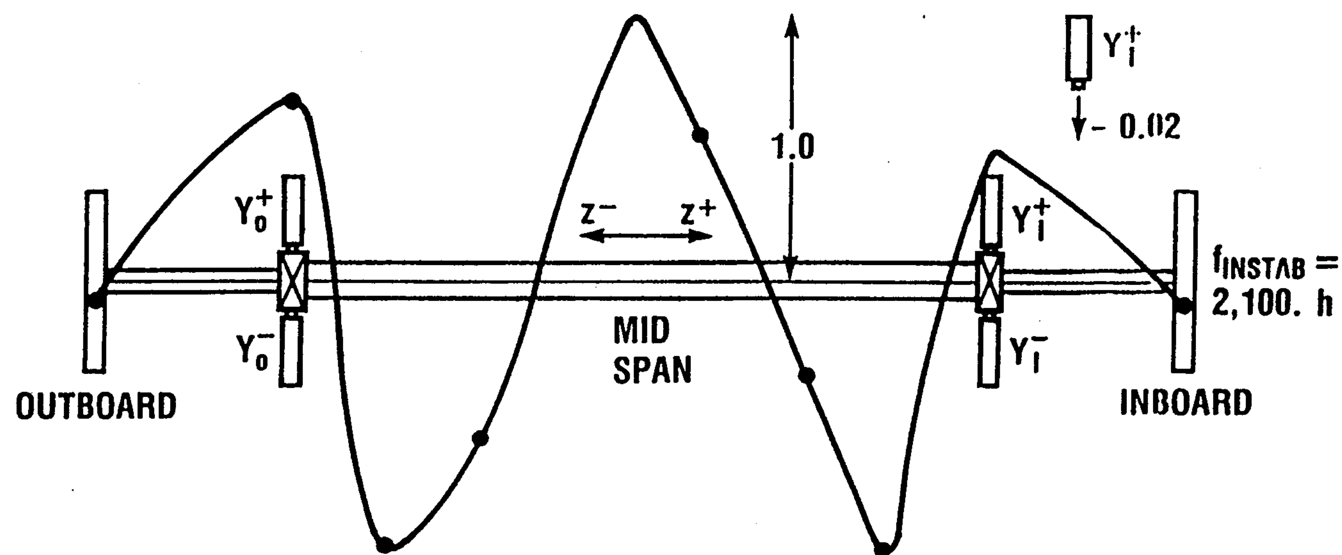


Fig. 19

UNSTABLE MODE SHAPE



CD-90-45088

UNSTABLE MODE SHAPE

Fig. 20

MAGNETIC BEARING TECHNOLOGY
Also Applies To

- Flywheels- Energy Storage for Space Applications
- Space Propulsion
- Auxiliary Power Units
- Army's More Electric Tank

Fig. 21