Thermal Simulation of Rotating Machine Equipped with Active Magnetic Bearings

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Abstract: Lately higher speed and higher power drive technology is more demanding in many industrial application such as several kinds of turbo machinery ex. compressor, expander and generator relating to various kind of gas processing. Active magnetic bearing should be a one of potential device to support such high power density rotor. On the other hands, high power density will induce several technical problems.

One of these technical problems is thermal problem. Hence the rotor supported by active magnetic bearing can only dissipate generated heat by means of convection and radiation (no conduction), elongation of the rotor may cause serious change in mechanical air gap, especially axial air gap between rotor and touch down bearings shall be carefully considered.

For handling this problem, thermal analysis of entire machine is needed.[1] The mathematical model of entire machine shall be consisting of rotor and all of non-rotating components such as active magnetic bearing's actuator, motor stator, housing and cooling jacket. Further more it is better to simulate transient thermal behavior of each machine components, author has developed Matlab/simlink based simulation tool for this purpose.

1. THERMAL SIMULATION

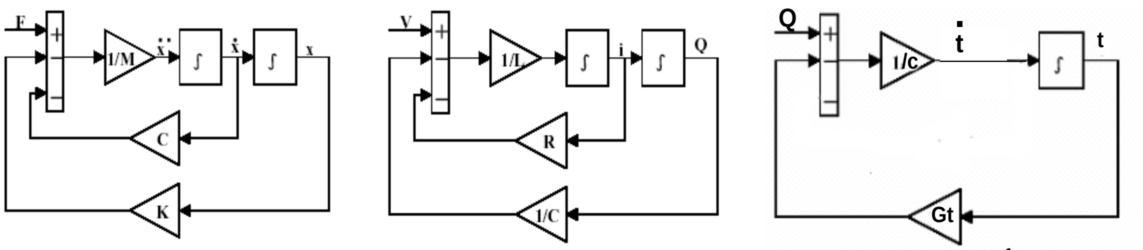
To design active magnetic bearings actuator, it is very much important to check the operation temperature of such actuator under given environment temperature, environment gas, and cooling condition. Normally such operational temperature is limited by insulation temperature of coil windings.

1. 1 THERMAL SIMULATION by simulink

Authors constructed block diagram of thermal system which can be expressed by fundamental components of thermal capacitance, thermal transfer block consisting of conductance, convection and radiation. With this system, the system has in-coming heat as system input and temperature as system output. It is interesting to compare above mentioned thermal system model to mechanical system as well as electrical system.

Fig.1 shows system parameter comparison between above mentioned thermal system, mechanical system and electrical system.

It is also remarkable that proposed thermal system does not have a component corresponding to spring in mechanical system or capacitance in electrical system.

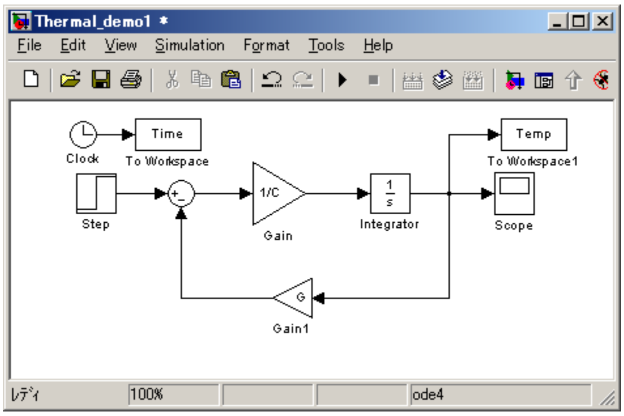


$$G=X/F=\frac{1}{Ms^2+Cs+k} \qquad G=q/V=\frac{1}{Ls^2+Rs+1/C} \qquad G=t/Q=\frac{1}{Cs+1/Rt}$$

Fig.1 system parameter comparison
mechanical system, electrical system. and thermal

1. 2 Basic behavior of simulink thermal system

Based on the proposed thermal system, temperature behavior of the given thermal capacitance and given thermal conductance with step response heat energy input was simulated. The simulink model of such fundamental system is shown in Fig.2 and temperature behavior is shown in Fig.3.



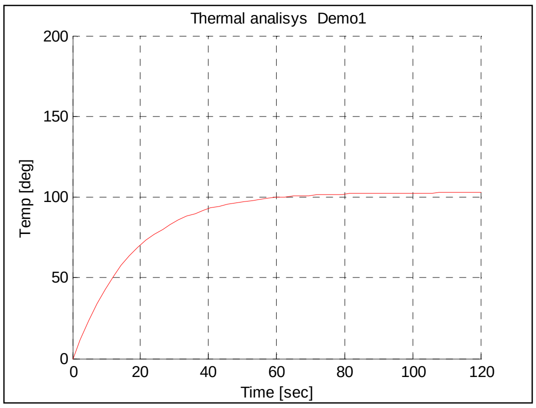
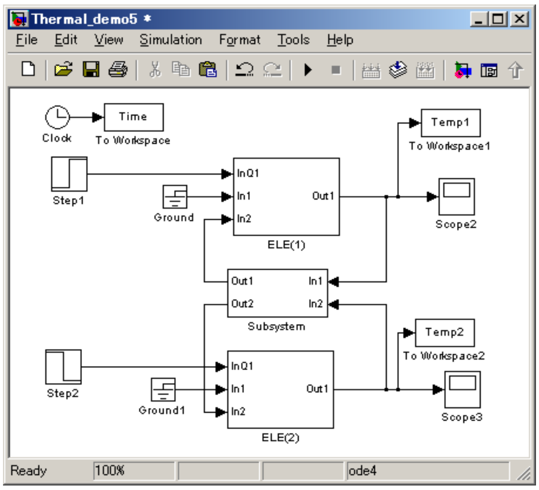


Fig.2 simulink thermal system model

Fig.3 Temperature behavior Fig.2

Hence this fundamental system has heat energy input and temperature as its out put, system can be connected to describe a larger and complicated system.

Fig.4 shows simulink model of 2 blocks and Fig.5 shows its temperature behavior in case of heat energy input in one block.



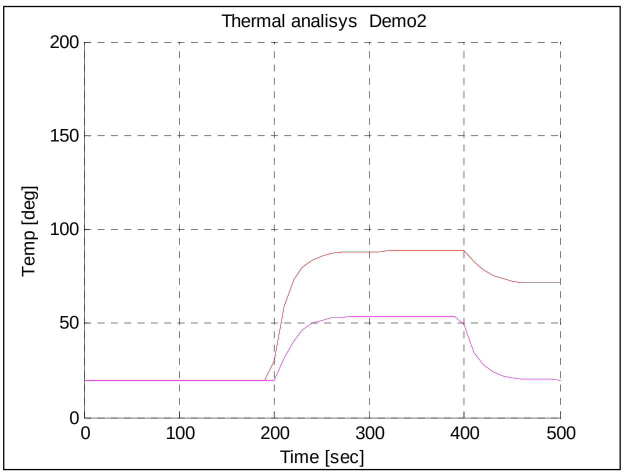


Fig.4 simulink 2 thermal block model

Fig.5 Temperature behavior of Fig.4

In this system description, cooling can be taken into account by setting negative heat energy input to the system block. It is also possible to set radiation as well as convection into this system model.

To verify proposed simulink thermal model, very simple naked coil was simulated. The measured temperature behavior of bear coil with coil current of 1[A] and corresponding simulation result are shown in Fig.6 and Fig.7

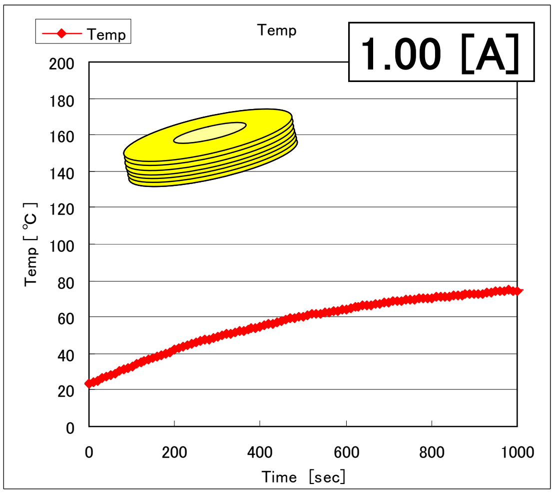


Fig.6 Measured coil temperature

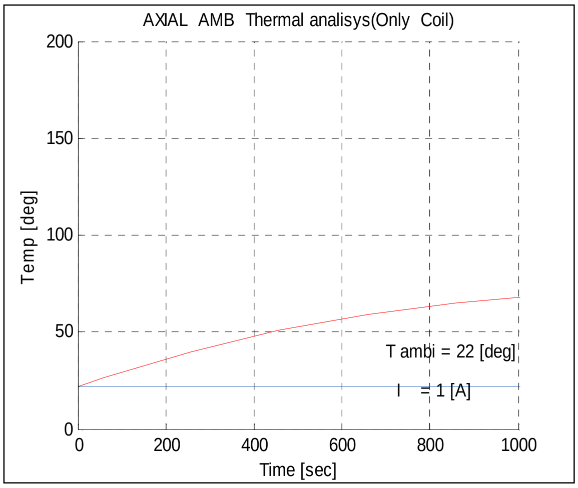


Fig.7 Simulated coil temperature

Judging from the comparison of measured and simulated data, since temperature rise behavior depending on time is quite accurate, thermal capacitance; convection and radiation for the coil are well estimated in this simulink model.

1. 2 THERMAL SIMULATION of AMB actuator

In case of simulation of electro-magnets temperature behavior, it is at least needed to establish coil and stator core mathematical thermal model.

1. 2. 1 THERMAL SIMULATION of axial AMB

Thermal model of Axial AMB actuator can be obtained by adding iron core block onto above mentioned coil model, even it is possible to enhance the model by adding casing structure around axial AMB or adding epoxy molded effect in the model.

Fig.8 and 9 shows basic thermal model structure of axial AMB and Fig.10 shows measuring set up.

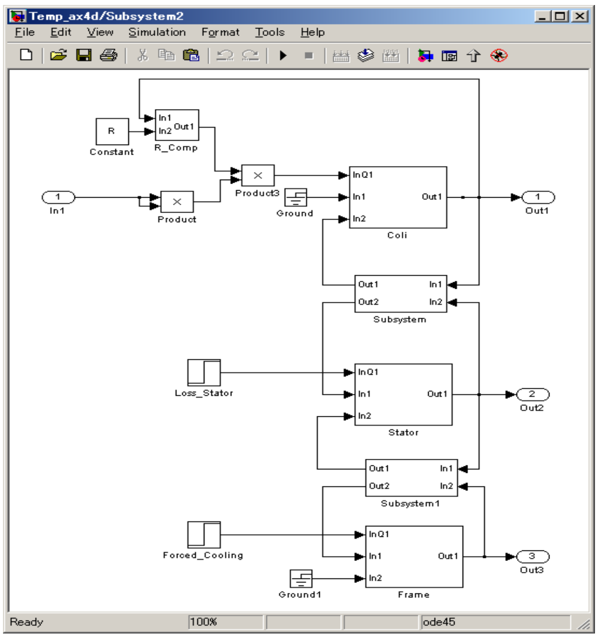


Fig.8 simulink model of AxAMB

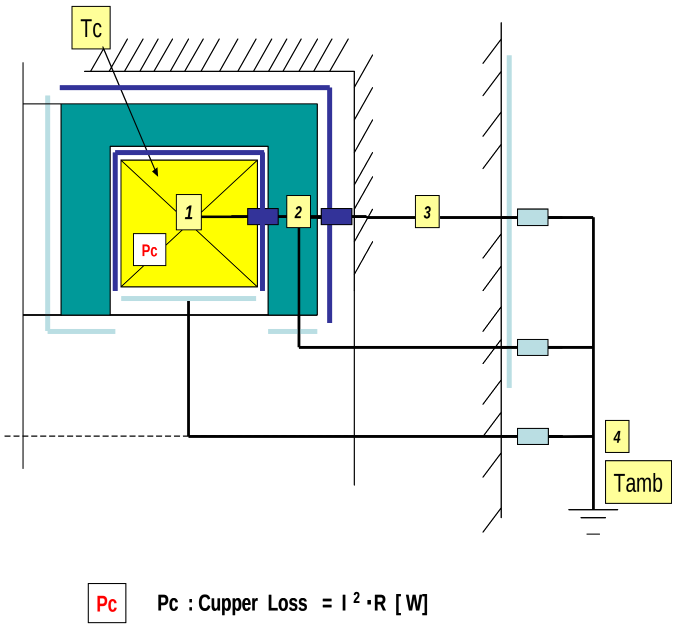


Fig9 Thermal model of Axial AMB

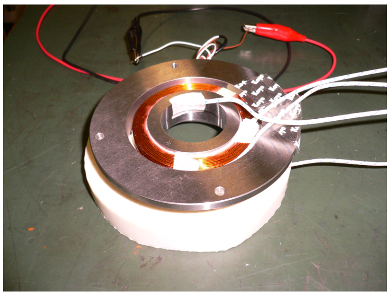


Fig.10 Temperature mesument of AxAMB

Fig 11 shows measured data of AxAMB without epoxy molding of the coil and Fig.12 shows simulated data.

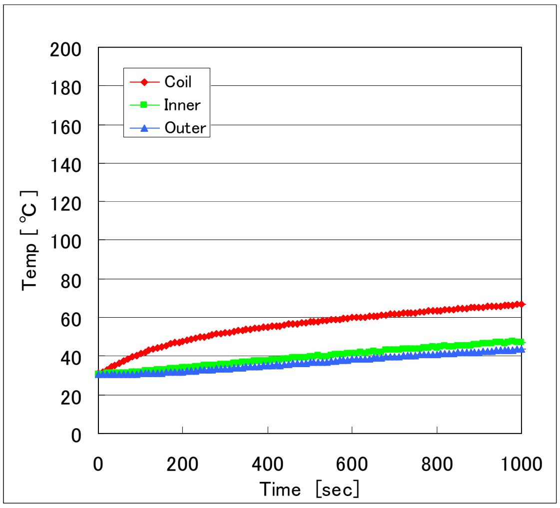


Fig 11 measured data of AxAMB without epoxy molding of the coil

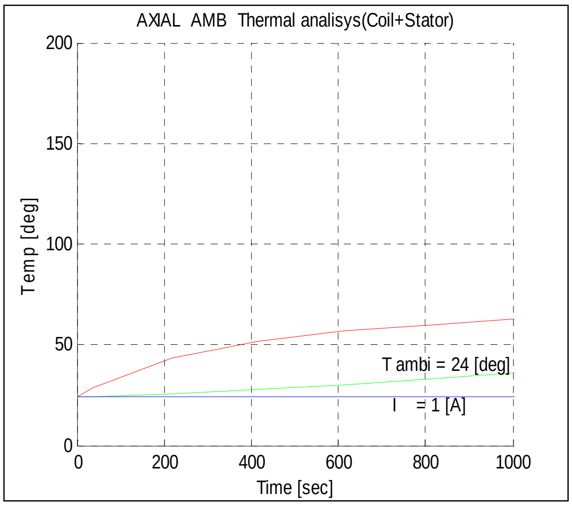


Fig 12 simulated data of AxAMB without epoxy molding of the coil

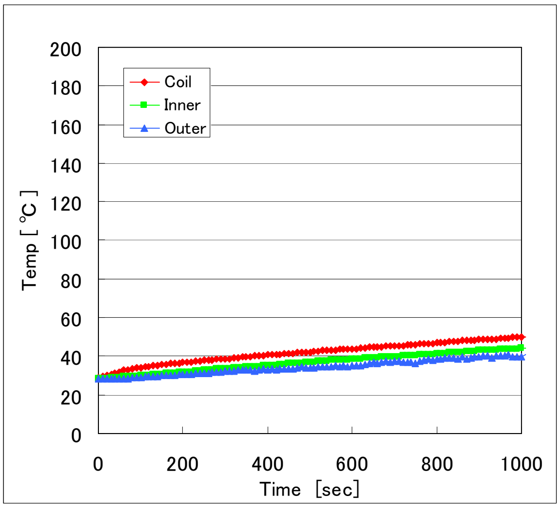


Fig 13 measured data of AxAMB with epoxy molding of the coil

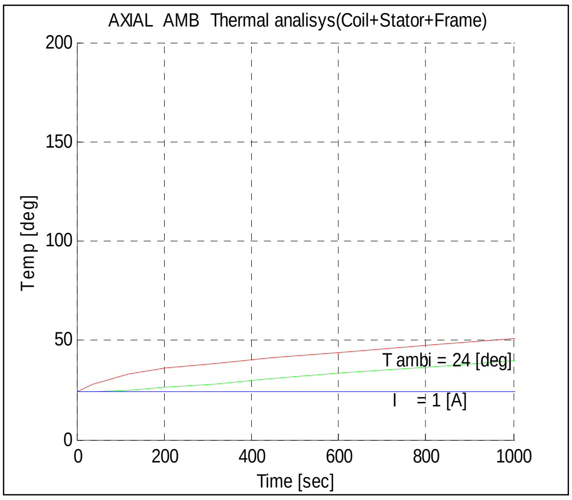


Fig 14 simulated data of AxAMB with epoxy molding of the coil

The temperature behavior of the coil inside of iron core is slightly slowly increased if compare to the naked coil.This difference is given by higher heat conductance area in bottom side of coil, outer side of coil and inner side of coil. due to contact between coil and iron core (on the other hand, radiation of corresponding area is reduced) Fig 13 shows measured data of AxAMB with epoxy molding of the coil and Fig.14 shows simulated data.

In case of coil is molded by epoxy, thermal capacitance of coil is increased and therefore temperature of the coil is more slowly increased. The thermal transfer capability is also increased due to more dense condition temperature difference between coil and core is also decreased.In other words, epoxy molding helps to avoid thermal shock of the coil very much.

1. 2. 2 THERMAL SIMULATION of radial AMB

Thermal model of radial AMB actuator can be also established in same manner by using thermal network in Fig.15

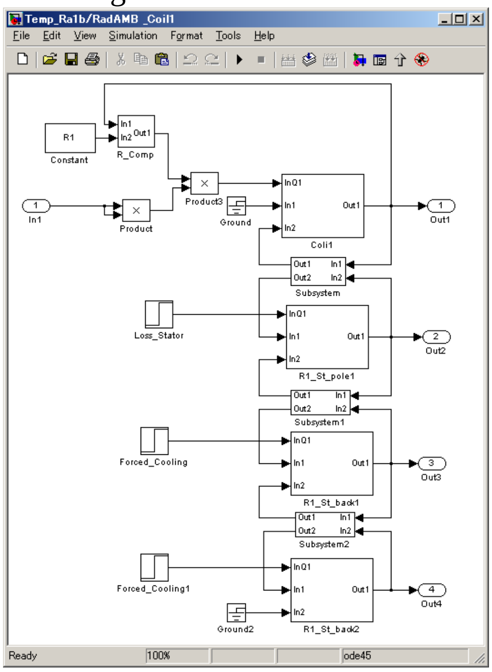


Fig15 Thermal model of Axial AMB

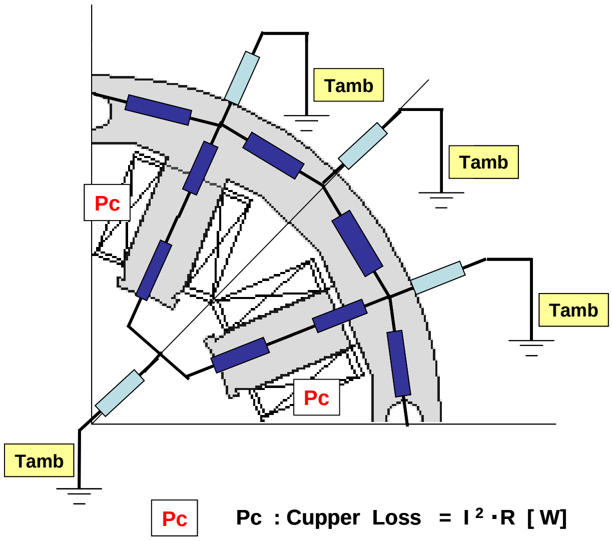
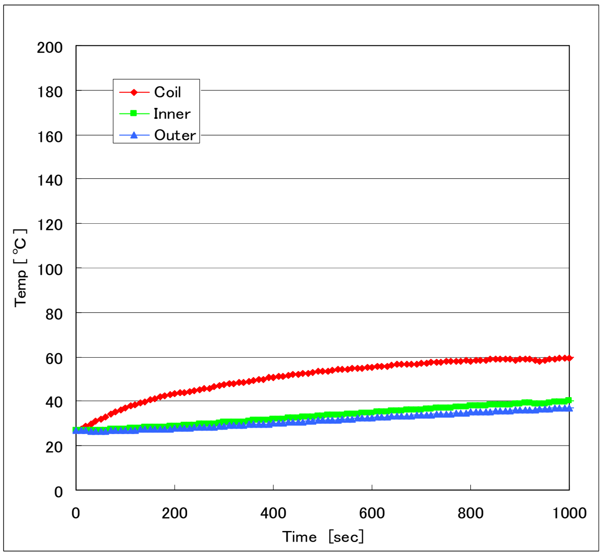


Fig16 Thermal model of Axial AMB

Fig 16 shows measured data of RadAMB without epoxy molding of the coil and Fig.18 shows simulated data

Fig 19 shows measured data of RadAMB without epoxy molding of the coil and Fig.20 shows simulated data. It is remarkable that in case of radial AMB with epoxy. Hence more epoxy volume is available compared to axial AMB, increasing of thermal capacitance is bigger, temperature of the coil is showing smaller temperature difference to the iron part. Authors also separately developed similar simulink model for motor stator.



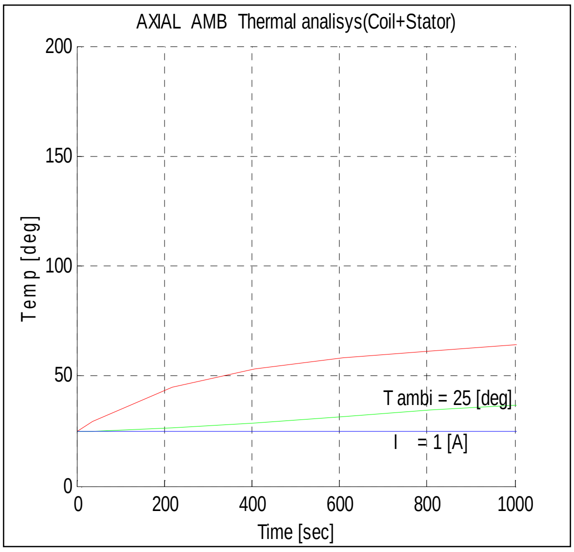
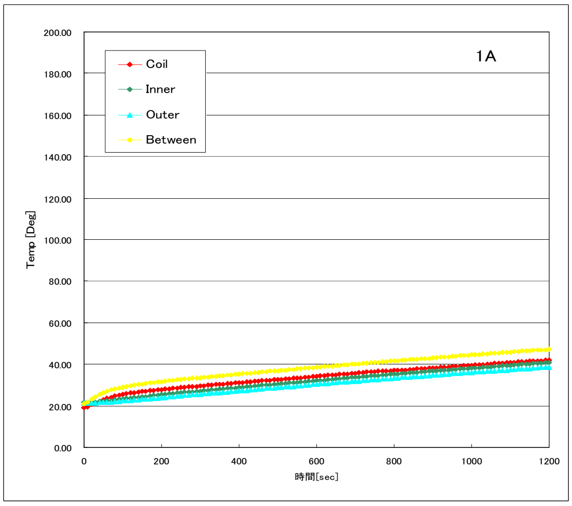


Fig 17 measured data of RadAMB without epoxy molding of the coil

Fig 18 simulated data of RadAMB withoutepoxy molding of the coil



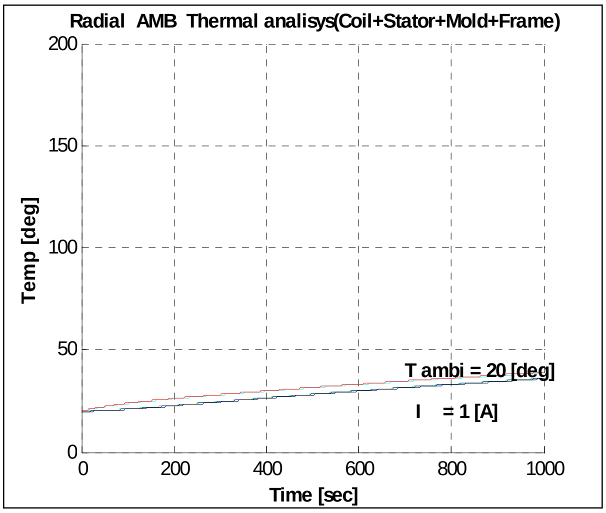


Fig 19 measured data of RadAMB epoxy molding of the coil

Fig 20 simulated data of RadAMB withoutepoxy molding of the coil

2.1 THERMAL SIMULATION of rotating shaft

Proposed simulink model of thermal block can be also applied to temperature analysis of a AMB rotor shaft. To build up thermal model of the rotor shaft, rotation speed dependant windage losses as well as eddy current losses of radial active magnetic bearing and losses at motor rotor shall be introduced in rotor mathematical model. The model of such rotor shaft is obtained by describing the rotor shaft as chain wise connected multiple beam models, which is quite similar like FEM based rotor model for rotor dynamics analysis. For the windage losses, it is, of course, needed to set calculated windage loss as heat input to each section of rotor shaft.[3]

For the eddy current losses, calculated eddy current loss shall be set as heat energy input at corresponding radial magnetic bearing rotor.[4] to [11]

Regarding heat dissipation of the levitated rotating shaft, thermal conductivity of radiation and

thermal conductivity of convection shall be considered. Thermal conductivity of radiation can be considered as independent to rotation speed shown in Fig 20, but on the other hand , convection is surely increasing depend on rotational speed.
The heat energy convective transfer from surface of the shaft to environment air is given by following equation.

$$J = \alpha \, (Ts - Ta) \qquad \text{---- eq 1}$$

h ere J : Heat energy transfer
α: Thermal conductivity of convection
Ts : Temperature of the shaft
Ta : Temperature of environment gas

Then in case of rotating shaft, thermal conductivity of convection can be also given by following equation.

$$\alpha = 3.26 \times (Ts - Ta)^{0.25} \times \{(V_w + 0.348)/0.348\}^{0.5} \qquad \text{----- eq 2}$$

Here V_w : relative surface speed. [m/sec]

Hence shaft is rotating; shaft surface speed can be taken as relative surface speed.Vw. Then thermal conductivity of convection α is getting larger and contribute more effective heat dissipation compared to stand-still shaft.

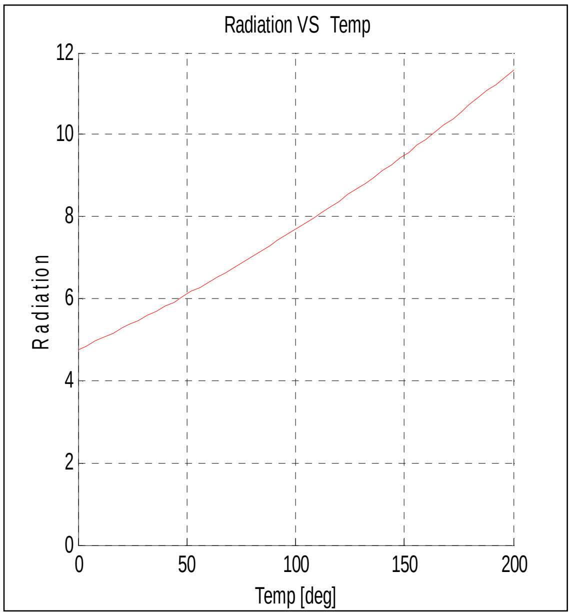


Fig 21 Thermal conductivity of radiation

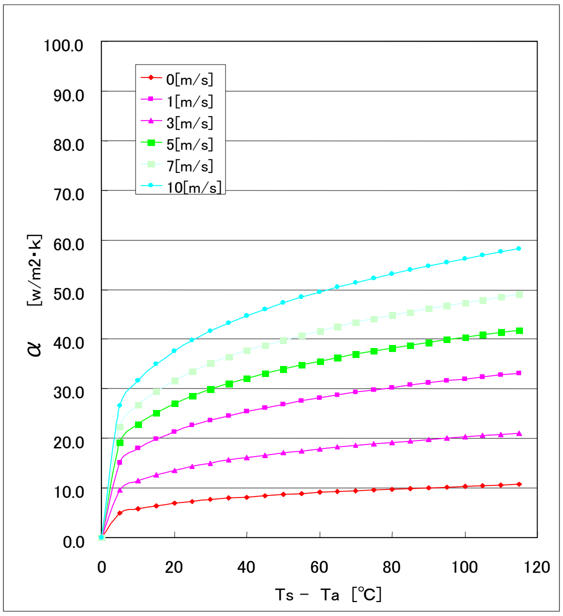


Fig 22 Thermal conductivity of convection depending on shaft surface speed

Fig.22 shows thermal conductivity of convection depending on shaft surface speed

2.2 THERMAL SIMULATION of entire machine

The final goal of this thermal analysis tool is to simulate entire rotating machine supported by active magnetic bearings. Fig23 shows thermal net work of entire rotating machine

As discussed former section, simulink based thermal model of axial AMB, radial AMB, motor stator, rotating shaft has already realized. It is very much straight forward idea to include casing component into these models and combined to establish entire AMB rotating machine. As also discussed, cooling effect such like cooling jacket can be included with negative heat input to the system.

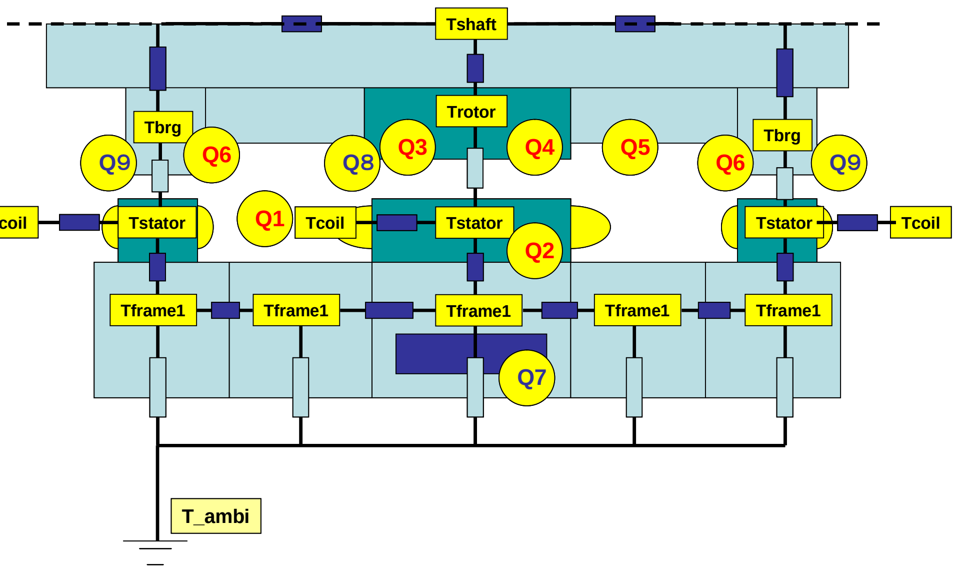


Fig.23 thermal net work of entire rotating machine

By eliminating windage losses and thermal convection on the shaft as well as inner surface of stator element and housing, it is possible to simulate for vacuum condition.

At this moment effect of axial gas flow or effect of forced cooling gas input are not modeled yet. For talking these effects, additional thermal transfer block shall be needed.

Fig.25 to Fig 27 are some example of temperature rise of time history. In these figure several point of the magnetic bearing supported rotor along axial direction are indicated.

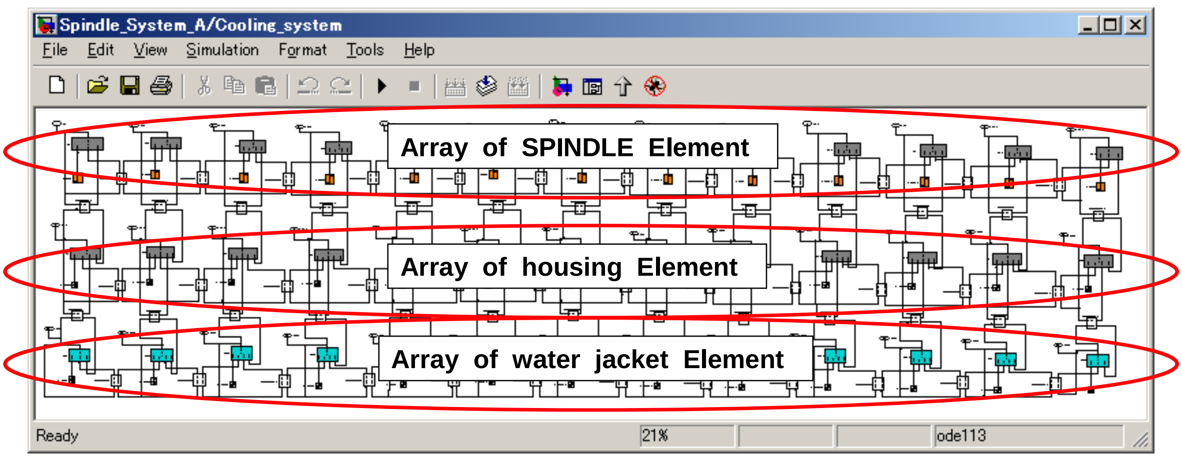


Fig.24 Simulink block diagram of entire rotating machine

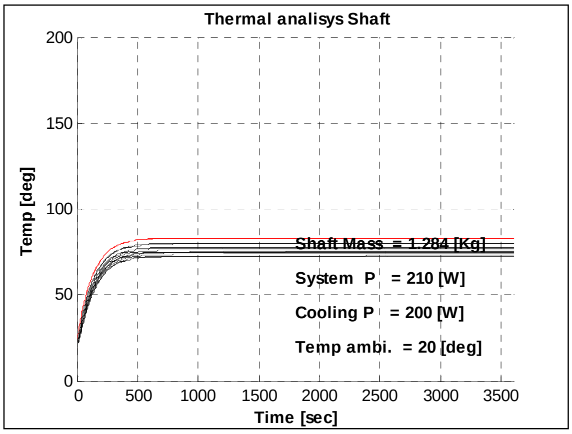


Fig 25 simulated data of 100,000 rpm spindle

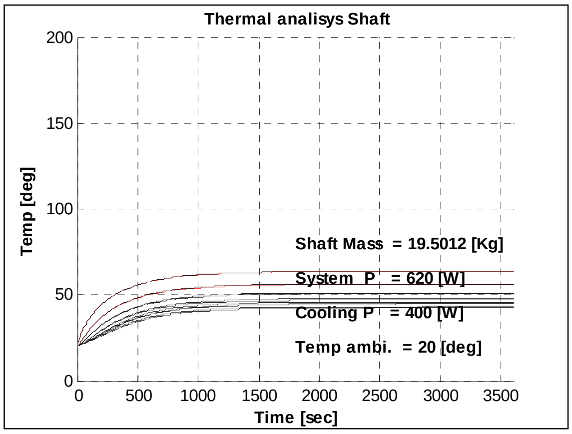


Fig 26 simulated data of 40,000 rpm spindle

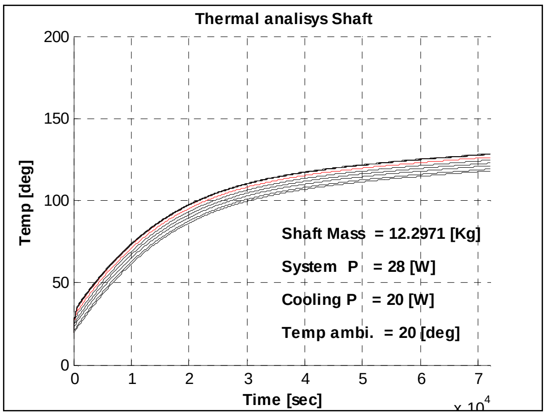


Fig 27 simulated data of 35,000rpm TMP spindle

3 Summaries

1. Simulink based thermal analysis model was developed. This model can be applied for temperature transient analysis of Axial magnetic bearing stator and radial magnetic bearing stator.
2. Same principle can be also used for temperature analysis of rotating shaft by introducing rotation speed dependant windage loss as well as eddy current loss in rotor.
3. By adding combining of above model, it is possible to enhance the thermal model for entire rotating machine.
4. Taking physical property of environmental gas, the model can be used for different gas operation.
5. The proposed model can be also be also apply vacuum operation machine by eliminating convection between rotor shaft and stator.
6. Cooling jacket effect can be also included by negative hast energy input to corresponding housing block.
7. At this moment effect of axial gas flow or effect of forced cooling gas input are not modeled yet. For talking these effects, additional thermal transfer block shall be needed.
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