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ECO-Shaker

Energy Saving Vibration Test Systems

Eco friendly vibration test systems reduce the impact on the environment.

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Energy Saving Vibration Test Systems

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1 ▸ Aim

■ Energy problems

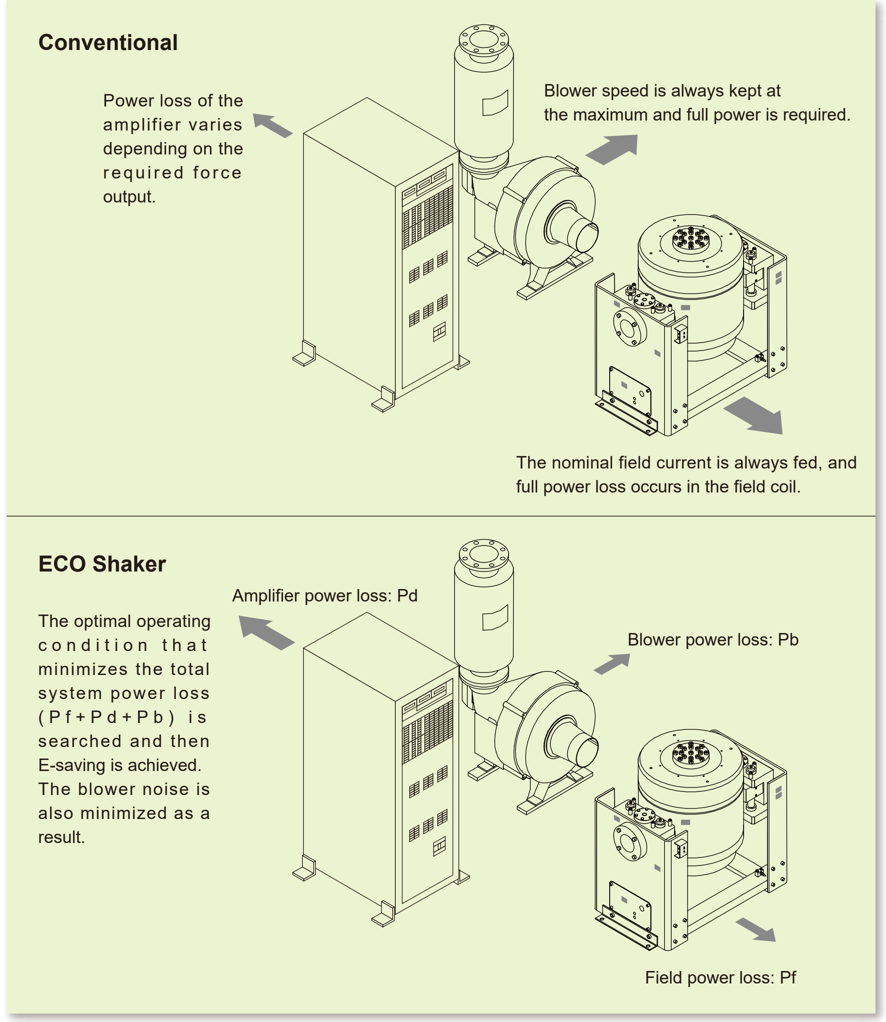
Among all the challenges of the environmental problems currently in front of us, the development of energy saving technologies for Electrodynamic (ED) shaker systems has become an expected demand from a majority of ED system users who are concerned about their carbon footprint.

Moreover, the energy saving efficiency of ED shaker systems can be greatly improved when the actual required output force is relatively small compared to the nominal force rating of the system. For example, the IMV EM2601 shaker system, which has a nominal excitation force of 54kN, consumes 130,000kWh per year when it is used at an output force rating of 50% of the nominal rating for 3,000 hours per year. If this power consumption could be reduced to 1/2, then there would be a significant contribution to energy-saving. The IMV ECO Shaker achieves this.

■ Power loss of Vibration Test Systems and the potential savings

Let us examine the potential for energy-saving operation of an air-cooled ED shaker system which is commonly used for vibration testing.

It is necessary for the ED shaker system that the field coil and the drive coil are continuously cooled during normal operation. In the conventional air-cooled ED shaker system, the blower is always driven at the nominal speed and the field current level is set to the nominal value to ensure that the system is always ready to provide the maximum possible excitation force if this is required by the test specification.



However, when an excitation force lower than the system nominal level is required, this is a significant waste of energy. For example, the blower speed could be reduced to save energy, but how could this be achieved? As the possible reduction in blower speed depends on the level of the required excitation force. To safely apply this simple principle for E-saving operation to the actual shaker system at any possible operating condition is not a simple task. Any error in the control of the blower speed could result in the shaker coils being burnt through overheating and damaged beyond repair.

Further, in the case that only a small excitation force is required, the field coil current could also be set lower since the ED shaker only needs a small magnetic field to meet the requirements of the vibration test. Once the field coil current is reduced, the heat generated by the field coils will be lower and consequently the blower speed can be further reduced. On the other hand, as the magnetic field becomes weaker, the armature drive current supplied by the amplifier will increase (this is a consequence of ‘Flemings Left hand Rule’ whereby the shaker force is proportional to the product of the armature current and the field current). This drive current control is automatically achieved by the vibration controller which ensures that the response acceleration from the armature is equal to the specified reference value.

How are the optimum settings determined for the blower speed and field current for each particular moment of each different test? The ECO-shaker system solves this problem through the Energy Manager (EM) software program. The EM software observes the drive current (armature current) and uses this observation as a constraint within the optimization routines. The EM software determines the optimum operating values for the blower speed and field current by calculating the minimum energy required by the ED shaker system to achieve the current test operating conditions. This real-time calculation process is carried out by the EM software as part of the automatic E-saving operation mode of the ECO-shaker system.

■ Low acoustic noise

In addition, since the E-saving mode operation minimizes the blower speed, the blower noise is substantially reduced when only a small excitation force is required. In this sense, E-saving operation achieves low acoustic noise operation at the same time.

■ Limitations of the manual setting approach

Manually setting the blower speed and field current at a level lower than the nominal level to achieve energy saving is possible. In traditional systems, this is typically performed by setting a switch or wired link. This method also requires some prior knowledge of the force level required to perform a particular test and then detailed manual calculations to check that the level set for the blower and field is acceptable. In practice, this manual method has never been widely adopted for the following reasons:

Limitations of the manual setting approach

- Accurate prediction of the required excitation force is difficult. For example, in Swept-sine testing, the acceleration response characteristics can show considerable differences across the frequency range of the test. If a larger excitation force is required compared to that predicted prior to the start of testing, for example near to a notch point, then the system would stop on a safety interlock (possibly armature over-current) and the test would be aborted at that point.
- To avoid the risk of aborting the test, the levels of blower and field must be set very conservatively with the consequent loss of energy saving. If the operating conditions change during the test, for example due to product fatigue, then even the conservative setting of blower and field may still not prevent the test from being aborted.

2 ▶Principle of operation

■ Optimization problem

As stated above, the ECO Shaker system solves an optimization problem to maintain the required excitation force while mininizing the required system power consumption. This optimization is based on monitoring the armature drive current information during the vibration test and determines the optimal operating condition for the Field current I_f, Drive current I_d, and Blower speed V. That is, denoting the power loss at the field coil as P_f, at the drive coil as P_d and that at the blower as P_b, then the total power loss P is described as:

$$P = P_f + P_d + P_b \tag{1}$$

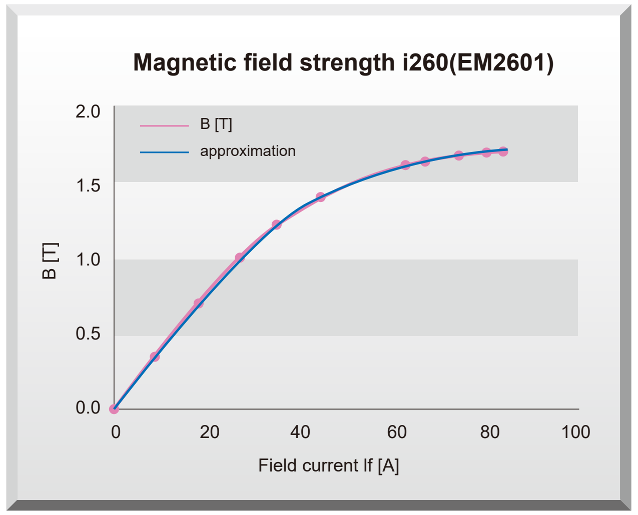
And the problem to be solved is:

> To determine the optimal operating condition (I_{f_opt}, I_{d_opt}, $V_{\_opt}$) which minimizes the total power loss P among all of the possible operating conditions that maintain the required excitation force F_1.

■ Observation of the required force

The required excitation force F_1 is observed by measuring the drive current I_d : Since the field current value I_f supplied to the field coil is known, the magnetic field B [T] at the gap of the magnetic circuit can be calculated by using an approximation function of I_f which was determined prior to the operation:

$$B = B(I_f) \tag{2}$$



Then, the force F_1[N] generated at the drive coil is calculated when the drive current I_d[A] is observed, by the formula

$$F_1 = B*L*I_d \qquad (3)$$

Where L[m] denotes the drive coil length.

The required excitation force does not remain constant through a test. A typical example is seen in Swept-sine testing in which the response characteristics vary with frequency. Therefore, even when a constant acceleration level is required over a frequency band, the consequent required excitation force varies with frequency.

Even in a fixed frequency test, the excitation level is often varied based on a time schedule of level changes.

In random vibration testing, it is general practice that the excitation level is varied according to a defined schedule while maintaining the reference spectrum to keep the same shape. On the other hand, the response characteristics of the system also vary according to changes in temperature and other conditions of shaker and of the specimen. As such, the required excitation force changes in general terms, according to a number of the parameters discussed above. Therefore the current (instantaneous) value of force is estimated according to equation (3) and using the measured value of the drive current, I_d. This measurement of I_d could be made as an average value or maximum value over a defined time interval according to the specification of the test.

■ Selecting the operating condition that provides the required ouput force with minimum energy consumption

Once the required value of the force F_1 is determined, the optimal combination of the currents (I_f, I_d) that minimizes the power consumption can be determined: For this purpose, the formula (3) is rewritten as below:

$$I_d = \frac{F_1}{B(I_f)*L} \qquad (4)$$

This formula describes the necessary drive current I_d to yield the required force F_1 when the field current is set at some arbitrary value I_f, with the knowledge of the magnetic field from the formula (2) :

When the combination of the currents (I_f, I_d) is determined, the power losses at each coil can be described as follows:

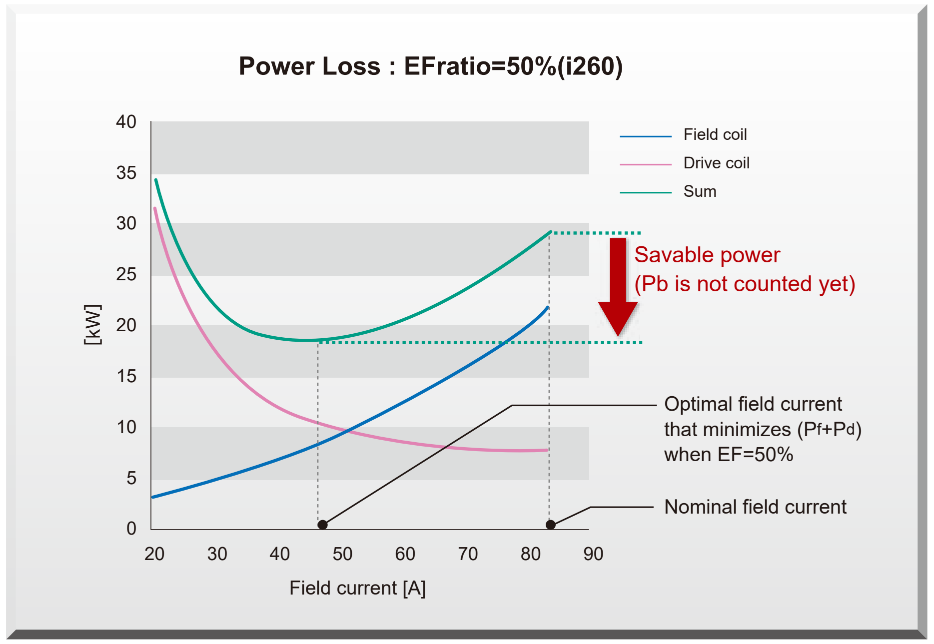
$$P_f = R_{f0}*I_f^2 \qquad (5\text{-}f)$$

$$P_d = R_{d0}*I_d^2 \qquad (5\text{-}d)$$

where R_{f0}, and R_{d0} denote each coil resistance.

The figure illustrates an example calculation result of power loss (P_f,P_d) necessary to output the required force F_1(50% in this example) according to various values of the field current I_f. As seen in the figure, there is an optimal field current setting that minimizes the total power loss $P=P_f+P_d$.

In addition to the above calculation, the resistance of the i coil increases as the coil temperature rises. The resistance increases several % per 10℃.The coil will heat according to the supplied current and with a temperature rise of several 10℃ the increased power loss will be of the order of several 10% compared to the value calculated in equation (5) . This increased power loss is not negligible.



The resistance change according to the temperature rise must be considered. Using the thermal coefficients C_f, C_d of the coils, the formula (5) is given in a more precise form as:

$$P_f = R_{f0}*[1+C_f*(T_f - T_{f0})]*I_f^2 \qquad (6\text{-}f)$$

$$P_d = R_{d0}*[1+C_d*(T_d - T_{d0})]*I_d^2 \qquad (6\text{-}d)$$

Where T_{f0},T_{d0} denote the temperature when the resistance value R_{f0}, R_{d0} were measured. The values of C_f, C_d are to be measured prior to the operation. The power loss in each coil (P_f, P_d) taking the coil temperature increase in to consideration can be calculated by (6). However, the coil temperatures (T_f,T_d) are not known at the operating current levels (I_f, I_d). Unless (T_f,T_d) can be determined, then formula (6) can't work.

■ Prediction of the coil temperatures using a Temperature Model

We must be able to solve equation (6) by any means possible. If we assume that we can solve equation (6) by a suitable method, then we can get the optimal current combination (I_f, I_d) that minimizes the total power loss P. For the first step, we must investigate “To what extent the blower speed can be safely reduced under the optimal operating condition?” . To achieve this final step, we must know the thermal equilibrium temperature of the coils under any given operating condition (I_f, I_d, V) as accurately as possible.

Here we introduce a mathematical model (Thermal Model : TM) that predicts the coil temperatures under a given operating condition (I_f, I_d, V) as shown below:

$$T_f = f(P_f, P_d, V) + T_{in} \tag{7-f}$$

$$T_d = g(P_f, P_d, V) + T_{in} \tag{7-d}$$

Where *f* and *g* denote the TM of the field coil and the drive coil which have some appropriate function form. The details of the functions, g and f, are not shown here to avoid complication. The functions g and f are determined from experimental data by measuring T_f,T_d at several test points (I_f, I_d, V).
Although the TM itself gives an estimate of the temperature rise of the coil ΔT , the actual coil temperature (T_f,T_d) also depends on the cooling-air temperature T_{in} as shown in (7). From this, it can be inferred that the optimal operating condition determined by the EM system is different in summer and winter. It is clear also by intuition that the E-saving efficiency is higher in winter. However, this indicates the importance of using the air inlet temperature as one of the reference parameters.

In addition to the coil temperature, a TM for the exhaust cooling-air temperature T_{out} is also realized:

$$T_{out} = h(P_f, P_d, V) + T_{in} \tag{7-out}$$

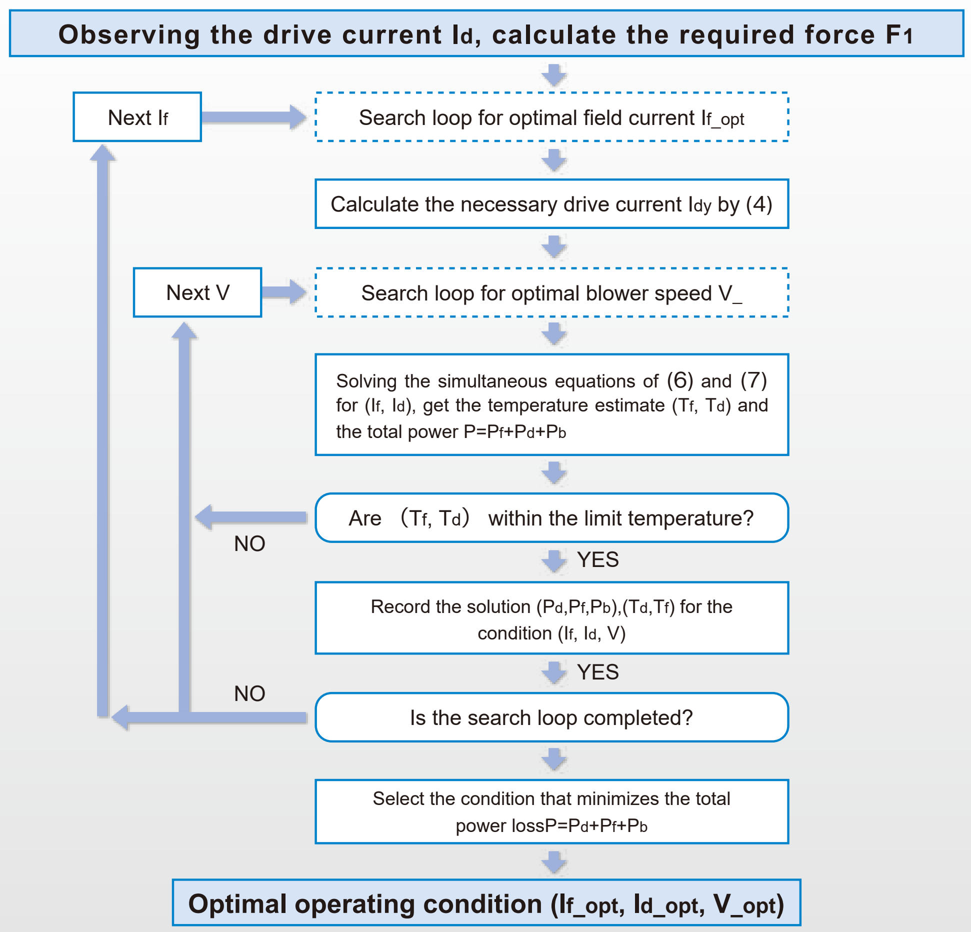
The outlet air temperature T_{out} is continuously monitored by a thermal sensor as well as the inlet temperature T_{in}. The validity of the TM is checked by comparing the estimated value to the measured value. Such safety functions have been implemented for improved safety during the operation of the system.

■ Optimal operating condition search

Finally, the optimal operating condition (I_{f_opt}, I_{d_opt}, $V_{\_opt}$) is found from the procedure shown in the flow chart below.

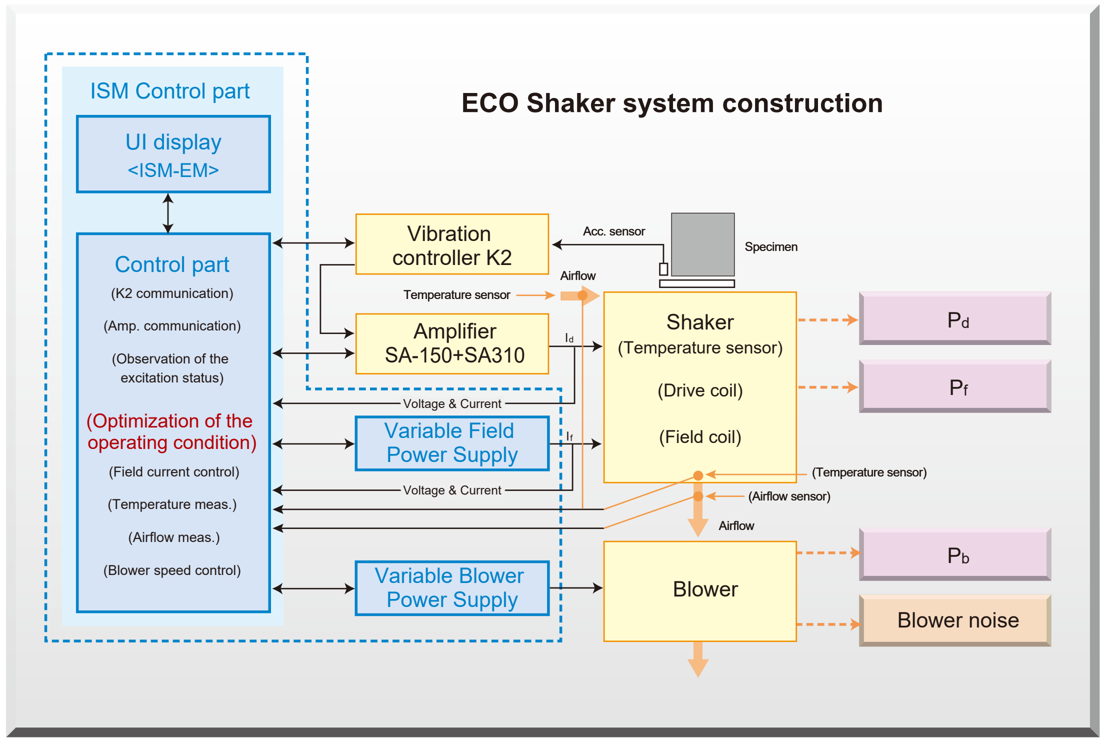
When the physical parameters of a shaker（R_{f0},R_{d0},T_{fo},T_{do},C_f,C_d,T_{in}） and the operating condition (I_f, I_d, V) are fixed, then four variables (P_f, P_d, T_f, T_d) from equations (6) and (7) remain to be determined. Since there are four simultaneous equations and four variables, then one definite solution exists for this problem. Within the possible solutions to the problem to define the operating condition of I_f, I_d, V, then only those that satisfy the constraint of the maximum coil temperature limit can be kept as valid solutions. Finally, the solution that minimizes the total power loss, $P=P_f+P_d+P_b$ is selected as the optimal solution to the problem of specifying the values for I_{f_opt}, I_{d_opt}, $V_{\_opt}$

Optimal operating condition search algorithm



3 Implementation

The actual ECO Shaker system construction is illustrated below:



The part enclosed by the dashed blue lines is added to the conventional shaker system to realize the energy-saving operation. This part comprises a ‘Variable Field PS’, a ‘Variable Blower PS’ and the ‘ISM Control part’ which controls both the Field and Blower.

The ISM Control part consists of a real-time controller for the energy management function and the UI application software <ISM-EM> running on a Windows OS.

The Energy Manager software <ISM-EM> runs on a dedicated DSP Board and ensures the complete safety of the vibration test system by exchanging information with IMV’s vibration controller K2. The ISM-EM software orchestrates all control functions within the vibration test system to ensure optimization of the system energy.

The <ISM-EM> software also communicates with the power amplifier (SA-150+SA-301) via the dedicated DSP Board to monitor the amplifier status and control fully the amplifier.

The Variable Field Current PS is a PWM power converter and supplies the DC current to the required level specified by the ISM Control software.

The Variable Blower PS is also a PWM power converter and supplies the AC current to control the blower at the speed specified by the ISM Control software.

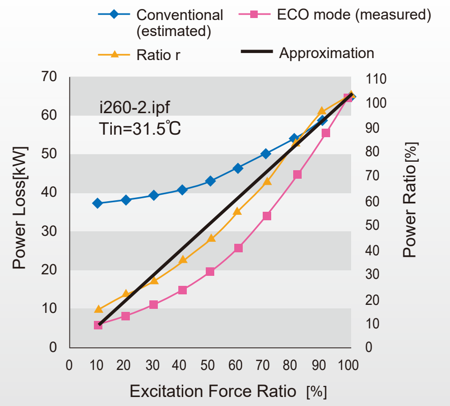
Each of the above two PS units has its own control module and power generation module and these modules are connected to the ISM Control software via CAN bus. The optimum operating values for the field current and blower speed for the given vibration test profile are calculated by the optimization procedure of ISM-EM control software and communicated to the relevant control modules via the CAN bus network. The shaker system is then operated at the determined minimum energy condition.

4 Performance

Energy-saving

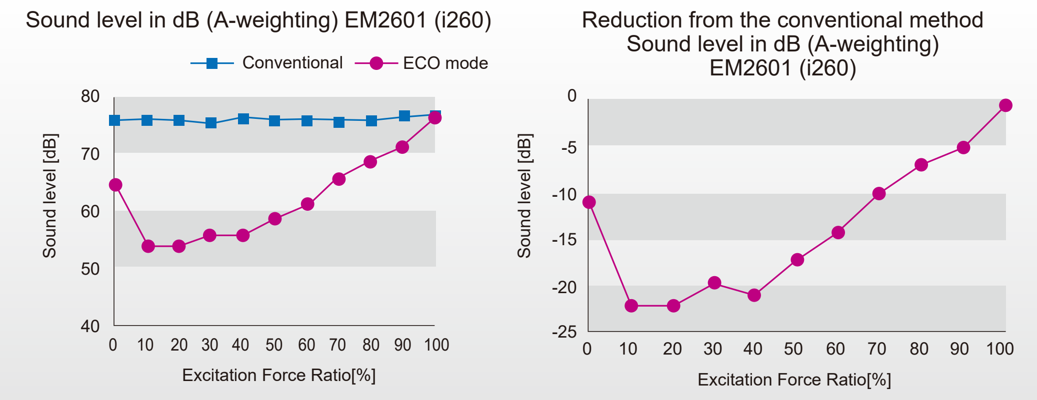
Actual performance of the energy-saving for the ECO Shaker is shown by the data below taken with IMV’s EM2601 system operated under the ambient temperature Tin=32℃:

EF	If	Id	V	Power loss			Save ratio
(Force)	(Field)	(Drive)	(Blower)	Conventional (estimated)	ECO mode (measured)	Ratio r	1-r
	[A]	[A]	[Hz]	[kW]	[kW]		
10%	28.0	124	10.0	36.9	5.3	14%	86%
20%	29.6	236	10.6	37.7	7.7	20%	80%
30%	36.4	296	16.0	39.0	10.6	27%	73%
40%	42.7	355	22.6	40.7	14.4	35%	65%
50%	48.7	412	29.4	43.0	19.2	45%	55%
60%	55.1	469	38.1	46.0	25.5	55%	45%
70%	61.0	530	47.6	49.7	33.6	68%	32%
80%	66.0	589	58.7	53.7	45.1	84%	16%
90%	84.0	623	59.8	57.7	55.4	96%	4%
100%	84.0	693	60.0	62.6	63.7	102%	



Blower acoustic noise reduction

Measured data for the acoustic noise reduction result of EM2601 system is shown as an example below:



5 Retrofitting

ECO Shaker technology is fully implemented in IMV’s EM-series, and this original form of the technology can provide the customer with the absolute best performance.

On the other hand, it is also possible to provide a conventional or existing shaker system with the latest energy-saving technology by retrofitting the equipment that is necessary for the ECO Shaker technology (the portion enclosed by the dashed blue lines in the System construction figure). In addition, it is required for the vibration controller to communicate correctly with the “ISM Control software” to realize the fully automated operation of ECO Shaker. So, the vibration controller should be an IMV K2.

It is required to determine the Thermal Model of the existing shaker which is the basis of the ECO-shaker technology. IMV may already have built up a data base of technical information required for the existing shaker. Please provide IMV with information on the existing system as the first step in considering the replacement ECO-shaker technology.