Machine vibration, noise, and dynamics characteristics control technology

Technology to Control Vibration, Noise, and Dynamics Characteristics for Quiet, Safe, and Efficient Machinery

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Abstract

Machinery inevitably generates vibration and noise when in operation, and such vibration and noise must be kept below a certain level to provide high-quality products and services. Since its inauguration, Kobe Steel has been continuously working on developing "machine vibration, noise, and dynamics characteristics control technology" to address these challenges. This contribution extends beyond Kobe Steel's machinery products to include stable operation in Kobe Steel's own factories and the resolving of challenges for users of Kobe Steel materials, contributing to the realization of a broader, secure society. This paper provides an overview of the technology, explaining the contributions made to society thus far, and offers a perspective on future to a green society, and ensuring safety and security in community development and manufacturing.

Introduction

Machinery inevitably generates vibration and noise when in operation. Excessive vibration can damage machinery to an extent that jeopardizes safety and necessitates plant shutdown. Noise is also physically and mentally distressing for workers and local populations. Therefore, keeping vibration and noise below certain standard values is critical to the continued operation of machinery and factories. This paper describes one of our core technologies, "machine vibration, noise, and dynamics characteristics control technology". Suppressing vibration and noise is a prerequisite to stable operations; this is fostered by key fundamental control technology supporting high-quality products and services.

Fig. 1 shows a diagram of this technology and depicts the basic structure of a machinery product. In a machinery product, commands are sent to an actuator that creates a driving force. The driving force is then transmitted through solids, liquids, or gases. Therefore, suppressing vibration and noise requires consideration of not only the spaces, structure, and transmission system in which the vibration and noise occur, but also of the driving force and the control commands sent to it. Kobe Steel has long been committed to the research and development of "machine vibration, noise, and dynamics characteristics control technology" by going back to the control of motion.

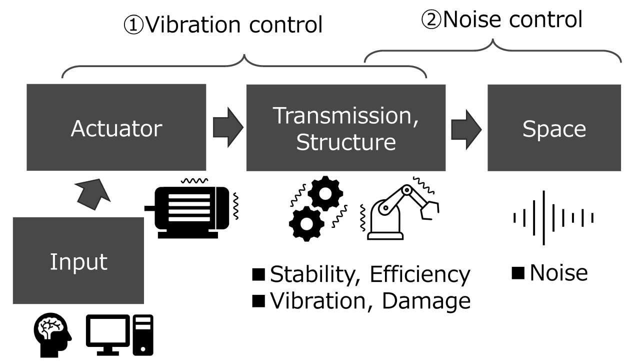

Fig. 1 Machine vibration, noise, and dynamics characteristics control technology

This paper describes our analysis, control, and improvement technologies in two primary areas. The first is vibration control technology, which centers around the transmission of force from the actuator to the structure. The second is noise control technology, which centers around the transmission of noise from the vibration of the structure to the surrounding space. Also presented are examples of how these technologies contribute to a green society.

1. Vibration control technology

1.1 Overview of vibration control technology

Vibration control technology includes vibration/dynamics characteristics analysis technology, measurement and analysis technology, and vibration reduction technologies based on these two categories of technologies. Kobe Steel have long focused on vibration control technologies to ensure the reliability of our products and production equipment. Products and equipment have become lighter and faster; more powerful and economical; and more capable of supporting increased productivity and decreased energy consumption and CO_2 emissions. These enhancements have introduced complex challenges in vibration, in turn leading to more advanced vibration control technology.

Kobe Steel's vibration control technology is mainly used in industrial machinery such as compressors (**Fig. 2** (a)), plant piping and equipment, and construction machinery. In steel and aluminum plants, our technology also contributes to the increased speed, and thus productivity, and stable operation of machinery and equipment such as rolling and plating machines (Fig. 2 (b)).

In recent years. Kobe Steel develops technologies that use data related to vibration to support machinery and equipment diagnostics, streamline maintenance management of the machinery and equipment in our steel mills and power plants, and provide services such as maintenance and replacement proposals for our machinery products.

1.2 Vibration/dynamics characteristics analysis technologies[1)]

Numerical analysis methodologies such as the finite element method (FEM), which is indispensable for understanding vibration phenomena, are also major elements of Kobe Steel's history in vibration research. We have spent many years progressing advanced large-scale FEM analysis using a variety of general-purpose analysis programs. However, we have also been developing our own software for highly accurate and efficient management of vibration phenomena. Focusing on vibration challenges in terms of the design of Kobe Steel products rather than relying solely on general-purpose software drastically reduces the time required for analysis. This sections introduces examples of software and analytical technologies developed in house.

1.2.1 Nonlinear dynamic analysis (SINDYS)[2), 3), 4), 5)]

SINDYS was developed in the late 1970s to solve complex vibration phenomena in coupled structural system and hydraulic fluid/control system such as hydraulic presses. It has been expanded from a general-purpose dynamics analysis system to a system suitable for use with thermal fluids and with control systems and machinery that exhibit large displacements.[2)]

The system uses ingenious numerical integration to perform efficient, highly accurate analysis of problems involving strong nonlinearities such as rattles, stops, and large displacements. It is capable of analyzing not only vibration phenomena, but also general dynamics phenomena, such as in the analysis of robot and hydraulic excavator operation. For example, simulating digging operations of hydraulic excavators revealed the losses contributed by each hydraulic component, line, etc., which led to innovations with industry-leading energy conservation implications (**Fig. 3**).[3)]

In recent years, the program has been used as a simulator that couples physical hardware and virtual mathematical models, known as HIL (hardware-in-the-loop) simulation.[4)] It has also been paired with general-purpose software such as NASTRAN (structural analysis) and Simulink (control design) and can be coupled with DEM (discrete element method) analysis to evaluate soil for its capacity for excavation in support of hydraulic excavator operation.[5)]

1.2.2 Pressure pulsation analysis (PULSAS)[1)]

Positive displacement compressors, such as reciprocating compressors, perform intermittent intake and discharge of gas. This generates pressure pulsations, and thus vibration, in the piping. Kobe Steel has a long history of studying pressure pulsation phenomena, dating back to the manufacture of Japan's first reciprocating compressor in 1915. PULSAS is a software program that uses FEM to analyze pressure pulsation. It has been applied to hundreds of cases of plant design and pulsation countermeasures, resulting in improvements such as ensuring compliance with

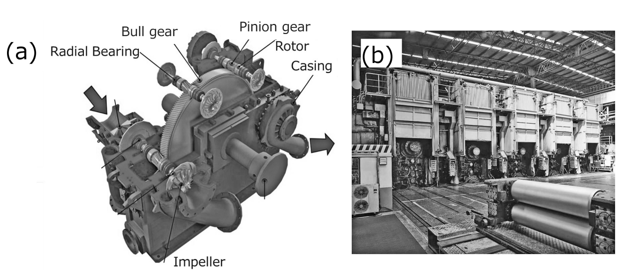

Fig. 2 Components improved through Kobe Steel's vibration control technology
(a) Integrally geared centrifugal compressor,
(b) Cold tandem rolling mill

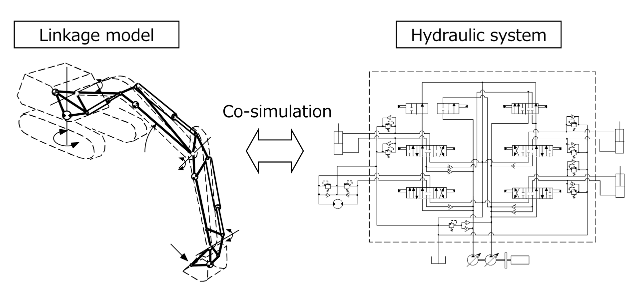

Fig. 3 Co-simulation with linkage model/hydraulic coupling[3)]

API Standard 618 (American Petroleum Institute standard) (**Fig. 4**).

1.2.3 Rotor dynamics analysis (ROTAS)[1)]

Economic growth has led to larger, faster, and more powerful rotating machinery. In tandem, however, this machinery has had to contend with increased vibration. In response to this, we developed software in the late 1970s to study theoretical natural frequencies and vibration in rotors in support of equipment design. In recent years, Kobe Steel has developed analysis technologies that account for coupled interactions involving the gear casing structure rather than the rotor alone to enable logical design, and has also developed technologies to predict the dynamic characteristics of sliding bearings with greater accuracy (**Fig. 5**).

1.2.4 FEM transfer path analysis (FE-TPA)[6)]

TPA (Transfer Path Analysis) identifies the dominant path along which vibration propagates from the input source to the target location. We extended this method, which is conventionally applied to experimental data, to numerical analysis (FEM) to develop technology that more precisely evaluates the contribution of each path. Now that we have enabled effective structural modification, our development is being used to reduce vibration in cranes (**Fig. 6**).

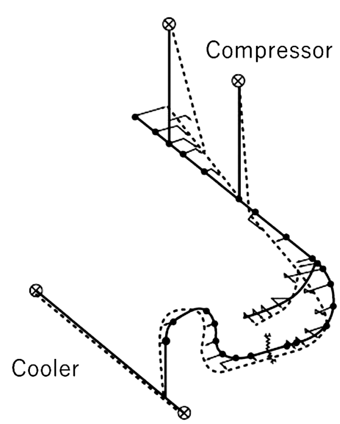

Fig. 4 Piping vibration due to pressure pulsation[1)]

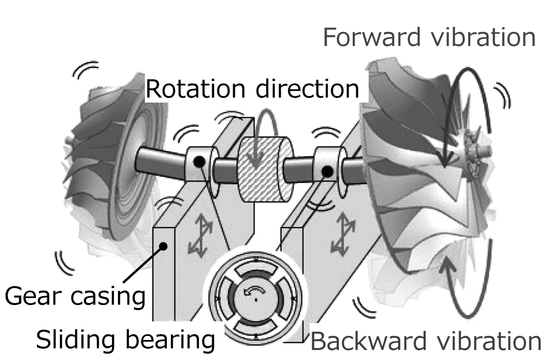

Fig. 5 Rotor stability analysis

1.3 Vibration measurement and analysis technology

Navigating challenges in vibration also necessitates technology that can analyze the measured data. Kobe Steel developed VIVIAN (VIsual VIbration ANalysis) for standard vibration analysis, such as FFT, filtering, and modal analysis (**Fig. 7**).

This program features simple, intuitive operation and supports high-speed processing of large data sets, causing it to become an indispensable element of Kobe Steel's research and development in the field of vibration. VIVIAN can incorporate new analytical methods, enabling the use of a wide variety of modes of vibration analysis. This platform is how we are promoting the use of analysis technology among all departments to support group-wide vibration analysis and testing of machinery and equipment.

We are also developing software that can

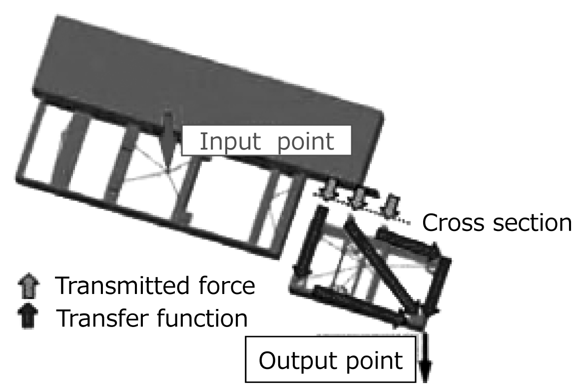

Fig. 6 Transfer path analysis using FEM[6)]

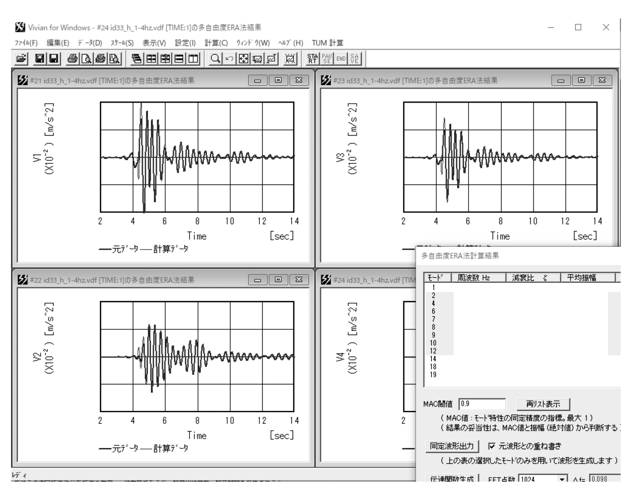

Fig. 7 VIVIAN (VIsual VIbration ANalysis)

diagnose damage caused by vibration as part of our endeavors in equipment diagnostics technologies such as machine status monitoring. As an example, **Fig. 8** shows a screenshot from software we developed for reduction gears and bearings in industrial machinery. This technology ensures the reliability of Kobe Steel's products so that customers can use them with confidence. Furthermore, it supports the stable operation of our steel mills and power plants.

2. Noise control technology

2.1 Development of Kobe Steel's soundproofing technologies

Kobe Steel's production operations employ large equipment. As such, the company has developed soundproofing technologies to reduce the noise generated by its factories to coexist with local communities. Economic growth has made noise reduction increasingly important for job satisfaction and general quality of life, leading to the development of construction machinery and compressors featuring low-noise operation. **Fig. 9**(a) shows an ultra-quiet excavator equipped with the Integrated Noise & Dust Reduction (iNDr) cooling system, an engine cooling system for quiet, dustproof, low-maintenance construction machinery. This system has been very well received by customers.[7), 8)] Reducing the weight of transportation equipment is also critical to reducing CO_2 emissions; however, weight reduction often leads to increased vibration and noise.

Kobe Steel's low-noise solutions for the transportation sector have contributed to society in terms of comfortable travel and reduced CO_2 emissions. One example innovation is our line of vibration-damping aluminum extrusions (Damp-Shape, winner of the Ichimura Industrial Award),[9), 10)] which has been incorporated into Shinkansen (bullet train) lines since the 500 series (Fig. 9(b)). We have also developed a number of soundproofing products, including Eco Kyuon,[11)] which uses the microperforated sound absorption technology[12)] described next.

The next section introduces numerical analysis of acoustics, experiment-based technologies, and low-noise design technologies that support developments in this field.

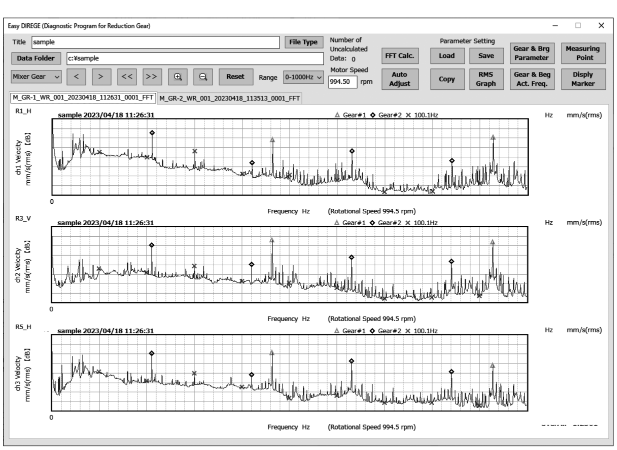

Fig. 8 Rolling bearing diagnostics software

2.2 Acoustic analysis technologies[13)]

In the 1970s, when numerical analysis technology was up and coming, Kobe Steel used FEM to develop sound field analysis technology for low-frequency noise reduction in applications such as jet engine muffling equipment. However, sound field analysis technology has not yet been practical for the development of general-purpose products. This is because acoustic phenomena in the audible range have short wavelengths and because the related analytical models have an enormous number of elements. In the 1980s, Kobe Steel was one of the first companies to develop and use the boundary element method (BEM), which analyzes sound fields by dividing only the boundaries of the region under investigation into elements. Since the 1990s, Kobe Steel has leveraged the strength of its numerical analysis technology to introduce various types of low-noise machinery and soundproofing products (**Fig.10** (a)). Around 2010, we developed acoustic radiosity as an extension of boundary-type

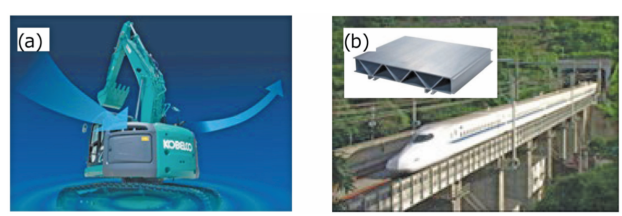

Fig. 9 Product development applying acoustic technology
(a) Hydraulic excavator with iNDr[8)]
(b) Damp-Shape[10)]

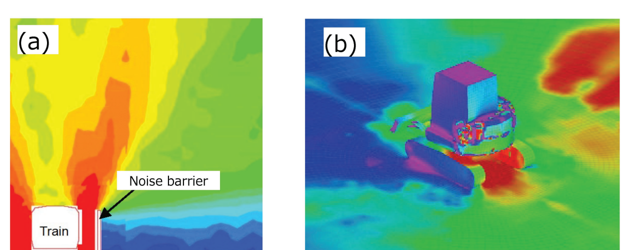

Fig.10 Numerical simulation of sound field
(a) Diffraction attenuation of soundproof walls (BEM)
(b) Noise from construction machinery (acoustic radiosity)

numerical analysis by zeroing in on the similarities between sound and light at high frequencies. We have since used acoustic radiosity to design low-noise construction machinery (Fig.10(b)).[7] We take advantage of having our own proprietary software in fostering the optimal design of new products.[14]

2.3 Acoustic experiment and evaluation technologies

In addition to numerical analysis technologies, we have spent many years developing technologies for constructing experiment-based acoustic models. Kobe Steel has one of the largest semi-anechoic chambers in Japan (**Fig.11** (a)). We use this to evaluate the acoustic performance of a variety of machines and structures. This includes our own products, such as construction machinery and compressors, and other structures and equipment, such as vehicles, office equipment, bridges, and houses. This has enabled us to provide effective solutions and amass expertise in the creation of acoustic models.

TPA, covered in Section 1.2, was the key experiment-based technology in these endeavors. Kobe Steel was at the forefront in developing this technology, which drove its role in creating Damp-Shape in the 1990s. TPA helped develop the acoustic model of a railroad car (Fig.11(b)) that became the basis for predicting interior noise upon a change in speed or when Damp-Shape is used. Kobe Steel also developed technology to reproduce predicted acoustic results as audible sound. Customers began opting to use Damp-Shape in the design phase because they were able to experience the effects of Damp-Shape before building the railroad car.

Because sound ultimately relates to human perception and sensitivity, we have conducted extensive research into not only the physical aspects of sound, but also its psychological and physiological effects. In this way, we have created construction machinery cabins that are more conducive to long-term comfort.[7] We are researching how to quantify sound perception based on changes in sound perceived by experienced inspectors. This will assist us in developing equipment diagnostics technology that will secure operations in view of the shrinking workforce.

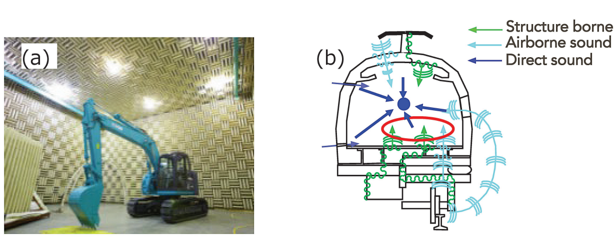

Fig.11 Acoustic experiment and evaluation technology
(a) Large semi-anechoic room,
(b) Transfer path analysis (TPA)

2.4 Technology for the design of low-noise devices

Acoustic metamaterials have been a focal point of development in recent years. These structures have a periodic array of tiny resonances, yielding acoustic performance far superior to that of conventional materials. Kobe Steel was among the first to use microperforated sound absorption technology (**Fig.12**), which is a type of acoustic metamaterial that uses the resistance and resonance of sound waves passing through tiny, periodically arranged holes. Eco Kyuon is aluminum paneling that uses microperforations to achieve sound-absorption properties. Unlike conventional materials such as fiberglass, which enter the industrial waste stream, these panels are made entirely of aluminum and are recyclable. Kobe Steel will continue its research efforts in this field[15] to support a comfortable, sustainable society with low-noise living and working spaces.

3. Developing compressors that contribute to a green society

To contribute a green society, Kobe Steel not only designs its machinery products to be highly energy efficient, but also directly reduces CO_2 emissions through technologies such as CCS (carbon capture and storage) and CCUS (carbon capture, utilization, and storage). This section describes how we used vibration control technology in the development of an integrally geared centrifugal compressor for high-pressure CO_2 for CCS and CCUS (**Figs.** 2 (a), **13**).[16, 17]

The main technical challenges overcome in this development are (1) increasing the strength of components subjected to high pressure; (2) improving aerodynamic performance at high pressures; (3) improving the stability of the rotor against vibration; and (4) improving the sealing performance of high-pressure gas. Issue (3) is strongly associated with vibration control

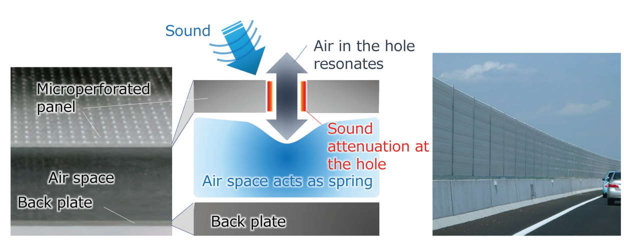

Fig.12 Microperforated sound absorption technology and Eco Kyuon[11]

technology.

A centrifugal compressor is a machine that turns an impeller on a rotor (rotating shaft) at high speed to impart energy (centrifugal force) to a gas to increase its pressure. The rotor is supported by sliding bearings, and a non-contact seal in the gap between the rotor and the casing inhibits the escape of compressed gas.

Fluid forces generated in the impeller and non-contact seals induce vibration in the rotor. As the pressure of the gas increases, the forces increase. Unstable and increasingly intense vibration can occur, necessitating a design that ensures rotor stability in these conditions.

Kobe Steel used ROTAS vibration analysis software to test and design this compressor. This compressor is equipped with features to counteract vibration such as high-damping bearings and a swirl brake, which reduces forces within the sealing fluid.[17)]

Rotor stability can be evaluated by applying an external vibration (excitation) to a rotating rotor subjected to high pressure, measuring the amplitude of the rotor vibration generated during excitation, and calculating a stability index value called the *logarithmic decrement* based on the amplitude.

Conventional techniques for inducing indirect rotor vibration involve externally exciting the entire compressor. However, Kobe Steel has developed a proprietary technique to induce rotor vibration directly by using the rapid switching action of four electromagnets to apply a moment to the impeller (**Fig.14**). This method results in a larger vibration amplitude during rotor excitation, greatly improving the accuracy of the logarithmic decrement for a reliable evaluation of stability.

Fig.15 compares the calculated and measured logarithmic decrements. The greater the decrement, the higher the stability. Lower values indicate a design that is prone to unstable vibration. Although there were some slight deviations from the measured values, the calculated results still far exceed the value stipulated by the API standard,[18)] which is used as a general indicator of rotor stability. In other words, the values indicate sufficient stability.

We have verifiably overcome other technical challenges with this prototype system, demonstrating that it is sufficiently reliable for long-term field use. It is anticipated that this high-pressure CO_2 compressor will be used for CCS and CCUS, making a significant contribution to reducing CO_2 emissions.

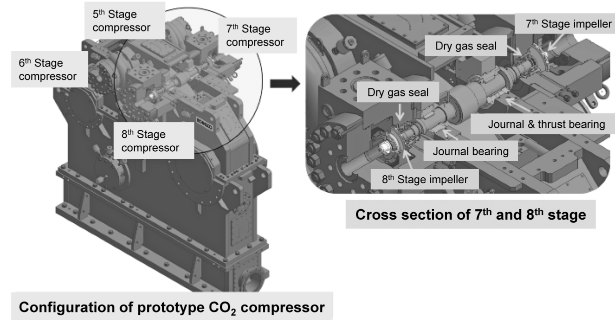

Fig.13 Integrally geared centrifugal compressor for high-pressure CO_2[16)]

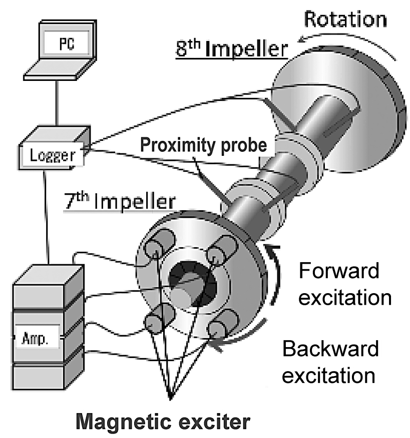

Fig.14 Magnetic excitation system

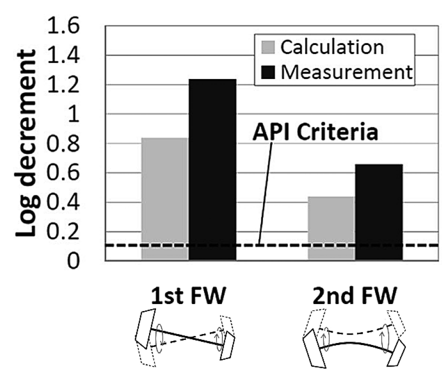

Fig.15 Logarithmic decrement of rotor

Conclusions

This paper has described how our "machine vibration, noise, and dynamics characteristics control technology" has long contributed to the stable operation of Kobe Steel products.

Kobe Steel will enhance and expand its portfolio of machinery products to support stable operations, which is a prerequisite to our goal of contributing to a green society. We are certain that our technologies covered in this paper will continue to be indispensable in this regard.

These technologies ensure the stable

operation of machinery and provide solutions to societal challenges such as traffic noise and other environmental noise. They also reduce vibration in elements of infrastructure such as bridges and diagnose deterioration in these structures.[19] We will continue refining these technologies to ensure safety and security in community development and manufacturing.

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