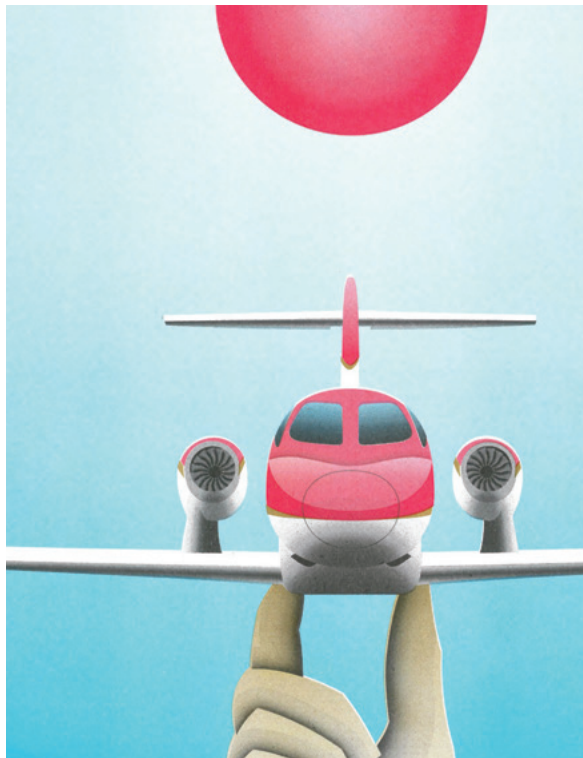


# Honda R&D

## Technical Review



2024  
Vol.36



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## Comment on the Cover

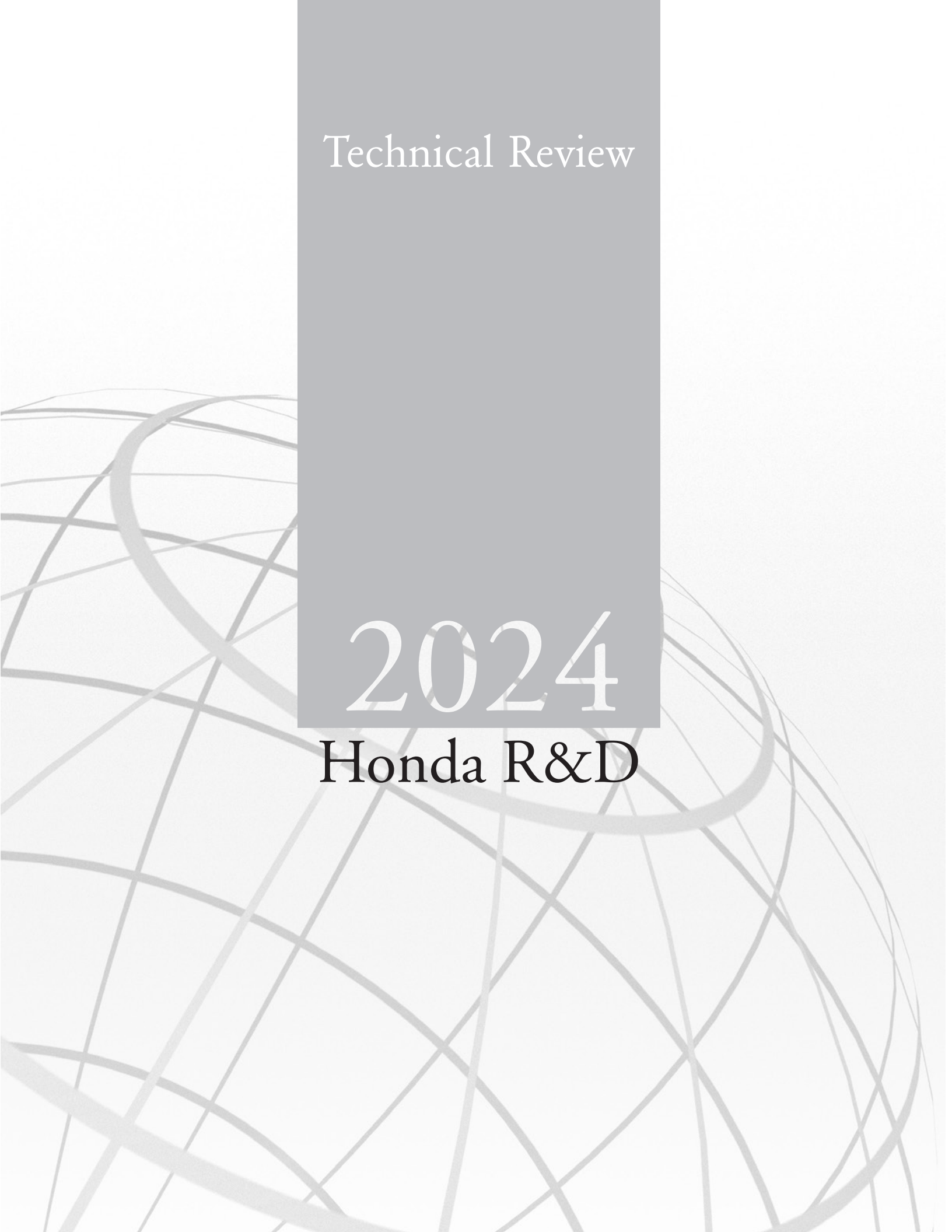
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Due to the update to the global brand slogan, I thought I would again try to express the dreams seen by the people of Honda. There are many products from which to choose, but I feel that the red Honda Jet is a product whose dreams are reflected in, and given concrete form by, its own body. It was with the hope that products imbued with such dreams and such spirit will be brought to life in future that I created this image.

The printing method is the same as that used for Vol. 35, and based on that experience I increased the number of colors used and adjusted them with meticulous care. I feel that I succeeded in broadening the range of my own expression a little.



Honda Motor Co., Ltd.  
Kosuke YONETA

The background features a light gray wireframe sphere on the left side, composed of intersecting lines. A solid gray vertical bar is positioned in the center of the page, serving as a backdrop for the text.

Technical Review

2024

Honda R&D



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# Quantum information technology: introduction and current state of research

Sebastian SCHMITT, Ph.D.<sup>1</sup>Avetik HARUTYUNYAN, Ph.D.<sup>2</sup>Bernhard SENDHOFF, Ph.D.<sup>3</sup>

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## ABSTRACT

While quantum technologies have made great progress in recent years, several fundamental challenges remain unsolved today. At the same time, the benefit in case of a successful realization of quantum technologies for practical problems is expected to lead to major disruptions in many application domains. In this perspective paper, we first outline the principles underlying quantum information technology. Then, we describe specific application domains relevant to industry where quantum computing, quantum sensing, and quantum communication could be successfully employed. Finally, we briefly introduce the research topics currently investigated at the Honda Research Institutes which should prepare a successful application of quantum technologies on realistic applications in the future.

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## 1. Motivation

The field of quantum information technology is currently witnessing breakthrough moments. Various quantum computing hardware systems have been realized and many of such systems have matured to be accessible via web-based services, notably from IBM, D-Wave, or IonQ. While these systems are primarily used for scientific proof of concept applications, there are first experiments on quantum hardware claiming to have breached the barrier to a quantum advantage<sup>(1),(2)</sup>.

It is commonly recognized that quantum technologies have a highly disruptive potential in many application domains. Shor's algorithm<sup>(3)</sup> for factoring numbers is the archetypal example, where an exponential speed-up over the best-known classical algorithms could be realized, and which would lead to a breakdown of classical public key encryption schemes like RSA. Another example is Grover's search in unstructured databases<sup>(4)</sup>, which offers quadratic speedup. However, both algorithms require fault-tolerant and error-corrected hardware devices with millions of qubits, which cannot be realized in hardware today.

The current quantum computer hardware devices are of the so-called "noisy intermediate-scale quantum" (NISQ)<sup>(5),(6)</sup> type, and face a number of serious obstacles: They (a) realize only a limited number of qubits (100-1000),

which restricts the attainable problem sizes, (b) suffer from noise and errors that are often poorly understood, (c) lack mechanism of error-correction and thus are unable to demonstrate useful complex quantum algorithms beyond proofs of principles, (d) allow only for limited flexibility and control to non-specialist end-users, and (e) are not certified in an assumption-free manner, which means that they are not experimentally verified to operate in a fully quantum regime with all the properties which in theory they should have.

The fundamental building blocks of quantum computers are quantum bits called qubits. Their realization in hardware is based on many different types of physical systems, notably two-level spin systems, trapped ions, photons, or superconducting flux qubits. These quantum devices have also become building blocks for quantum sensing, where quantum properties and specific quantum phenomena are used to precisely measure physical quantities. Quantum devices are very sensitive to environmental changes. While this is a major obstacle for quantum computing, for quantum sensing it enables unprecedented sensitivities and precision<sup>(7)</sup>.

The combination of high risk and high potential makes the field of quantum information technology very attractive for many different players. A huge amount of venture capital is funding many startup companies,

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<sup>1</sup> Honda Research Institute Europe GmbH

E-mail: sebastian.schmitt@honda-ri.de

<sup>2</sup> Honda Research Institute USA, Inc.

<sup>3</sup> Global Network Honda Research Institute

traditional industry players are investing heavily (e.g., Quantum Economic Development Consortium (QED-C)<sup>(8)</sup> or Quantum Technology and Application Consortium<sup>(9)</sup>), and government initiatives are launched with an estimated investment of US\$25 billion in 2021<sup>(10)</sup>.

There are realistic short- to midterm opportunities for quantum technology to provide a benefit for certain applications. However, the identification of industrially relevant problems with significant benefits and the timing remains unclear. At the same time, there is no shortage of scientific roadmaps that formulate strategic research directions<sup>(11), (12)</sup>.

We need to be aware that the recent disruptive advances in AI demonstrated with large generative models such as the large language models GPT and BERT or text-to-image models like DALL-E or Stable Diffusion have only been possible with respective advances in the computing capabilities like GPUs. Even though it will not happen in the short term, quantum computing has the potential to exponentially speed up the training of next generation AI models. This could allow online training of very large generative models.

For the foreseeable future, quantum computing will not be “off-the-shelf”. The successful application of quantum information technology will require experts, and it is necessary for most large companies to establish in-house expertise to be ready to exploit quantum information technology and to be able to correctly judge the state of research and the quality of potential partners.

The high risk involved mandates to maintain an informed and austere position when evaluating the state of the art and what we might expect in the next years.

In the following sections, we want to strike a good balance between showing that quantum technologies will become practically relevant in the mid-to-long term while not concealing that currently the technology faces many unsolved issues in the hardware and the software domain. At the Honda Research Institutes (HRIs) we want to facilitate the discussion in Honda on quantum information technology and encourage the assembly of the necessary expertise to exploit its exciting potential early, efficiently, and decisively.

## 2. From Quantum Physics to Quantum Technology

### 2.1. Introductory remarks on quantum physics and quantum information technology

The principles and laws of quantum physics were conceived to correctly describe, interpret, and predict several famous experiments that could not be explained by classical physics. The abnormalities that we find in the laws of quantum physics are a result of the strangeness of the experimental observations. Quantum physics describes phenomena in the microscopic world of atoms and elementary particles, which are often counterintuitive

to what we observe in the macroscopic world. The measurement process in a physical experiment connects the microscopic to the macroscopic world and it is one of the central aspects both in quantum mechanics as well as in quantum information technology. There is no clear differentiation between classical and quantum worlds and recent physical experiments with large molecules<sup>(13)</sup> show that quantum phenomena are not restricted to the smallest of particles only.

Major fundamental principles of quantum physics are:

1. quantum mechanical systems and particles are described by a state vector also called wave function, which describes in which of all possible states the system can be found;
2. there exists an inherent uncertainty in values attributed concurrently to some physical variables like position and momentum of a particle;
3. quantum states of particles have additional (microscopic) properties, which have their own governing rules and conservation laws.

The state vector is typically a superposition of different states that the particle can be in. Therefore, the first principle of is often also referred to as the superposition principle. Particularly, the first two principles imply that in the microscopic world there is an inherent and irreducible uncertainty, and any description needs to be based on probabilities. The probabilistic nature of the microscopic world can only be partially removed with a macroscopic measurement.

An example of a purely quantum mechanical property of the third principle is the so-called spin of a particle. Technically, the spin is an intrinsic angular momentum, however, it is better to avoid the classical interpretations of this as something rotating in the microscopic world. The total spin is conserved when particles interact. That is, the total spins of all particles before an interaction must be the same as after an interaction. This is true regardless of how far apart the particles are separated after the interaction. This leads to a phenomenon called “entanglement” where two (or more) quantum systems which are spatially separated still need to fulfill a joint governing rule. As a direct consequence, if one of the entangled particles is measured and a certain spin value is observed, this immediately implies a specific value for the spin of the other particle. This non-local nature of entanglement has spurred great controversy and has led Einstein and others to believe that quantum mechanics can only be an incomplete description of reality since such “spooky action at a distance”<sup>(14)</sup> cannot be real. However, the very strange quantum nature of reality has been confirmed in many experiments by now and seminal experiments were awarded the Nobel Prize in Physics in 2022<sup>(15)</sup>. Also, it is exactly these three principles and the resulting entanglement property that are the building blocks of the (potentially) unique capabilities of quantum computers, quantum sensing and quantum communication.

The basic units of information in a classical computer

are the two binary states “{1}” and “{0}” called bits. In a quantum computer these two states are replaced by quantum bits called qubits. The probabilistic nature of the microscopic world implies that the qubits can be a mixture of different states: just like in the spin example, they are with a certain probability concurrently in state “{0}” and “{1}”. This superposition principle combined with the entanglement property of quantum physics, leads to a new type of parallel computing that we briefly elucidate and compare to classical parallel computing in the next section. Isolating quantum systems from the surrounding environment so that they maintain quantum properties, typically called quantum coherence, is technically demanding. While this poses a major challenge for quantum computing applications, it is positively exploited in the field of quantum sensing. There, measurement devices are devised that have very high sensitivity to environmental influences and thus allow for unprecedented sensitivities for measuring physical quantities like magnetic fields. Similarly, quantum communication relies on the fact that spatially separated quantum systems can maintain their quantum coherence even over long distances and thus allow for detecting unauthorized eavesdropping. This enables the implementation of highly secure communication channels.

## 2.2. Quantum simulation: simulating quantum systems with quantum systems

The simulation of quantum mechanical systems on classical computers is computationally costly and cumbersome. This was the reason for Feynman and Benioff to propose the concept of quantum computers where such simulations would be much more efficient<sup>(16), (17)</sup>. Since then, the field of quantum simulation has evolved substantially, and several realistic quantum effects have been computed on actual quantum hardware<sup>(18)</sup>.

Currently, these simulations are on a rather fundamental level, elucidating basic scientific questions. However, it is conceivable to simulate industry-relevant processes or materials on larger quantum computers or quantum simulators for e.g., battery design.

## 2.3. Quantum computing: from classical bits to quantum bits

We have already mentioned that in quantum computing the bits of classical computing are replaced by qubits and in Table 1 we have summarized the significant differences.

It is interesting to consider the differences between parallel computing in a classical high-performance computer and intrinsic parallel computing in the quantum computer, which is sketched in Fig. 1. The performance gain of both relies on parallel computing, however, the way the parallelization works is profoundly different. In the classical parallel computer, a task is divided into suitable subtasks, which are executed in parallel on different physical processing units. The main task is to develop an algorithm that divides a problem into subproblems that can

Table 1 Comparison of classical bits and quantum bits

| Classical bit                      | Qubit                                                                           |
|------------------------------------|---------------------------------------------------------------------------------|
| State is either {0} or {1}         | Superposition of different states: “ $\alpha \cdot \{0\} + \beta \cdot \{1\}$ ” |
| Read-out is deterministic          | Read-out is probabilistic                                                       |
| Read-out does not affect the state | Read-out changes the state of the qubits                                        |
|                                    | Multiple qubits can be entangled                                                |

be processed in parallel with efficient information exchange between the subprocesses and whose solutions can finally be combined to the solution of the original problem.

In the quantum computer,  $N$  qubits can occupy each of the possible  $2^N$  states at the same time with a certain probability. This is a consequence of principle 1 – the superposition principle. But such a superposition of all possible states is still just one quantum state. Applying one quantum operation to this one state inherently results in an operation on all states in the superposition. Therefore,  $2^N$  states can be manipulated by applying one operation to a  $N$ -qubit system. This is usually referred to as quantum parallelism: without explicit physical realization,  $2^N$  states can be processed at once, which is in weird contrast to our daily experiences. However, the naïve exponential speed-up of processing  $2^N$  states with just one operation in parallel has a catch and cannot be directly realized in practice. Reading out the results requires measuring the quantum state, and a measurement only returns one of the possible  $2^N$  states as a result. Therefore, one would need on the order of  $2^N$  measurements to get out all results, which directly spoils the quantum advantage.

Therefore, the art of solving a practical problem with the help of a quantum computer is to formulate an algorithm that makes smart use of the superposition property. The results of the  $2^N$  calculations need to be utilized in such

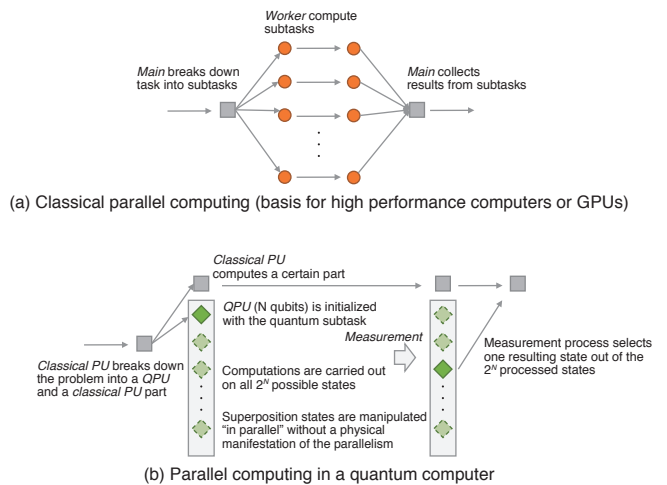


Fig. 1 Schematic representation of classical and quantum parallel computing

a way that it produces a state where the solution to the original problem can be extracted directly. This is a complex endeavor, and only a few algorithms have been proposed for specific problems like e.g., factorizing large numbers (Shor's algorithm<sup>(3)</sup>), finding needles in a haystack (Grover's search<sup>(4)</sup>), or solving sparse linear algebra systems (Harrow-Hassidim-Lloyd (HHL) algorithm<sup>(19)</sup>).

However, these types of algorithms are currently far out of reach to be run on actual quantum hardware. They require thousands of perfect qubits and quantum gate operations, which have very low error rates, and which can maintain quantum properties (coherence and entanglement) for long times and over large number of elementary quantum operations.

In contrast, current NISQ devices encompass only up to few hundred qubits with rather short coherence times and large gate errors. Full error correction schemes, where multiple physical qubits are utilized to mitigate errors and to encode one logical qubit are believed to require a factor of at least 1000 times more physical qubits. Such an increase in the scale of the number of qubits is currently not within reach for the foreseeable future.

Therefore, most current research on quantum computing focusses on how to utilize the current NISQ devices efficiently. Various hybrid quantum-classical algorithms have been proposed, where the quantum device consists of quantum gates, which have freely tunable parameters (see Figure 2). This parametrized quantum circuit produces a final quantum state, which depends on these parameter values, and which is set up to encode the solutions to a predefined application problem. The best possible solution is then obtained by employing a classical optimization routine to determine the optimal values of the parametrized quantum circuit. Such variational algorithms have been successfully used in many proof of principle applications such as quantum chemistry, quantum machine learning, or combinatorial optimization problems<sup>(5), (6), (9), (20), (21)</sup>.

Besides their application to NISQ devices, the proposed

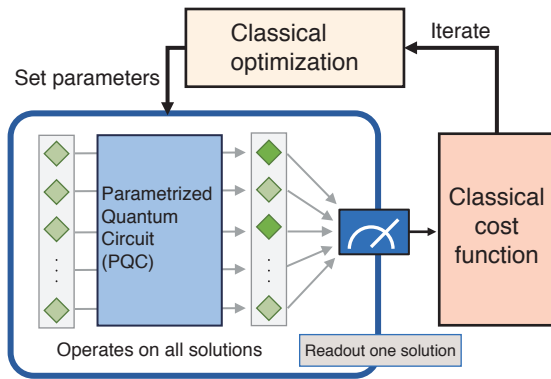


Fig. 2 Schematic representation of a typical hybrid quantum-classical approach on NISQ devices where the parameters of a quantum circuit are determined by classical optimization.

algorithms are expected to be highly beneficial for future fully error corrected fault tolerant quantum devices as well. It is generally believed that quantum computing will not replace classical computing, but both techniques will coexist and will be complementary. There will be applications where classical computing is and always will be more effective than quantum computing, but there will also be specific application scenarios where quantum computation will be favorable. And most likely for many applications these hybrid quantum-classical approaches developed today in the NISQ era will be efficient approaches as these can leverage the best of both worlds.

#### 2.4. Quantum sensing: exploiting quantum phenomena for new high-precision devices

It is expected that quantum sensors can surpass the sensitivity of classical technology for practical applications in the near term. They promise to provide unprecedented sensitivity for the measurement of physical quantities like electric and magnetic fields, rotations and acceleration, pressure and strain, frequency, and time. Quantum sensors exploit quantum phenomena and their very high sensitivity to external influences to achieve high precision measurements.

Quantum sensing devices typically rely on utilizing one or more of the following characteristics of quantum systems. (a) the discrete energy levels of small quantum objects, (b) quantum coherence and superposition of quantum states, and (c) quantum entanglement, of which the latter two are very sensitive to environmental disturbances. To ensure proper functioning as a quantum sensor<sup>(7)</sup>, additional requirements need to be fulfilled:

1. these devices need to allow that their energy levels can be measured,
2. the sensor devices need to be initialized into a well-defined state,
3. the operator needs to be able to manipulate the sensor coherently by, e.g., time-dependent fields,
4. the sensor must interact with the physical quantity to be measured such that changes in the quantity produce a change of the quantum system's energy levels.

The sensitivity  $\eta$  of a network of  $N$  quantum sensors can be shown to scale like  $\eta \propto 1/(\gamma (NT)^{1/2})$ , where  $\gamma$  is the strength of the interaction mentioned in the above requirement 4. and  $T$  is the coherence time. This scaling behavior is called the standard quantum limit (SQL), which is an improvement over the sensing limit of a single device by a factor of  $1/N^{1/2}$ . Recently, it has been proposed<sup>(22)</sup> that the scaling can even surpass the SQL when states of the sensor network are entangled. In that case, the sensitivity increases by another factor of  $1/N^{1/2}$ .

#### 2.5. Quantum communication: towards unbreakable security

The field of quantum communication is already quite

advanced and mature<sup>(23)</sup>. The main value of quantum communications is its security. Instead of qubits, the quantum states of light, so-called photons, are used to transmit information between two parties. It takes advantage of quantum entanglement between two or more photons to protect the information from undesired interceptions. The information can only be recovered by measuring the photons, which unavoidably changes the photons. Therefore, anyone trying to eavesdrop must also measure these photons, which then leaves a detectable trace. The major challenge of the field of quantum communication is the design of efficient ways to encode data into quantum communication channels.

The major application considered today is the so-called quantum key distribution (QKD). The goal is to create a shared secret key between two parties that is perfectly secure. This shared key is used to generate private keys which are then used to encrypt and decrypt communication messages between the two parties using classical encryption methods.

Secure quantum communication can also be used to build quantum networks to transmit digital information, e.g., for banking, medicine, navigation, or transportation applications. Quantum networks have not been practically realized yet and there remain many technical challenges<sup>(24)</sup>, however, their impact would be substantial.

### 3. Impact of quantum technology for selected applications

#### 3.1. The case for quantum computing technologies

The application domain with realistic industry-scale use cases, where quantum technologies can demonstrate a significant advantage, has not yet been identified. To date most success-cases have either been confined to simplified benchmark problems or have been theoretical (like Shor's algorithm).

However, if some technical challenges can be overcome there are application domains, where benefits can be expected even in the short to midterm. In the long-term, when fully error corrected quantum computing hardware with very high number of qubits will be available, the impact will be enormous.

Applied quantum chemistry and material science are industrial application domains of high relevance. Simulating and understanding the chemistry and dynamics of the materials in batteries, particularly the lithium chemistry of cathode materials, is crucial for the development of novel and better batteries. Simulating quantum processes and properties of molecules and compounds on a quantum computer is much more efficient than doing it on classical computers. Similarly, the search for better catalyst materials to enhance the efficiency of fuel cells is also a field with large potential for quantum computers.

Most engineering design processes employ simulations of flow dynamics and of static and dynamic stability of

components using finite-element methods and sparse linear systems to solve partial differential equations. These simulations are computationally very demanding and current computational restrictions limit prediction accuracy and complexity of components and systems that can be simulated. It has been shown<sup>(25), (26)</sup> that physical simulations can substantially benefit from fault tolerant quantum computers leading to enhancements of a variety of industrial products.

Combinatorial optimization problems, such as scheduling optimization or assignment problems frequently occur in electromobility services, manufacturing and supply chain logistics. They are equally likely to substantially benefit from fault tolerant quantum computers. Indeed, combinatorial optimization problems are among those that also benefit from annealing type quantum computers, which are currently available and which we reviewed in Ref.<sup>(27)</sup>.

The utilization of quantum computing for data driven machine learning tasks is pursued in the very active field of quantum machine learning<sup>(28)</sup>. Several algorithms have been proposed which reduce the computational time to train quantum machine learning models. Additionally, and probably more importantly, many quantum machine learning algorithms are expected to need less training data samples to achieve good performance. This will reduce the barrier for deploying quantum machine learning models in realistic application scenarios substantially. Areas which can benefit a lot are quality assurance by automatically analyzing ultrasonic test data from manufactured parts, online monitoring of process data from large manufacturing plants, fault and anomaly detection for complex engineering systems or logistics applications. It is expected that quantum machine learning can thus lead to much more efficient utilization of sparse realistic data in various domains.

Specialized hybrid quantum-classical algorithms are being developed for the currently available NISQ devices for which the following near to mid-term benefits can be expected: in hybrid quantum optimization routines, the possibility to generate quantum states that contain exponentially many classical solutions in superposition leads to a more efficient exploration of the vast search space of combinatorial optimization problems. As a result, more solution candidates can be evaluated and tested during the search. This would lead to more efficient optimization approaches and higher quality solutions. If the algorithms are designed properly, the final states of such quantum optimization algorithms should be able to encode many similarly good solutions of the given problem at the same time. This would provide multiple, structurally different options all of equal quality to the decision makers.

Approaching very complex realistic problems on NISQ quantum computers will not be possible due to the limited number of qubits in such devices. However, quantum approaches can provide a benefit in such cases as well, as they can be used to efficiently find many solutions to simplified problems. These can then be used as

initializations for classical algorithms applied to the original complex problem.

### 3.2. The cases for quantum sensing

Quantum sensors can be realized for a variety of applications, such as gravimeters, interferometers and magnetometers, to name a few. The advantage of exploiting quantum phenomena is particularly notable for magnetometers. These devices use the spin of electrons or atomic nuclei to measure a magnetic field. Superconducting quantum interference device (SQUID) sensors exploit superconductivity to measure very small electric currents induced by magnetic fields. SQUID sensors are widely deployed in applications since decades due to their high sensitivity. However, superconductivity requires extremely low temperatures which makes SQUID sensors difficult to handle. Recently proposed alternative quantum magnetometers use nitrogen-vacancy (NV) centers, which will be discussed in Section 4.4.

Highly sensitive magnetometers have several unique and interesting applications, e.g., in-vivo monitoring of structural health of batteries, wearable sensors for magnetoencephalography (brain activity detection) or satellite-free indoor/outdoor navigation by using the earth magnetic field.

## 4. Research focus of Honda Research Institutes

The Honda Research Institutes (HRIs) are currently assessing the current state of the art in quantum technologies and are evaluating their potential future impact. One key challenge is to understand the current capabilities and limitations of quantum technologies as well as to develop concise and well-founded expectation of how these technologies will develop in the near- and mid-term future. One prerequisite is to advance our own experience and thereby expertise and assemble a network of partners from university and companies.

### 4.1. Electric vehicle scheduling and charging applications

The optimal management of electromobility services plays an important role in achieving zero emission targets. On the one hand, to be sustainable green energy sources should be used as much as possible and on the other hand, customer needs have to be satisfied, and revenue generated.

A directly related technical problem is the optimal operation of a large fleet of electric vehicles (EVs). EVs need to be scheduled to fulfill customer requests for trips for which the state of charge of the battery must be sufficient. Since electricity cost varies substantially over time, the operator can save cost by optimizing the charging schedule of the EVs. Additionally, large operators may have access to on-site generation of renewable energy e.g., using photovoltaic (PV) systems, which could be used to reduce cost,

contribute to stabilizing the grid by balancing the demand or increase independence of the electricity grid. A schematic overview of the various components of such a service is shown in Fig. 3.

Apart from these targets for the mobility service, there exist several technical and operational constraints that need to be fulfilled, e.g., for each time slot only one EV can be assigned to one charging station.

Although the electric vehicle scheduling problem is in principle well suited for quantum computing, its realistic set-up is more challenging:

1. The realistic problem formulation has many constraints, and especially inequality constraints are difficult to handle with a quantum computer.
2. The real operational environment will differ from the simulations used for the optimization. Therefore, the solutions must be sufficiently robust to cope with these variations. Robust optimization techniques are currently not available for quantum computers.
3. The operation of a service should achieve many different, often even conflicting objectives. The solution to such a multi-objective optimization problem is a set of Pareto-optimal solutions, where each solution represents an optimal trade-off between the objectives. Current quantum optimization approaches can only handle single objective problems.

All these three issues are addressed in current research projects at HRI in the context of electro-mobility service applications.

We have investigated a simplified but still realistic EV charging problem where the task was to find a valid assignment of several EVs to different charging stations while minimizing some additional cost function<sup>(29)</sup>. The problem can be formulated as a max- $k$ -graph coloring problem with an additional cost function, see Fig. 4(a). We

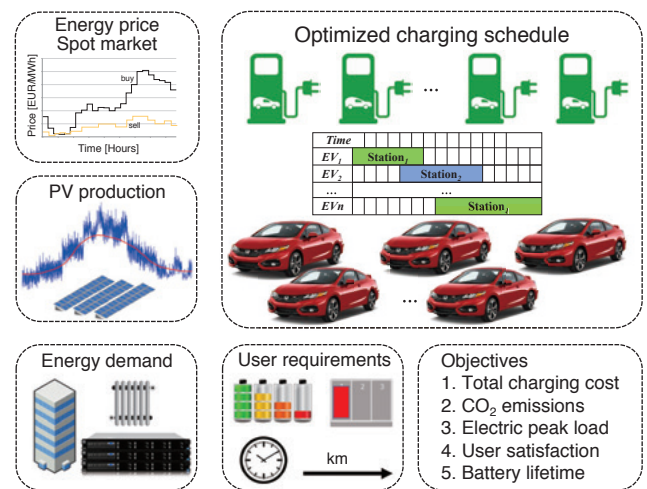


Fig. 3 Schematic overview of the components of an electromobility service

approached this problem with the quantum approximate optimization algorithm (QAOA), which is one of the standard hybrid quantum-classical algorithms for NISQ devices. One main benefit of the QAOA is the capability to find multiple optimal solutions of each problem instance in one optimization run. This was made possible since the final optimized quantum state, which encodes the solutions to the original problem, was found to be in a quantum superpositions of all the optimal solutions of the problem for many instances. Fig. 4(b) shows a summary of the statistics of the number of found optimal solutions averaged over many runs for various small instances of the problem with up to  $N=8$  EVs. The fraction of instances, where up to 100% of all possible optimal solutions are found is rather high. Whether or not this property can be robustly found for other more realistic problems (e.g., larger  $N$ ) is still open and will be investigated further.

#### 4.2. High-dimensional qudit systems

Another research topic at HRI is the exploration of an alternative computational paradigm for quantum computing. Currently, the predominant quantum computing hardware and algorithms are based on qubits. However, a less common approach utilizes multi-level quantum systems with more than two states<sup>(30)</sup>. These are called qudits and are quantum mechanical  $d$  states systems. Their multi-level nature provides a larger state space to store and process information and it is expected that this should provide some benefits for quantum computing implementations in hardware.

Additionally, many of the building blocks of current qubit devices, such as superconducting transmon qubits or trapped ions have more than two levels of which currently only the two lowest ones are used for actual computing. Therefore, it seems natural to extend these systems to use more than two levels and realize quantum computing hardware with multi-level qudits.

Furthermore, it is expected that qudit-based systems will be advantageous for realistic applications. Many combinatorial optimization problems require the representation of integer values, which will be much easier to achieve using qudits. For example, for the EV scheduling the assignment of an EV to one out of several charging stations can be encoded in an integer variable, whose value specifies the ID of the charging station to which the EV is assigned.

HRI is a member of the large European research project “Next level quantum information processing for science and technology” (NeQST)<sup>(31)</sup>, which is funded by Horizon Europe the EU’s key programme for research and innovation. The target of the project is to advance qudit technology in the full value chain of quantum information processing. These include the advancement of qudit hardware systems realized with trapped ion quantum computers and the concurrent development of characterization and automatized design tools. Also, the end-user friendly high-level control and simulation software, which shall enable non-specialists to utilize the qudit hardware is researched. Efficient simulation of physical models such as gauge theories and practical optimization problems are major application domains for NeQST. The focus of HRI within the NeQST project is on developing and showcasing qudit algorithms for electromobility applications.

#### 4.3. Quantum machine learning

HRI also evaluates the possible advantages of quantum machine learning approaches. As a first step, we approached classification and regression problems with variational hybrid quantum circuits using qudits<sup>(32)</sup>. A single qudit with  $d$  quantum states (levels) naturally lends itself to encoding the outcome of a multi-class classification task by associating each qudit state with one class label. With such a setup we could show that a parameterized quantum circuit

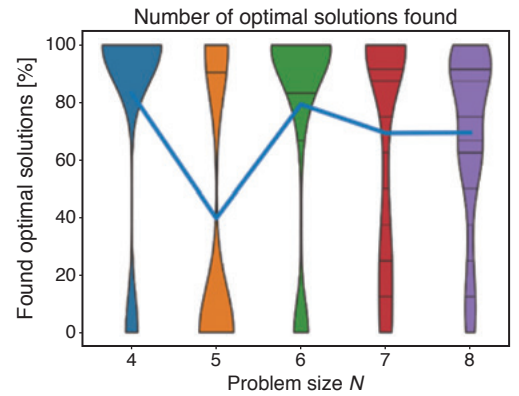
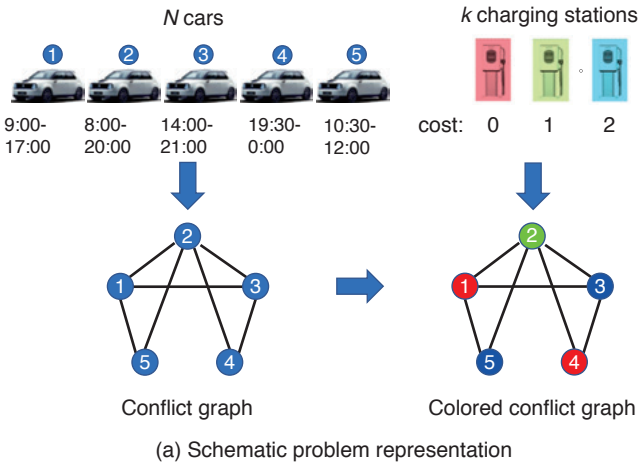


Fig. 4 (a) Representation of the EV charging problem as a max-k-graph coloring problem  
(b) Number of optimal solutions found in one quantum optimization for problems with sizes from  $N=4$  to  $N=8$  EVs

is able to not only learn linear but also non-linear decision boundaries in multi-class classification problems as depicted in Fig. 5. In Fig. 5(a) the left panel shows the alignment of quantum states with the class labels, while the two middle panels show the ground truth and learned classification boundaries. The achievable accuracies are shown in the right panel as function of the depth of the quantum circuit (layers). Fig. 5(b) shows the learned decision boundaries of a quantum classification circuit on the reduced MNIST dataset (left and middle panels), as well as the accuracies as function of the depth (right panel) of the quantum circuit for various numbers of classes (digits).

#### 4.4. Quantum hardware devices for quantum sensing

HRI has evaluated many application scenarios and has selected several specific showcases to be explored in more detail. Specifically, we are researching novel platforms for quantum magnetometers which will be useful for different applications, see Section 3.2. Each of these application fields has some requirements on the sensitivity, device dimensions, weight and power consumption. It is our strategy to first develop one common quantum platform based on solid state systems (color centers in diamond). This quantum system has been shown to enable high quality sensors of electromagnetic fields<sup>(33)</sup>.

Quantum sensors in diamond, specifically, nitrogen-vacancy (NV) devices, have several potential advantages for real-world use cases. They are sensitive to very low magnetic field strengths (below  $10^{-9}$  Tesla) and offer high orientational and spatial resolution. Also, they can be operated at ambient room temperature and have the unique property to combine optical and microwave (MW)

measurements, both of which constitute an operational advantage.

However, NV centers in diamond still encounter serious challenges. One intrinsic problem is the optical readout via excitation and fluorescence detection which destroys the information stored by the NV center. Moreover, spin fluorescence contrast is rather low which reduces the quantum information that can be read out. To overcome this problem HRI will exploit a cavity-enhanced microwave (MW) readout mechanism. This technique operates by measuring changes in an applied MW field following cavity enhanced interactions with a spin ensemble<sup>(34)</sup>.

When the MW frequency is tuned to near-resonance with the NV center's resonance frequency, both absorptive and dispersive interactions occur. These interactions encode the spin resonance in the amplitude and phase of the transmitted or reflected MWs. These effects are enhanced more than ten thousand-fold by placing the ensemble in a high-quality-factor cavity resonant with the applied MWs. Dispersion and absorption by the spin ensemble then modify the resonance frequency and linewidth of the composite cavity-spin system, respectively. Consequently, detection of the transmission through or reflection from the composite cavity provides readout of the spin resonance with very high accuracy (Fig. 6).

We will employ the distributed sensing approach i.e., a collective measurement taken by  $N$  independent sensors, which can enhance the sensitivity by a factor  $1/N^{1/2}$  as described earlier. Additional enhancement of the sensitivity can then potentially be realized with distributed quantum sensing with entangled sensors.

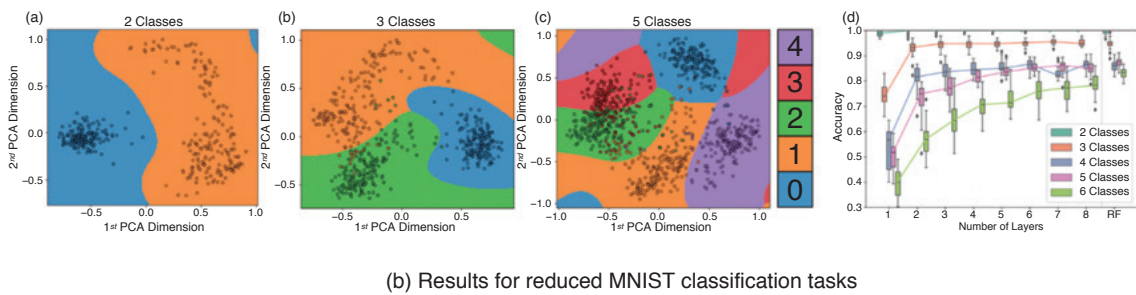
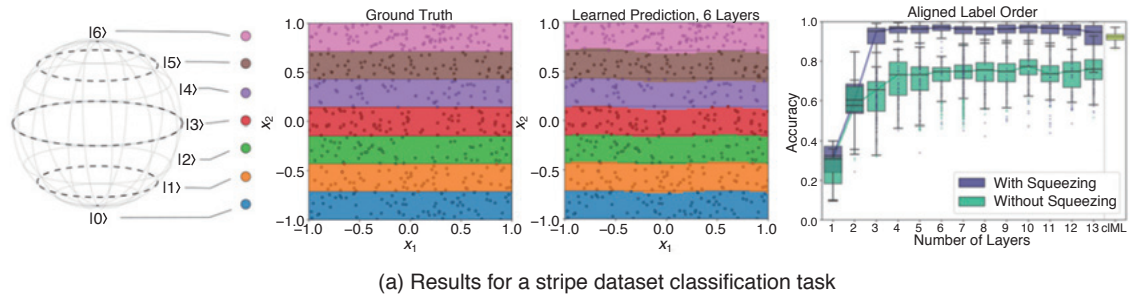


Fig. 5 (a) Results of a  $d=7$  multi-class classification problem with data re-uploading quantum classifier circuit  
(b) Results of a quantum classification circuit on the reduced MNIST dataset for various numbers of classes (digits)

#### 4.5. Quantum hardware devices for quantum communication

Quantum communication exploits the photon as an information carrier and the entanglement property of spatially separated photons to secure communication channels, see Section 2.5. A very important prerequisite for a successful application of photons in quantum communication is to have a high fidelity and on-demand single photon emitter (SPE) source. The requirement is that the SPE is emitting exactly one photon at a time into a given spatiotemporal mode, and all the photons are pure and coherent to ensure interference and entanglement capability of two single photons.

Current SPE technologies rely mostly on attenuated pulsed lasers, which is far from ideal as the photons then have low SPE purity. Alternatives are solid-state SPEs based on color centers in solids (e.g., nitrogen vacancy (NV) centers in diamond), quantum dots (QDs), and atomically thin two-dimensional (2D) materials<sup>(35)</sup>. The biggest advantage of solid-state SPEs is that the single photons are on demand and the purity can be extremely high (potentially >99%). 2D materials are very promising due to their high photon extraction efficiency, and because

they can be readily integrated into photonic systems due to their flexibility and flat surface structure. Recently, single photon emission has been discovered in many different systems<sup>(36)</sup>. However, challenges remain like the low photon extraction efficiency, spectral inhomogeneity, and difficulty in integrating with available photonic technologies<sup>(37)</sup>.

The research of HRI on quantum communication related topics is driven by the strong expertise in growing single atomic layers of 2D materials based on transitional metal dichalcogenides (TMDs)<sup>(38)</sup>. Specifically, nanoribbons of TMDs with about 10 nm width provide beneficial freedom for adjusting their electronic structure and thereby enabling single photon emission. The possibility of controlling the properties of nanoribbon-based SPE enables the engineering of several favorable properties such as increasing quantum yields, deterministic spatial positioning, or great versatility for integration with waveguides, electronic circuits, or photonic cavities for integrated quantum photonic technologies.

The initial results on quantum emissions obtained in the laboratory from synthesized WSe<sub>2</sub> nanoribbons under cryogenic temperatures as depicted in Fig. 7. Panel (a) shows a microscopic image of the nanoribbon, and panel

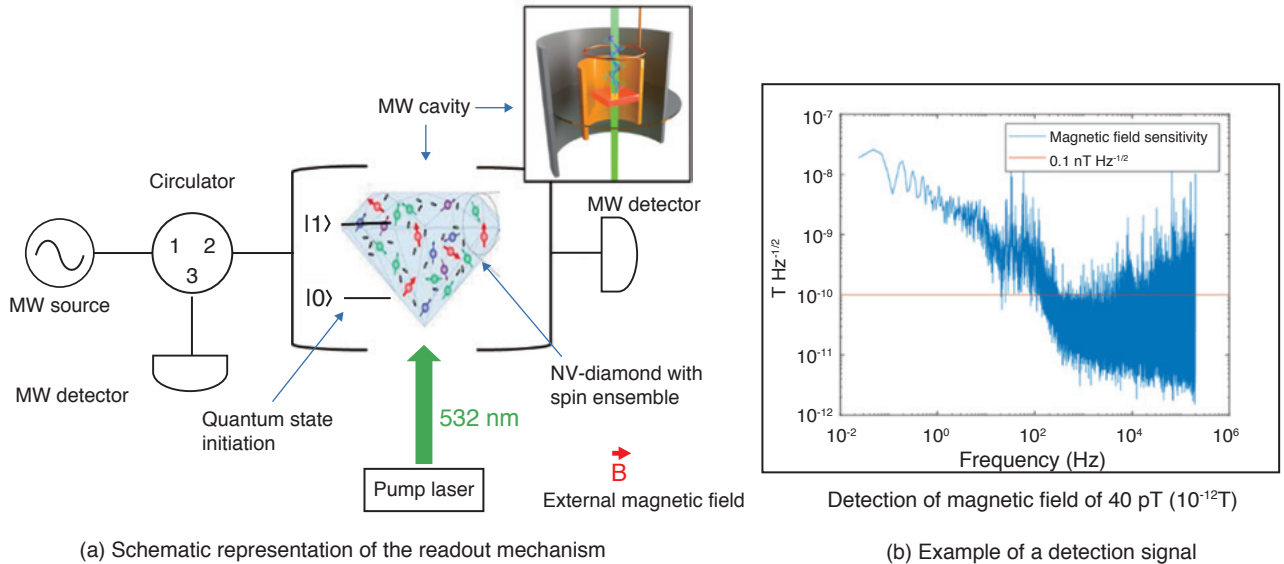


Fig. 6 Schematic representation of the cavity-enhanced microwave readout mechanism and example for a detection signal of an external magnetic field down to very small fields ( $40 \cdot 10^{-12} \text{ T/Hz}^{-1/2}$ )

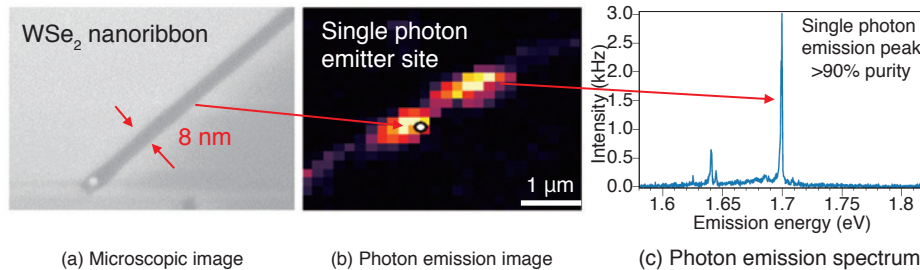


Fig. 7 Single photon emission from WSe<sub>2</sub> based nanoribbon as a single photon source for quantum communication

(b) shows the photo-emission optical image across the nanoribbon. Panel (c) shows the spectral resolution and intensity of the single-photon of the emitter source with higher than 90% single photon purity. These results show great potential to develop a new type of single photon emitter as light sources for quantum communications as well as other quantum applications.

## 5. Conclusion

Quantum information technologies have undergone rapid development in recent years. Many foundational breakthroughs have been realized and the public interest that has been generated is immense. As a result, overly enthusiastic and sometimes questionable predictions have been made. Nevertheless, there is a well-founded need for industry to increase awareness and expertise in this potentially disruptive field of research with its many observations and effects that are counterintuitive to our experience in the macroscopic world. Quantum information technologies encompass a variety of directions (computing, sensing, communication, simulation) and all of them have different states of readiness and different domains of applications. It is safe to say that all fields still face serious technological challenges while it is equally safe to say that all have realistic application scenarios in the short to midterm future. These application scenarios, some of which we have researched at the Honda Research Institutes and described above, are unlikely to demonstrate the full disruptive potential of quantum information technology. It also seems more beneficial, realistic, and impactful to demonstrate some solid and reproducible limited advantage of the first generation of quantum information technology than to expect the disruptive potential to be suddenly unleashed. Nevertheless, the potential for disruption in the long-term should also not be underestimated and nobody can say to date whether long-term will be 10 or 30 years. In a nutshell, we would summarize the current state of quantum information technology in the following statement: *the risk of not doing it simply outweighs the risk of doing it*.

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#### ■ Author ■



Sebastian SCHMITT



Avetik HARUTYUNYAN



Bernhard SENDHOFF

# Development of Three-wheel Electric Vehicle Series for Expanding Application to Delivery Business

Hideaki NAKAGAWA<sup>1</sup>

## ABSTRACT

Honda has recently developed three-wheel electric scooters for commercial use to reduce CO<sub>2</sub> emissions from the transportation sector and to respond to the growing demands for motor vehicles for delivery services. In the conventional three-wheel scooter series using a gasoline engine, there has been two types of cargo carriers; the one having the carrier as an integral part of the main vehicle body that tilts when the scooter leans and another one having the carrier on a non-tilting carriage in the rear. In our attempts to electrify both types of three-wheel scooter, we suggested an idea of making the electric powertrain common to keep the production cost low. Accordingly developed is the high-efficiency powertrain that enhances driving performance while making the vehicle more user friendly. The increased number of gears in the drivetrain coupled with the need for a differential gear for the two rear wheels also increases the backlash (free play), which causes issues such as vibrations and hammering noises. To deal with these issues, the electric power controller is programmed to apply a light torque to the drivetrain to take up the free play when the throttle is fully closed. Thus developed is the quiet, low vibration, and powerful electric three-wheelers appropriate for delivery services.

## 1. Introduction

The reduction of CO<sub>2</sub> emissions has been a worldwide issue to tackle for quite a while to slow global warming. As a means to deal with the issue, the electrification of motor vehicles is taking place rapidly. In the motorcycle sector of Honda, electric scooters were introduced in the market several times since 1994. After the repeated experimental practices toward popularization of electric scooters for commercial use since 2010<sup>(1), (2)</sup>, the BENLY e: was introduced into the market in 2020<sup>(3)</sup>. The introduction of BENLY e: is an indication of possible CO<sub>2</sub> reduction from the transportation sector. A spread of electric scooters is starting mainly in the post offices for mail delivery. That in mind, in our attempts to further expand the electric scooter line up, we focused our attention on the three-wheelers that have a high demand for commercial use.

Due to an increase of demand for home delivery and catering from the “stay home” campaign to deal with Covid issues, the sales are increasing in utility motorcycles and scooters, especially the three-wheelers (Fig. 1). However, when applying an electric powertrain to three-wheelers, there were issues such as a higher production cost due to an increase of the number of parts and the vehicle weight and a lower electric power efficiency than in the two-wheel

counterpart. To clear up the said issues and respond to the demands, we have recently developed the utility three-wheelers; GYRO e: and GYRO CANOPY e: which are more user-friendly than ever due to the application of the electric powertrain (Fig. 2). Described in this paper are how the utility three-wheelers are used and how the scooters have evolved from the gasoline engine type to the electric type from technical perspectives.

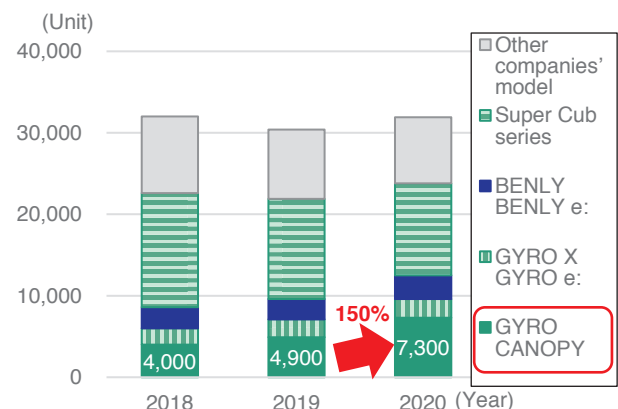


Fig. 1 Sales results of moped type 1 business category

<sup>1</sup> Honda Motor Co., Ltd.

E-mail: hideaki\_nakagawa@jp.honda



Fig. 2 Honda e: business-use electric scooter series

## 2. Current Status and Issues in Delivery Business

Upon the application of electric powertrain to the utility three-wheelers, we focused our attention on the cargo capacity, which is critical in the delivery business, and the impacts to the surroundings at the time of delivery.

### 2.1. Characteristics of Conventional Three-wheel Scooter Series

Regarding the already existing Honda GYRO series three-wheelers using a 50 cc gasoline engine, the basic model GYRO X was first introduced in 1982, and the variations GYRO UP and GYRO CANOPY were added later on. The characteristics of GYRO series is the Neidhart rubber coupling<sup>(4)</sup> that connects the single-wheel front unit to the two-wheel rear unit. The front unit carrying the rider leans like a motorcycle when turning. On the other hand, the rear unit does not tilt and maintains both tires perpendicular to the road surface.

Depending on whether the cargo carrier is located on the front unit or the rear unit, the loading capacity and/or the direction of force on the cargo change. The basic model GYRO X and the GYRO CANOPY equipped with the large windscreen and the roof have a cargo carrier that tilts along with the vehicle body when turning. In this design, the cargo is less affected by vibrations and centrifugal force when running. Meanwhile in the GYRO UP, whose production was terminated in 2008, the large and low-floor cargo carrier parallel to the ground was located on the two rear wheels, which made this model suitable for transportation of large and/or heavy goods.

### 2.2. Types of Cargo on Current Three-wheelers

The cargos being delivered by the GYRO series can be roughly divided into the following two types according to the above-mentioned differences in cargo carrying characteristics.

Cargo (1): Bulky and heavy goods (beer case, box for tools and/or materials)

Cargo (2): Goods that should be kept from vibrations and/or centrifugal force (food, small appliance, etc.)

Figure 3 shows the share of various types of cargo on the three types of GYRO series models. The GYRO UP's large and low-floor cargo carrier parallel to the ground is suitable for the Cargo (1). On the other hand, the cargo carrier of GYRO X and GYRO CANOPY, which remains flat when stopping for loading or unloading and less affected by vibrations and centrifugal force when running, is appropriate for the Cargo (2). Moreover, the GYRO series allow locking of the rubber coupling by a single pulling of the lever when stopping to maintain stability of the cargo carrier. Due to this characteristics, the three-wheeler is much better when loading or unloading cargo than the two-wheeler. In consideration of a wide range of usability, the new electric three-wheeler was studied to be able to handle the above two types of cargo (1) and (2) when developing various types of new electric three-wheelers.

### 2.3. Consideration to the Surroundings and User Friendliness

As mentioned above, the commercial users of scooters are increasing due to the increase of demand for delivery services. To deal with demands of delivery at a specified time typical in food delivery, the scooter sometimes has to be operated in quiet hours such as early morning and/or late night. However, in the case of the three-wheeler powered by a 50 cc gasoline engine, which falls in the Class 1 motorized bicycle category in Japan, the noise is an issue especially at higher engine speeds when starting a loaded scooter. It has been clarified from the user interviews that the night-time delivery is voluntarily restricted in some regions to keep quiet for the residents. A quiet electric three-wheeler is a solution for the issues the delivery motorbike users have. On the other hand, there remains issues such as an increase of weight from carrying of large batteries as well

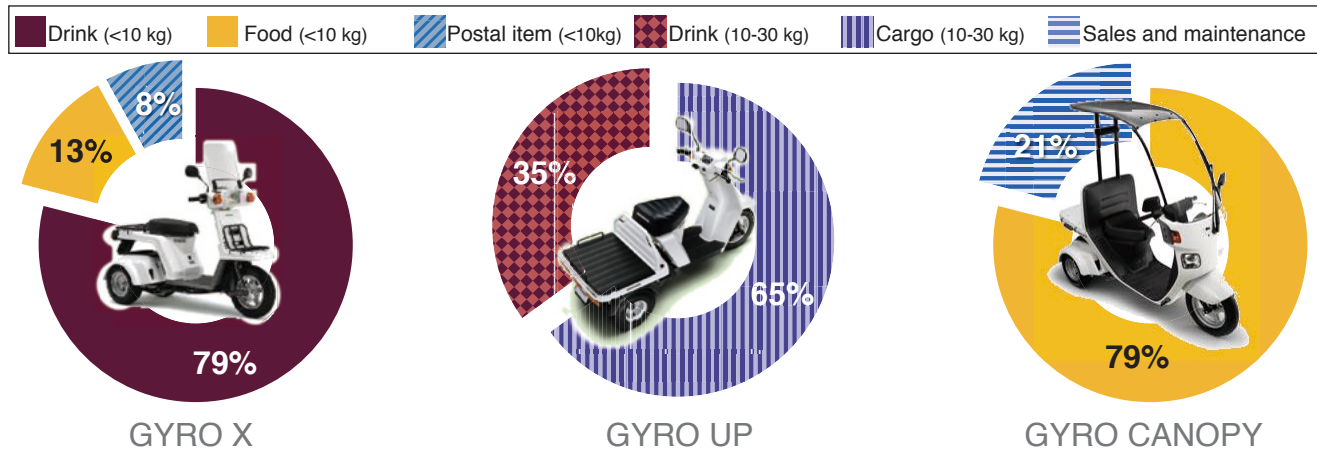


Fig. 3 Load composition ratio based on GYRO series owner survey conducted by Honda in 2018-2019

as in user-friendliness. The user-friendliness is crucial in the utility three-wheelers which are used by a wide variety of users such as part-timers who have only the regular automobile driver's license (which allows operating of 50 cc motorbikes in Japan). To live up to the expectations of the above-mentioned users, we set goals at an enhancement of driving performance and quietness as well as at a higher level of user friendliness by application of an electric powertrain.

### 3. Configuration of Electric Scooters for Delivery Services

Described in this chapter are the configuration of the scooters to deal with the earlier-mentioned manners of cargo carrying and the key points of advancement from the gasoline engine scooters.

#### 3.1. Configuration of Scooter for Two Types of Cargo Carrying

As mentioned in the preceding chapter, the requirement differs depending on the manner of cargo carrying roughly classified into the types (1) and (2). To meet the requirement, two different configurations are necessary just like in the conventional models. Figure 4 shows the direction of force from the cargo in each type of configuration. For delivery of bulky and heavy goods (1), the non-tilting, low-floor cargo carrier is appropriate because the weight of cargo affects the rider less. For goods (2) that should be kept from vibrations and/or centrifugal force, e.g., for purposes such as food delivery, the tilting cargo carrier is appropriate because the cargo is free of side force and subjected only to the downward force when turning.

Keeping in mind the above mentioned, we chose to employ two different cargo carrier configurations while using a common electric powertrain for both GYRO e: and GYRO CANOPY e:. Figure 5 shows the common

powertrain and two types of cargo carrier. The electric powertrain is basically designed for GYRO UP having a large, low-floor cargo carrier in which the hurdles are higher such as the limited space and a higher strength requirement. Regarding the integrated motor, the same one as used in the two-wheeler BENLY e:I is employed. With those measures taken, the electric three-wheeler series have become a reality to respond to the various needs of cargo carrying while keeping the production cost at a low level.

#### 3.2. Key Characteristics of Electrification of Powertrain

Bearing in mind the issues and requirements mentioned in the Chapter 2, the following two goals were set in this electrification project.

- Goal 1: To help ensure user-friendliness for various types of users, the new models have to be easier to handle than the gasoline-engine three-wheelers.
- Goal 2: Taking advantage of the torque characteristics of the electric motor, the driving performance should be enhanced.

Regarding the battery for driving of the scooter, the same quick changing system as in the BENLY e: called Honda Mobile Power Pack e: is employed<sup>(5)</sup>. This quick-change system allows extension of operating hours, which is a key requirement of commercial users. In the newly developed models, two units of Honda Mobile Power Pack

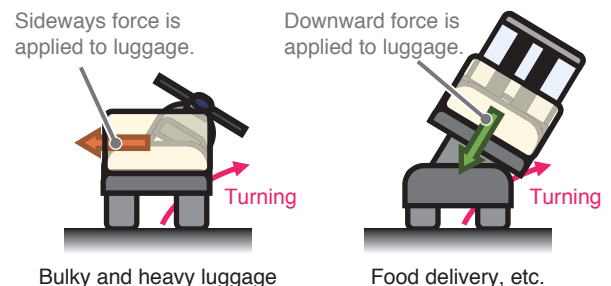


Fig. 4 Direction of force to cargo when turning

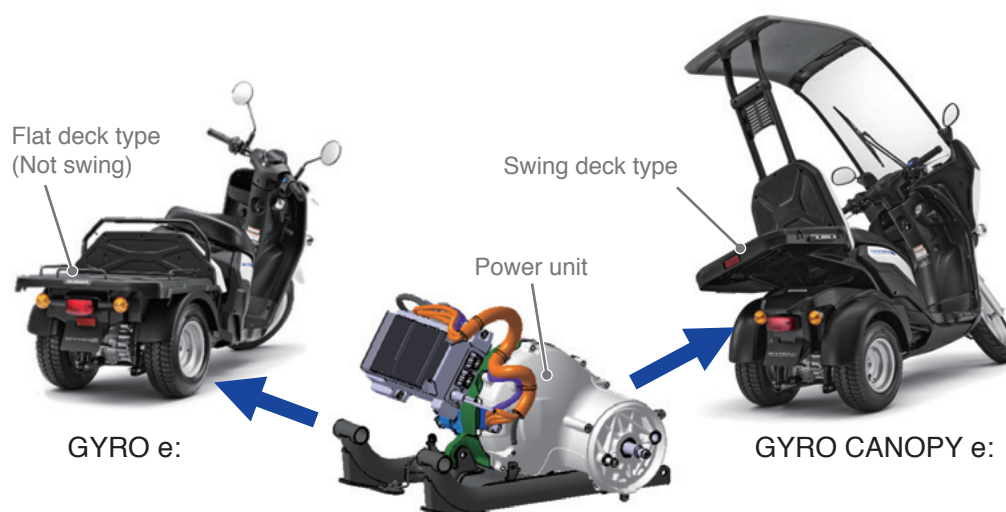


Fig. 5 Integrated power unit and each deck structure

e:, which weigh 10 kg per unit, are used.

The goal 1 “easy to handle” means easy man-handling of the vehicle. For easy handling, a low center of gravity (CG) of the vehicle is preferable because the lower the CG, the less the handling effort becomes if the handlebar height is the same. In the layout of electrical components, the one that large affects the CG height is the location of the batteries for the drive motor. To minimize effects of the batteries as heavy as approximately 20 kg to the handling, the battery packs are laid parallel in the proximity of vehicle’s CG under the seat just like in the BENLY e: (Fig. 6).

Also, for easier handling than the gasoline-engine model, the reverse assist that can be actuated from the button is equipped applying the control system derived from the BENLY e:<sup>(3)</sup>.

The goal 2 “enhancement of driving performance” is also a key requirement for enhancement of handling

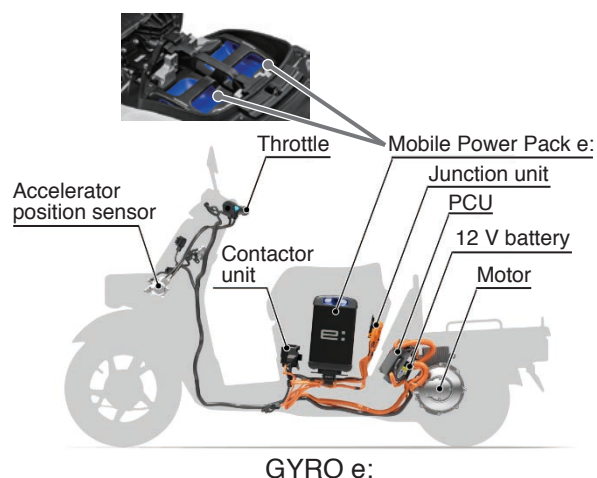


Fig. 6 Parts position of EV system

characteristics when carrying cargo. The details of enhancement of driving performance are discussed in the following chapter.

## 4. Measures to Deal with Technical Issues in Electrification

### 4.1. Higher Efficiency Electric Powertrain for Three-wheeler

Described hereafter are the measures to enhance the driving performance mentioned in the Goal 2, Section 3.2. As the maximum power output on the motor shaft is regulated for each vehicle category by the Road Transport Vehicle Act in Japan, it is necessary to enhance the efficiency of power transmission to the rear wheel to increase the power output on the rear wheel axle. Figure 7 shows the difference of transmission efficiency between

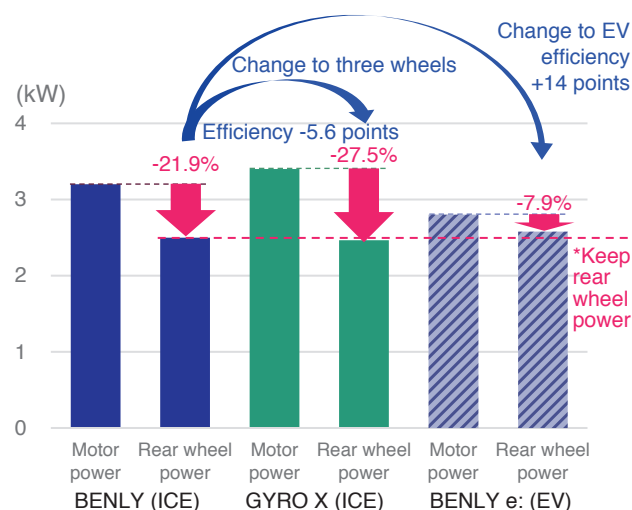


Fig. 7 Transmission efficiency by each model

the utility two-wheeler and three-wheeler using a gasoline engine along with the transmission efficiency of the utility electric two-wheeler. When the two-wheeler BENLY and the three-wheeler GYRO X both using a gasoline engine are compared, the transmission efficiency is lower by 5.6 points in the GYRO X having two driving wheels in the rear. On the other hand, when the two-wheeler BENLY using a gasoline engine is compared to the electrified version BENLY e:, the transmission efficiency is higher by 14 points in the electric version due to the unnecessary of the clutch and the use of gears instead of the belt-driven CVT. This realizes the same level of power output on the rear axle as the gasoline engine from the electric motor having a smaller power output on the motor shaft.

We have therefore employed the clutch-less gear drive transmission also in the three-wheeler to achieve a higher transmission efficiency than the gasoline engine three-wheeler. Regarding the differential gear important for a vehicle having two drive wheels in the rear, the component proven in the gasoline engine three-wheeler is employed as it is. Figure 8 shows the electric powertrain in which the clutch-less gear drive system developed in the electric two-wheeler is coupled with the components developed in the gasoline engine scooter. While the transmission efficiency lowers by 5.6 points due to the increase of the number of

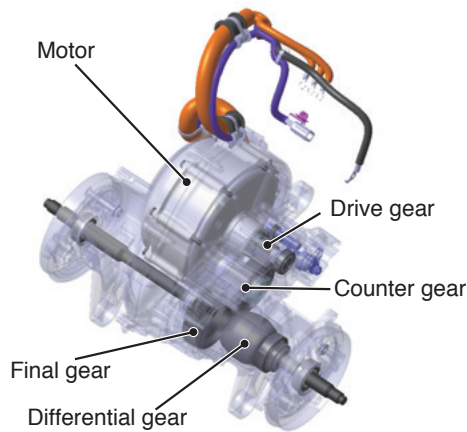


Fig. 8 Power unit for GYRO e:

drive wheels when the gasoline engine three-wheeler is compared to the two-wheeler counterpart, the lowering of transmission efficiency is as small as 2.0 points in the same comparison of electric models, resulting in an enhancement of transmission efficiency by 3.6 points in the electric three-wheeler (Fig. 9). With this higher efficiency transmission system employed, we have achieved 16% higher power output on the rear axle from the motor having the same motor shaft power output as the gasoline engine.

#### 4.2. Considerations for Surroundings; Reduction of Noises and Vibrations

In the process of product development, the vibrations and the hammering noises were noticeable when accelerating and decelerating. These issues are due to the increase of total backlash resulting from the increased number of gears in the drivetrain from the motor shaft up to the rear wheel axle including the differential gear, which is non-existent in the two-wheeler. This phenomenon may occur when the force is applied to the motor shaft at the moment the driving starts from the momentary absence of contact between the gears when accelerating and decelerating. The vibrations and hammering noises may occur when the drive shaft rotor moves in the direction of thrust force from the helical gear, on which an abrupt force is applied, and touches on the case (Fig. 10). Figure 11 shows the difference of backlash in

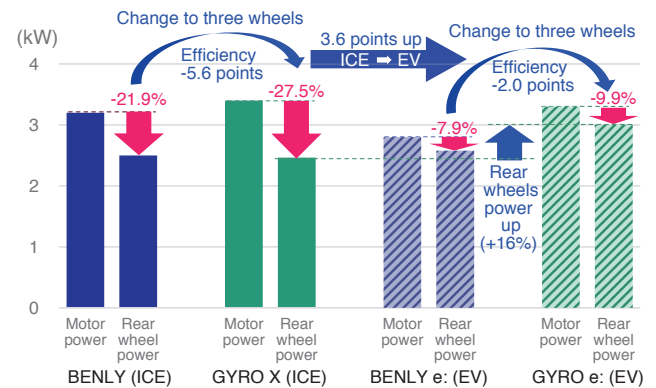


Fig. 9 Transmission efficiency by three wheels

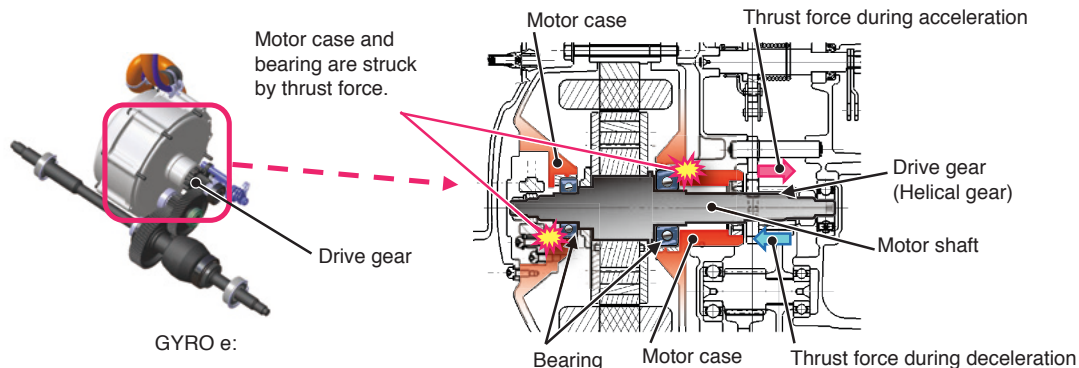


Fig. 10 Mechanism of hammering sound generation

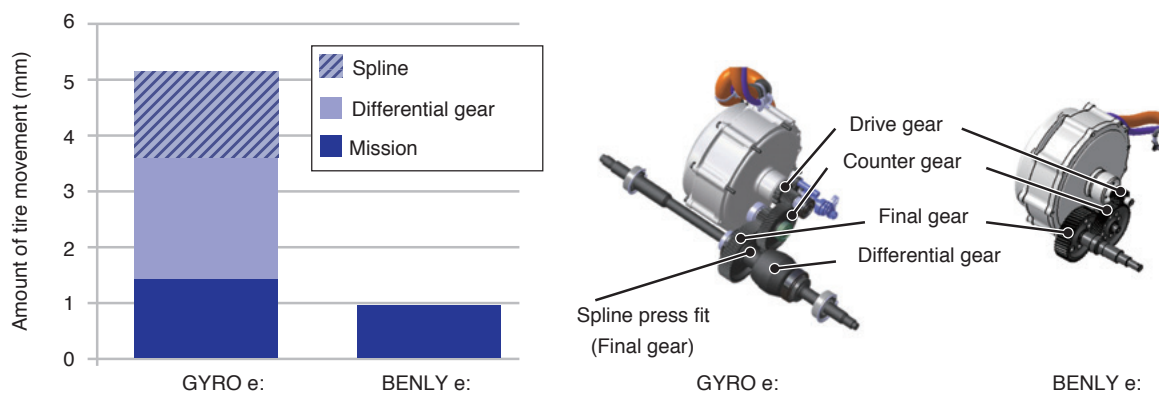


Fig. 11 Amount of backlash by each model

the electric two-wheeler and three-wheeler. In an attempt to control the hammering noises while maintaining the high-efficiency drivetrain as mentioned in the preceding clause, we suggested an idea of such a torque control that takes up the free play between gears. It is such a control in that a light torque is applied in the drivetrain to take up backlash even when the twist grip is fully turned off. Figure 12 shows the torque command of this control method. As shown, while the regenerative torque is applied when the twist grip is fully turned off in the two-wheeler, a light positive torque instead of a regenerative torque is applied only in the prescribed zone in the three-wheeler. The effect on the electric power consumption is minimized (5% more) by the minimization of torque to take up backlash and the optimum setting of the zone the torque is applied. Figure 13 shows the changes of

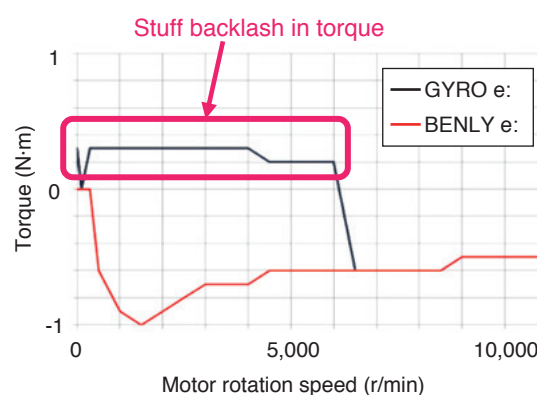


Fig. 12 Forward rotation torque command (Throttle closed)

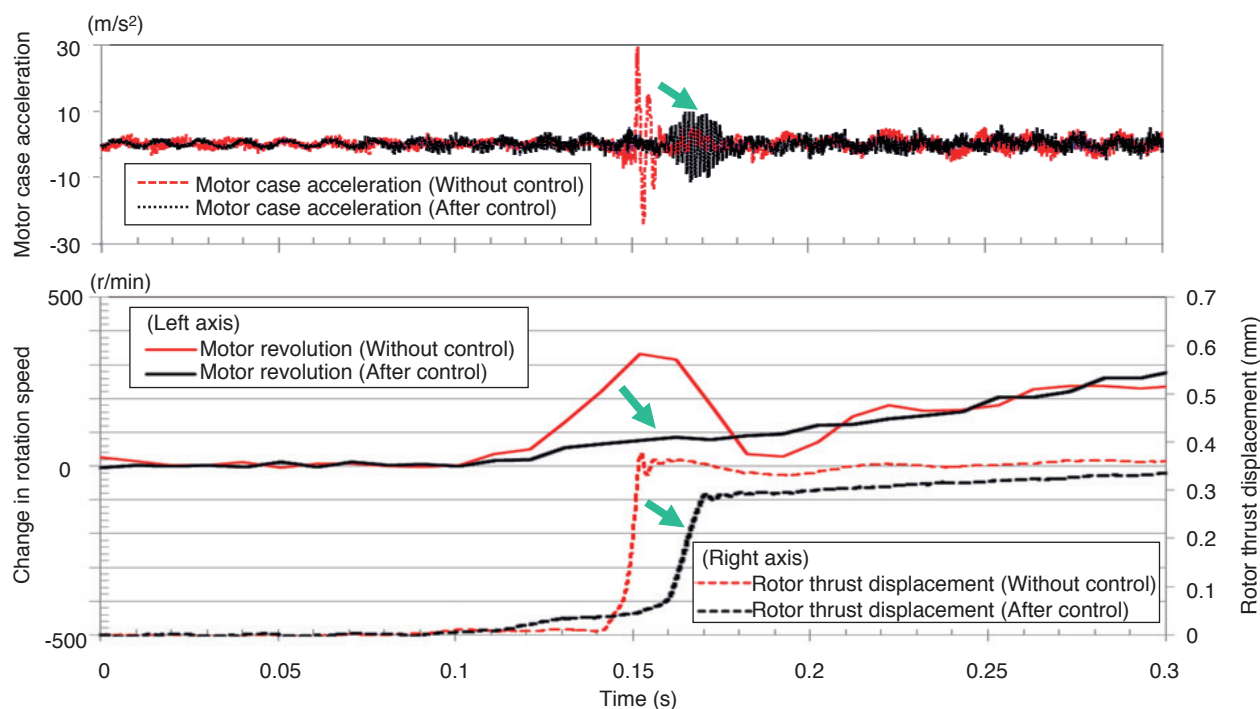


Fig. 13 Changes in conditions before and after countermeasures

characteristics from the backlash controller. Figure 14 shows noise reduction effects. As the graph in the middle of Fig. 13 shows, the addition of the torque to take up the free play between the gears help reduce abrupt changes of spinning speed and slows rotor displacement in the thrust direction as the lower graph in Fig. 13 shows. Thereby reduced vibrations and knocking noises when the rotor touches on the motor case are seen (in the upper graph of Fig. 13).

Realized by these technical measures is the more user-friendly electric utility three-wheeler featuring the quietness, lower vibrations, and the higher driving performance.

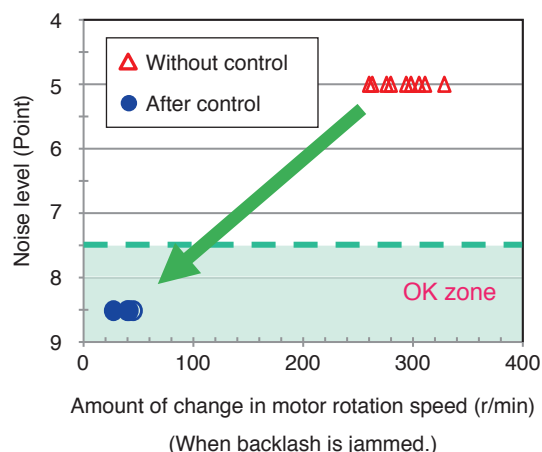


Fig. 14 Countermeasure effect in control

## 5. Conclusion

- (1) With the electric powertrain developed presuming application to the non-tilting cargo carrier having higher hurdles, the two types of three-wheelers have been developed to meet various demands of cargo carrying while using a common electric powertrain.
- (2) Applying the same battery mounting system as BENLY e: which allows locating of the batteries, which affects largely to the CG height, at a low part of the vehicle, and incorporating the reverse assist, the electric three-wheelers featuring easier handling than the gasoline engine three-wheeler have been realized.
- (3) By the change from the belt-driven CVT to the clutchless gear drive along with the newly developed torque controller to take up free play to control vibrations and knocking noises, the driving performance higher than the gasoline engine three-wheeler has been achieved while keeping the noises and vibrations at a low level.

The sales of GYRO e: for corporate users started from March 2021 and GYRO CANOPY e: from October 2021. The users who have actually used it perceive advancement and comment positively. The utility electric scooters such as the BENLY e: offered to the market from January 2020 are

seen more frequently now. We would like to hear customers saying “I bought a good scooter. It turned out electric.” especially in these days the electrification is drawing attention. We anticipate these electric three-wheelers serving as a pioneer.

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## ■ Author ■



Hideaki NAKAGAWA

# Method of Magnetizing Rotor with Wide Air Gap Using Magnetic Circuit that Concentrates Magnetic Flux

Toshitaka KATO<sup>1</sup>Shinji NEMOTO<sup>1</sup>Tokio TAIRA<sup>1</sup>

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## ABSTRACT

A post-assembly magnetization method was developed to increase magnetic field strength by concentrating magnetic flux in the pulse-type magnetization of small-diameter multipole high-speed rotors with wide air gaps. By concentrating the magnetic flux generated by two sets of magnetizing coils located on the outer periphery of the rotor, a Y-shaped magnetic circuit that passes through one set of magnetizing coils can be created that applies a high magnetic field locally. Magnetizing coils were placed at locations  $\pm 135^\circ$  from the one set of magnetizing coils through which the concentrated magnetic flux passes. This magnetizing coil arrangement can form a large magnetic circuit that passes around the inner periphery of the rotor. The magnetic flux that is not concentrated by this magnetic circuit flows in the direction opposite to the magnetization of the magnet. Therefore, the similar placement of auxiliary coils at the  $\pm 67.5^\circ$  locations suppressed the magnetic flux that leaked from the magnetic circuit. This technology created a high magnetic field in a rotor with a wide air gap and realized the target magnetization ratio of 99.0% or higher in single magnets.

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## 1. Introduction

Environmental awareness on a global scale is bringing increasing calls for the reduction of CO<sub>2</sub> emissions from the operation of mobility devices and enhancement of fuel economy. As a result, the spread of electrification is tending to accelerate in all fields of mobility. To achieve more widespread electrification, motors that are more compact or that have more poles for higher torque are being installed in various types of mobility devices. Motors are also appearing that achieve higher speeds in order to realize high power with a small diameter. These include Surface Permanent Magnetic (SPM)-type motors that have permanent magnets affixed to the rotor surface in a Halbach array<sup>(1)</sup>. In these motors, the rotor periphery is made of resin material parts in order to keep the centrifugal force at high speeds<sup>(2)</sup>. For that reason, the air gap between the stator and rotor is 8 to 12 times wider than in conventional motors. The method of generating pulse magnetic fields by using a jig called a magnetizing yoke is extensively employed as a method for post-assembly magnetization of permanent magnets built into the rotor. Magnetizing yokes are fabricated with specially designed coil arrangements to generate magnetizing fields in the magnet arrangement of the target rotor<sup>(3)</sup>. The closer the air gap between the magnetizing yoke and the rotor, the more efficiently magnetization can be carried out. This means that greater

energy is needed to magnetize rotors with wide air gaps, such as high-speed SPM rotors, than for conventional rotors. In order to strengthen the pulse magnetic fields to be applied, it is necessary to establish production conditions with increased electrostatic energy. However, increasing the device capability to provide adequate electrostatic energy calls for increased investment in production equipment, and results in decreased productivity for various reasons such as increased heat generation of the magnetizing coil due to higher current values, and lower coil insulation durability and coil deformation due to electromagnetic force. As an approach to reducing electrostatic energy, methods of partially magnetizing the permanent magnets assembled on the rotors are also known<sup>(4), (5)</sup>. However, when partial magnetization is performed on a small-diameter, multipole SPM rotor, the magnets next to the magnetization targets are magnetized in the opposite direction. It is no simple matter to establish post-assembly magnetization methods that maintain electrostatic energy levels for rotors with wide air gaps using conventional magnetization methods. Conventionally, increasing magnetic field strength under conditions of the same or lower electrostatic energy was an issue. In order to address this issue, it is necessary to efficiently apply the effective magnetization components of the magnetic field generated from the coils to the permanent magnets. The coil arrangement is of great importance in achieving this. In addition, if the magnetic field strength

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<sup>1</sup> Corporate Development Center

E-mail: toshitaka\_kato@jp.honda

can be increased by the coil arrangement alone, there will be no great impact on production equipment and other such facilities, enabling minimizing of the impact on production of new products.

With a conventional coil arrangement that applies a magnetic field from the outer periphery of a rotor, the magnetic field strength is limited. Attention was therefore focused on a coil arrangement that also considers the magnetic paths including the rotor interior. A coil arrangement that enables concentration of the magnetic field and suppresses the demagnetizing field paths was investigated, a magnetizing yoke was fabricated, and the permanent magnet magnetization ratio was evaluated.

This paper introduces a technology that combines a magnetizing coil arrangement that realizes a high magnetic field in pulse-type magnetization together with an auxiliary coil arrangement that suppresses the demagnetizing fields occurring in partial magnetization.

## 2. Magnetization Principles and Issues

### 2.1. Post-assembly Magnetization Method

Post-assembly magnetization is a manufacturing method that uses a device called a magnetizing yoke to magnetize materials that become magnets during rotor production. Dedicated magnetizing yokes are designed according to the number of poles and the diameter of the rotor. When fabricating anisotropic magnets, since the direction of magnetization is determined by applying a magnetic field, the degree of magnetization is determined by the magnetization direction and strength on the magnet through which magnetic flux from the magnetizing coil passes<sup>(6)</sup>.

As an example, Fig. 1 shows the composition of a magnetizing yoke for use on an eight-pole rotor. The numbers of rotor poles and magnetizing coils are the same, and the coils are firmly fixed in place with resin. In consideration of productivity, the magnetizing yoke and rotor have an air gap of about 0.25 to 0.3 mm. The design elements for magnetization are the wire diameter, number of turns, and coil arrangement of the magnetizing coils. The magnetization conditions include the source voltage, which is electrostatic energy, and the electrostatic capacity. An

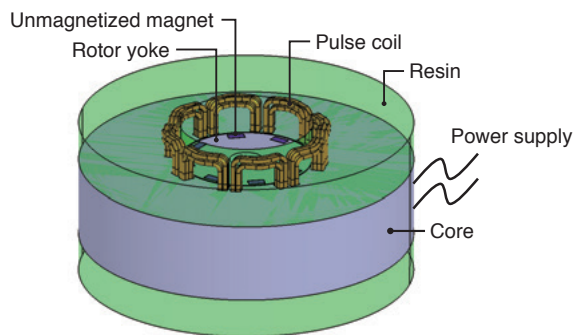


Fig. 1 Composition of magnetizing yoke

appropriate magnetizing yoke is designed according to the rotor specifications.

### 2.2. Principles of Magnetization

Magnetization is carried out by a magnetic field generated from a magnetizing coil when a high current is momentarily passed through the coil. At this time, the magnetic field  $H$  is as shown in Eq. (1), where  $I$  is the magnitude of the current and  $r$  is the distance from the magnetic field source.

$$H = \frac{I}{2\pi r} \quad (1)$$

Consequently, when the magnetizing coil and the target magnet are close together in the magnetization field, a strong magnetic field is applied.

### 2.3. Magnetization Target

Figure 2 shows the composition and magnetization direction of the target SPM Halbach array rotor. The target rotor has an outermost diameter of 67 mm, a cumulative thickness of 33 mm, and uses Nd-Fe-B-based sintered magnets as the magnet material. Since the design assumes a high rotation speed in order to achieve the target output, and a resin ring is mounted to help prevent magnet scattering due to centrifugal force.

Figure 3 shows the magnetization characteristics. A

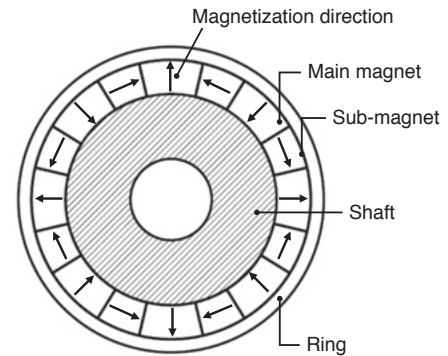


Fig. 2 Small-diameter, multipole, and high-speed rotor

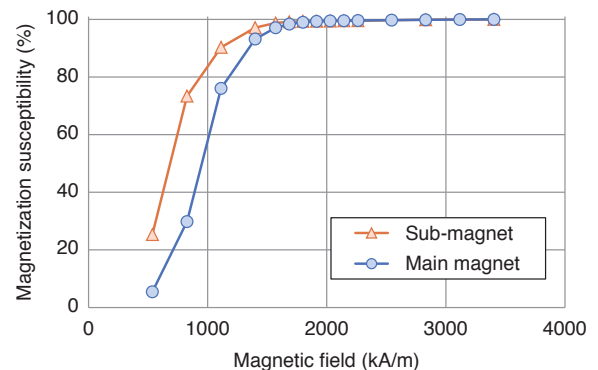


Fig. 3 Magnetization characteristics of magnets

magnetization ratio of 99.0% or more can be obtained by applying a magnetic field strength of 1800 kA/m or more in the main magnets and 1635 kA/m or more in the sub-magnets. Therefore, these values were used as the respective target magnetic field strength values in the single magnets.

#### 2.4. Issues in Magnetization of High-speed Rotors with Wide Air Gaps

The first issue is that mounting a resin ring on the outer periphery of the magnets to help prevent magnet scattering increases the distance between the magnetizing coil and the target magnet, which greatly reduces the magnetizing field. Figure 4 shows that magnetic field strength decreases according to the distance from the magnetic field source.

The second issue is that reducing the diameter of the target rotor narrows the magnetic circuit between the poles, and an adequate magnetizing field cannot be applied to the inner periphery of the magnets. This is because the spacing between the poles of the magnetizing coil becomes narrower and the magnetic circuit becomes smaller<sup>(7)</sup>.

#### 2.5. Initial Investigation by Magnetic Field Analysis

Figure 5 shows the model initially investigated using the electromagnetic field analysis software JMAG in magnetization of this rotor. The same number of magnetizing coils were arranged as the number of main magnet poles. This is the magnetizing coil arrangement used

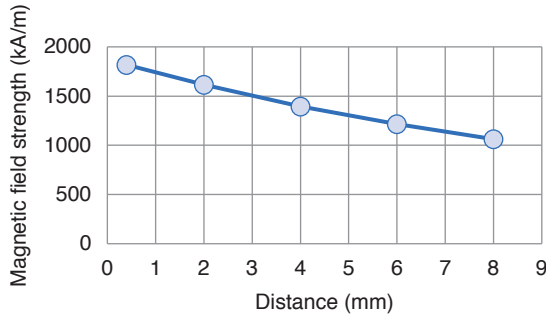


Fig. 4 Relationship between magnetic field and distance

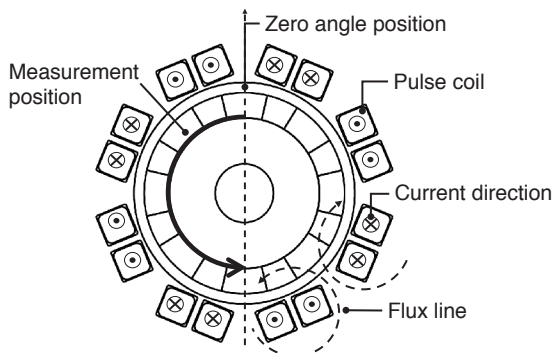


Fig. 5 Pulse coil position and measurement position

by the conventional post-assembly magnetization method. The conditions for magnetic field analysis were current of 12,000 A and nine coil turns.

Figure 6 shows the results of the magnetic field analysis of the initial investigation at the measurement positions (magnetic field strength at the innermost periphery of the magnets) in Fig. 5. The results show that the magnetic field strength is lowest at the center of the innermost periphery of the sub-magnets and does not reach the target value needed for magnetization.

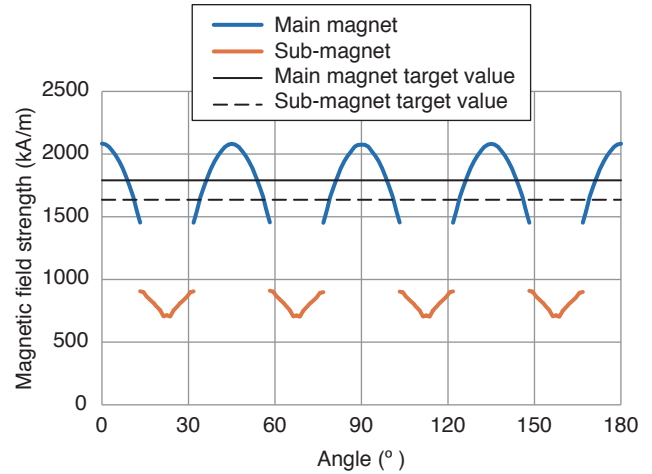


Fig. 6 Magnetic field on inner periphery of magnet

### 3. Magnetic Circuit of Magnetizing Field by Concentration of Magnetic Flux

#### 3.1. Magnetic Circuit Passing Through Rotor Inner Periphery

As the magnetic fields of the magnetizing coils need to efficiently apply the magnetic flux component that contributes to the magnetization direction of the magnets, the wire diameter, number of turns, arrangement, and other characteristics of the magnetizing coils were investigated. Figure 7 shows the models of magnetizing coil arrangements (coil spacing) and uses contour diagrams to express the distribution of magnetic flux density obtained by analyzing those models. The magnetic field strength can be seen to shift to the inner periphery side as the coil spacing widens. Figure 8 shows a graph of magnetic field strength for different spacings between the main magnet and sub-magnet magnetizing coils. The magnetic field strength was measured in the innermost periphery of the magnets. This graph also shows that, compared to the narrow coil spacing, the magnetic field strength with a wide coil spacing is approximately 1.5 times stronger at the main magnets and approximately 2.5 times stronger at the sub-magnets. In addition, the rotor magnetic poles alternate between N and S poles. For this reason, maximization of the spacing between the N-pole magnetization and S-pole magnetization

of the corresponding magnetizing coil was investigated. Figure 9 shows a diagram with the small magnetic circuits produced by adjacent magnetizing coils removed to expand the coil spacing up to the position of magnetizing coil B. The solid line indicates the predicted magnetic circuit for the expanded coil spacing, and the dashed lines indicate the flow of magnetic flux before removal of the magnetizing coils. The motor has periodicity, so a large magnetic circuit was proposed that passes around the inner periphery of the rotor where the magnetic flux from magnetizing coils B and C is concentrated, by similarly expanding the coil spacing up to the magnetizing coil C.

### 3.2. Analysis of Magnetic Field of Magnetic Circuit that Concentrates Magnetic Flux

Figure 10 shows the composition and magnetic circuit of the high magnetic field-magnetizing yoke. Magnetizing coils B and C were placed at locations  $\pm 135^\circ$  from magnetizing coil A. The magnetic flux generated from

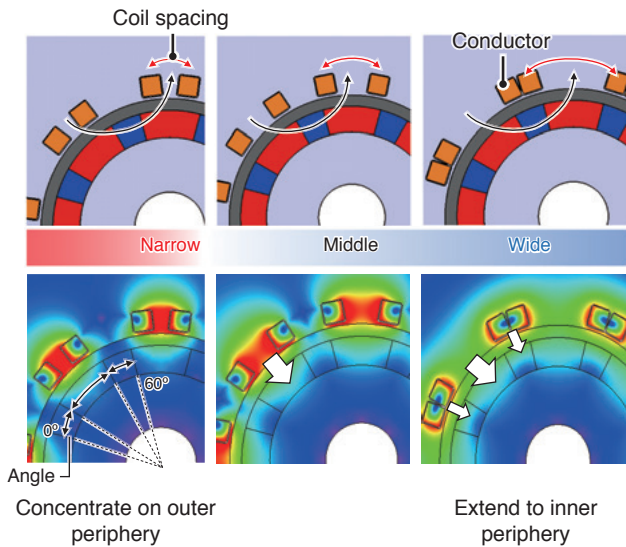


Fig. 7 Coil spacing and magnetic flux density

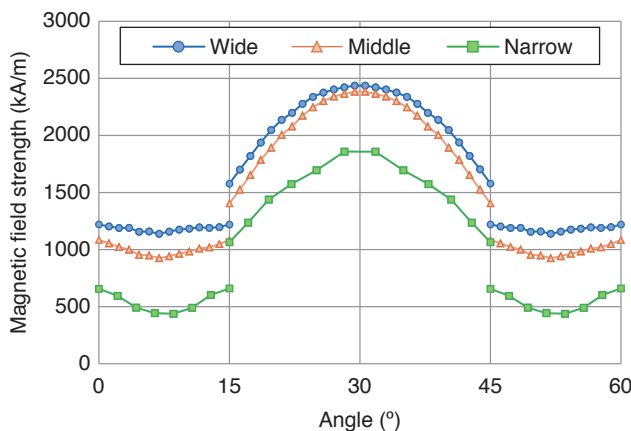


Fig. 8 Comparison of magnetic flux density of magnets

B and C is concentrated and flows to A, creating a large magnetic circuit that passes around the inner periphery of the rotor. Figure 11 shows the results of magnetic field analysis (due to model symmetry, these are the results for the half-circumference from 1 to 9). At the poles where the magnetic fields of 1 and 7 are strengthened, the magnetic field strength at the innermost periphery of the main

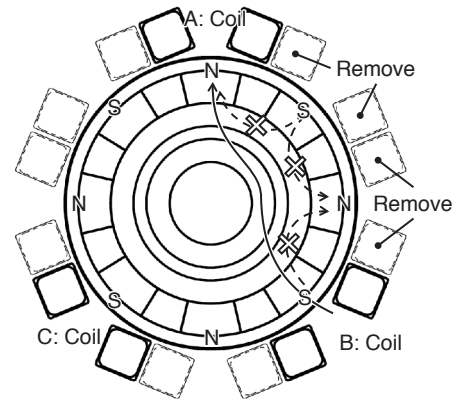


Fig. 9 Investigation of expansion of coil spacing

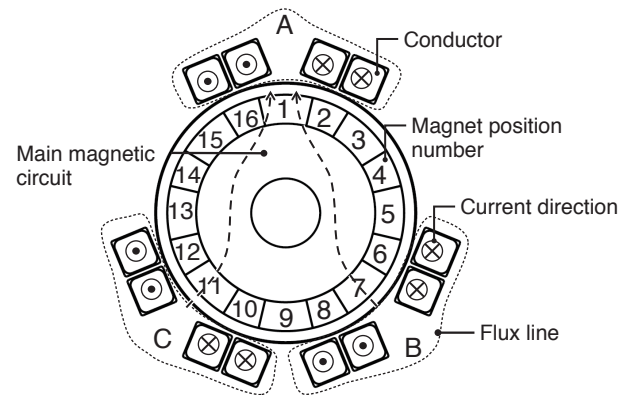


Fig. 10 Magnetic circuit

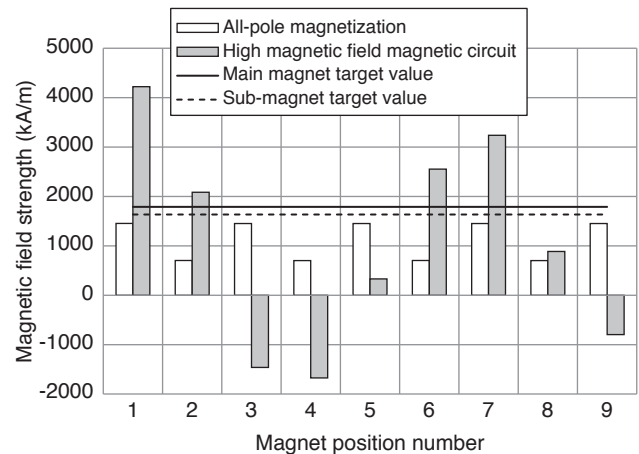


Fig. 11 Magnetic field analysis results

magnets was observed to increase by 290.42% at 1 and by 222.86% at 7. In addition, increases of 296.3% and 363.2% were confirmed at sub-magnets 2 and 6, respectively. These analysis results confirmed the ability to create a magnetic circuit that applies a high magnetic field locally by concentrating the magnetic flux.

### 3.3. Issue with Magnetic Circuit that Concentrates Magnetic Flux

The issue here is the magnetic flux that is not concentrated. In the magnetic field analysis results in Fig. 11, magnets 3 and 4 have negative magnetic field strength, indicating that they are magnetized in the reverse direction from the original magnetization direction. Figure 12 shows the distribution of the magnetic flux that is not concentrated. It is thought that, due to the magnetic circuit passing around the inner periphery of the rotor, magnetic flux occurred outside of the target magnetic circuit partway along the path. In addition, the magnetic permeability of the magnets is larger than that of the shaft, which indicates that magnetic flux passing through the magnets produced a demagnetizing field.

### 3.4. Use of Auxiliary Coils to Suppress Leakage Flux

A magnetic circuit with newly placed auxiliary coils was devised and analyzed with the goal of suppressing the magnetic flux generated outside the magnetic circuit. Figure 13 shows the model for suppression of leakage flux. Since the magnetic fields from the coils are formed concentrically, auxiliary coils D and E were respectively placed at locations  $\pm 67.5^\circ$  from A, which are the angles at which symmetrical magnetic fields are applied to the main magnets 3 and 5 and sub-magnet 4 when placed on its radial extension. The magnetic fields generated from the auxiliary coils suppress the magnetic flux in the reverse direction that deviates from the main magnetic circuit. In addition, this auxiliary coil placement applies magnetic fields in the correct direction to magnets 3, 4, and 5. Figure 14 shows the results of suppressing leakage flux with auxiliary coils. The magnetic fields of the auxiliary coils interfere with the main magnetic circuit, so the magnetic field strength decreases. The magnetic field strength after

countermeasures decreased to 70.66% for 1, 77.68% for 7, and 77.13% for 2. It was confirmed that the reverse magnetic field due to the magnetic flux that leaked to the outside of the magnetic circuit was enhanced by 78.44% for 3 and by 93.81% for 4.

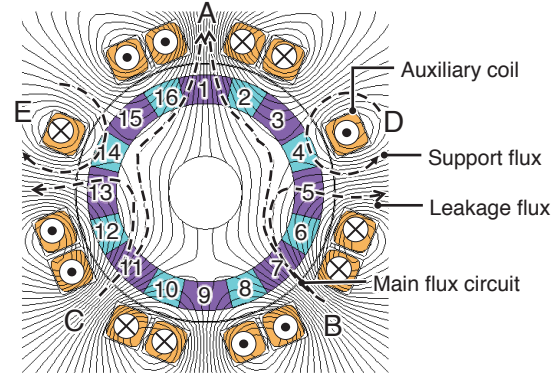


Fig. 13 Suppression of leakage flux

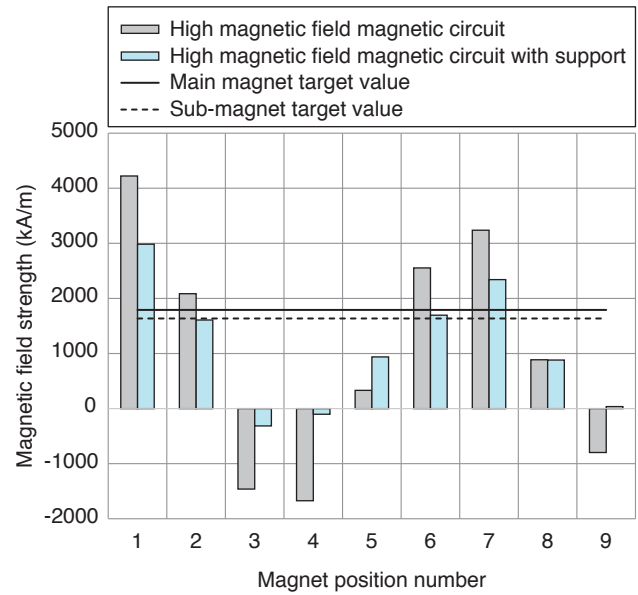


Fig. 14 Results of reverse magnetic field suppression

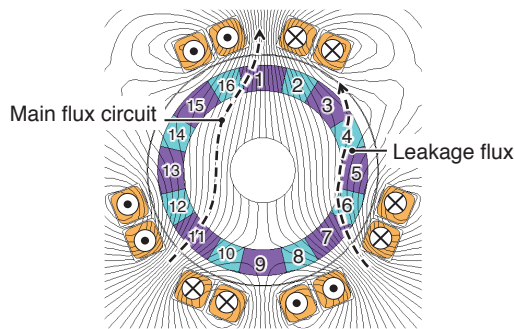


Fig. 12 Leakage flux analysis

## 4. Experimental Results

### 4.1. High Magnetic Field-Magnetizing Yoke

A magnetizing yoke with a high magnetic field-magnetic circuit was fabricated that enables post-assembly magnetization of rotors with wide air gaps. Figure 15 shows the developed high magnetic field-magnetizing yoke. The structure is divided into two sets of coils that concentrate the magnetic flux and one set of coils through which the concentrated magnetic flux passes, and the auxiliary coils are placed in the divided gap. The magnetic circuit is also indicated by the dotted lines.

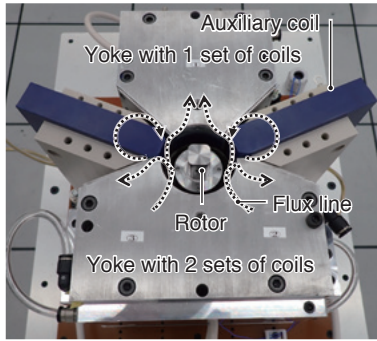


Fig. 15 High magnetic field magnetizing yoke

#### 4.2. Measurement of Magnetic Field Strength

The strength of the magnetic field generated from the magnetizing yoke was measured in order to set the magnetizing conditions. Measurement used a so-called search coil consisting of copper wire wound in multiple circular turns. The measurement component used a search coil (20 turns; compensation value:  $T = 142.9 \times 10^{-9}$ ) made by OP DENSHI KOGYO CO., LTD. The voltage induced by the magnetic flux passing through this search coil is obtained<sup>(8)</sup>. Figure 16 shows the method for acquiring the magnetic field and a photo of placement at the measurement point. The search coil is placed at the measurement point perpendicular to the magnetization direction of the magnet and acquires the magnetic field. Equation (2) shows the formula for calculating the magnetic field strength from the voltage.

$$H = T \times \int v dt \times \frac{4 \times \pi}{1000} \quad (2)$$

Magnetic field strength:  $H$  [kA/m] Voltage:  $v$  [V]

Figure 17 shows graphs of (a) the voltage waveform acquired by the search coil and (b) the magnetic field strength. The magnetic field strength was calculated from the acquired induced voltage waveform using Eq. (2).

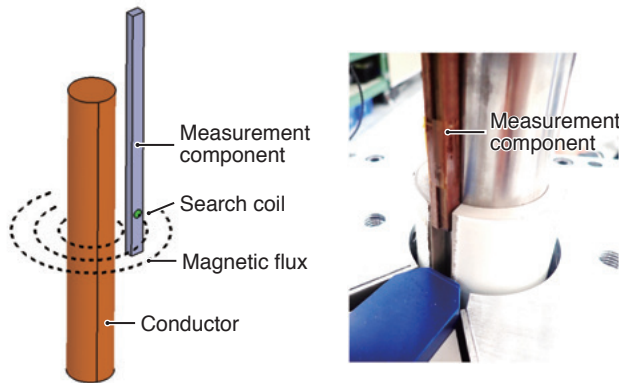


Fig. 16 Measurement method by search coil

Measurement was performed at the measurement points i (main magnet) and ii (sub-magnet) shown in Fig. 18, with the electrostatic capacitance set to 5000  $\mu$ F and the source voltage set to 1, 2, and 3 kV. In addition, for reasons of measurement device size, the voltage waveform cannot be acquired at the point with the lowest magnetic field strength in the innermost periphery of the magnets at measurement position ii. Therefore, the magnetic field strength in the innermost periphery of the magnets obtained by CAE was used as the magnetizing condition. Figure 19 compares the measurement results (average value of five measurement times) and the analysis results. In the main magnets, the difference between the measured and CAE values is 13.6% at 9 kA, whereas this difference is 0.89% in the sub-magnets. Compared to the measured magnetic field strength of the main magnets, the CAE results are lower. However, a magnetic field strength of 1800 kA/m or more is adequately achieved in the measurements, so focus was placed on the magnetic field strength of the sub-magnets. The difference between the measured and CAE

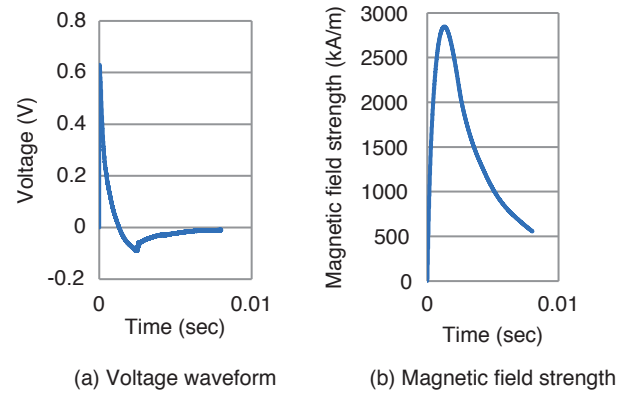


Fig. 17 Conversion of voltage to magnetic field strength

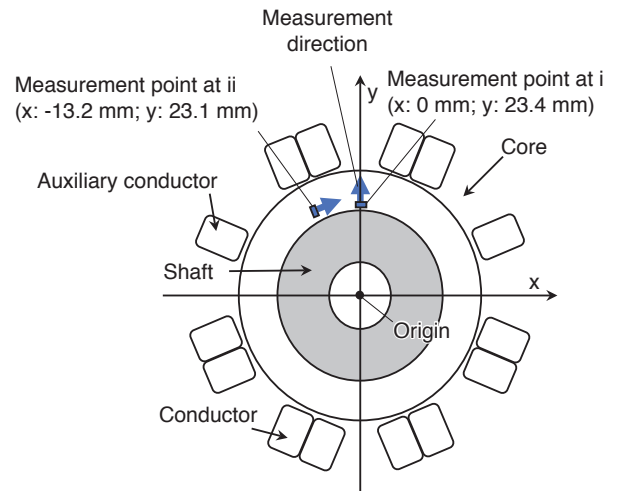


Fig. 18 Measurement points

values of the magnetic field strength of the sub-magnets is within 1%, indicating that the value of the magnetic field strength in the innermost periphery where it is the weakest can be accurately predicted. A magnetic field strength in the innermost periphery of the sub-magnets of 1635 kA/m or more can be obtained at 12,700 A, so this was set as a magnetizing condition.

#### 4.3. Evaluation of Magnetization Ratio

The target magnets used Nd-Fe-B-based sintered magnets (equivalent to N44Z-SGR made by Shin-Etsu Chemical Co., Ltd.) as the material. The total magnetic flux of the magnetized magnets was measured with a search coil. The total magnetic flux is used to assess the degree to which the magnet is magnetized. Figure 20 shows the measurement method. The magnet can be measured by integrating the voltage induced by the change in magnetic flux when the magnet is set in the center of a search coil with multiple turns and then pulled out in the direction of magnetization. The magnetized magnet is saturation magnetized by an air core coil (a device that uniformly generates a 4376 kA/m magnetic field in a  $\phi 100 \text{ mm} \times 100 \text{ mm}$  range). The magnetization ratio was calculated by comparing the magnetization level of the magnets magnetized in the experiment and the magnetization level

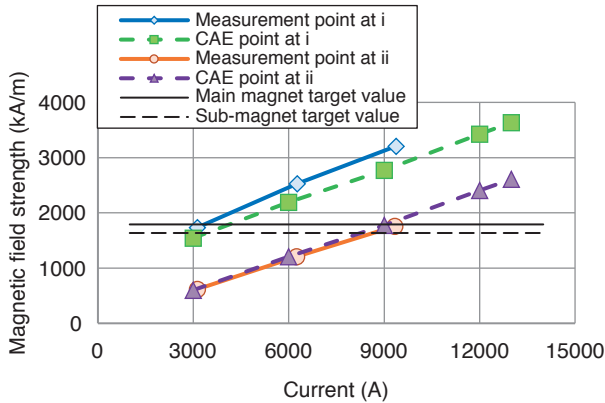


Fig. 19 Measured and analyzed magnetic field strength

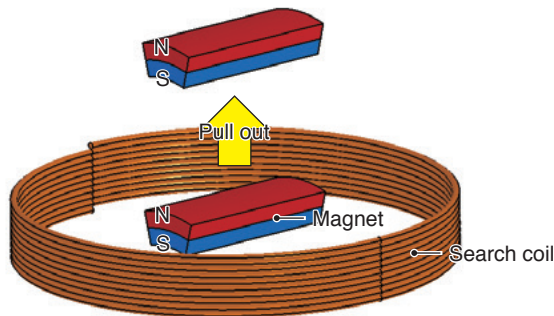


Fig. 20 Measurement of total magnetic flux

when saturation magnetized as shown in Eq. (3).

$$\text{Magnetization ratio} = \frac{\text{Magnetization level after magnetizing experiment}}{\text{Magnetization level after air core coil magnetization}} \times 100 [\%] \quad (3)$$

As the range in which the magnetic field can be strengthened by concentrating the magnetic flux is limited, the phase of the rotor is rotated three times and magnetization is performed a total of four times.

Figure 21 shows the rotor phase rotation procedure with the magnets that could be magnetized to 99.0% or more indicated by shading. All the magnets are magnetized by rotating the rotor so that the magnets can be placed in locations with an intense magnetic field in order of strength.

Figure 22 shows the magnet magnetization ratio results. It can be seen that the magnetization ratio increases when

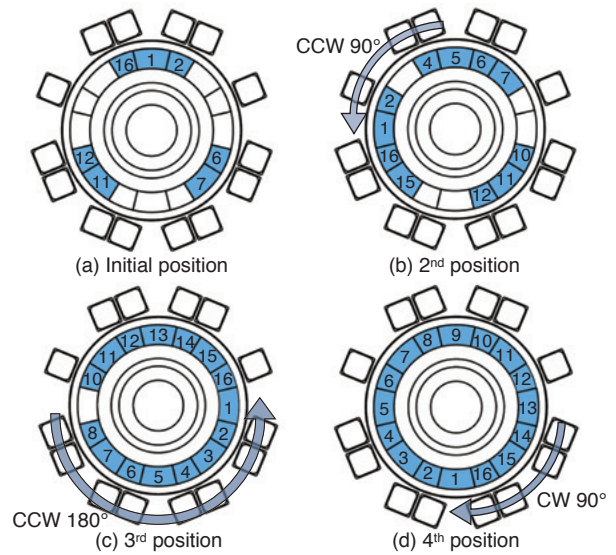


Fig. 21 Rotor phase rotation procedure

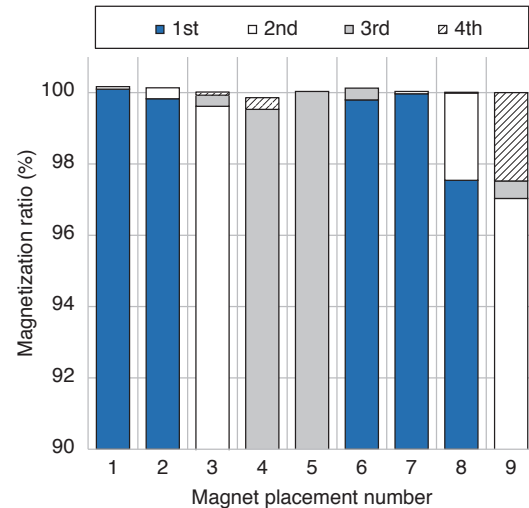


Fig. 22 Magnetization ratio measurement result of 99.0% or more

the magnets are placed in locations where a high magnetic field is locally applied. The target magnetization ratio value of 99.0% or more was achieved in all magnets.

## 5. Conclusion

A post-assembly magnetization method was developed that increases the magnetic field strength by concentrating the magnetic flux in pulse-type magnetization of small-diameter multipole high-speed rotors with wide air gaps.

- (1) By designing a magnetizing coil arrangement and concentrating the magnetic flux, high magnetic fields could be applied to specific locations.
- (2) Countermeasures were taken to address the issue that demagnetizing fields are produced by the magnetic flux that was not concentrated in the main magnetic circuit. The demagnetizing fields can be suppressed by placing auxiliary coils between the three sets of coils that comprise the main magnetic circuit.
- (3) By rotating the phase of the rotor three times, the high magnetic fields concentrated in specific locations could be applied to magnetize all the magnets.

As a result of the above, the target magnetization ratio of 99.0% or more was achieved.

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### ■ Author ■



Toshitaka KATO



Shinji NEMOTO



Tokio TAIRA

# Linkage System for Fleet Management and Building Energy Management Using EVs

Tatsuya IDE<sup>1</sup>

Kazumasa HONDA<sup>1</sup>

Senryu OH<sup>1</sup>

Yoshiya NAKAGAWA<sup>1</sup>

Takuya TANAKA<sup>1</sup>

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## ABSTRACT

This research targets the social implementation of a system that helps to reduce electric utility costs and CO<sub>2</sub> emissions with low investment by utilizing EVs as storage batteries and performing energy management that efficiently shares electricity between EVs and buildings. This paper introduces a fleet management system, an energy management system, and a battery sharing management system that links these two systems, and presents the effects to help reduce electric utility costs and CO<sub>2</sub> emissions as verified by a proving test.

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## 1. Introduction

At the 26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26), it was agreed to pursue efforts to limit the increase in global average temperature to 1.5°C above pre-industrial levels<sup>(1)</sup>.

The transportation sector accounted for 17.7% of Japan's CO<sub>2</sub> emissions in FY2020<sup>(2)</sup>. The introduction of electric vehicles (EVs) is a means of helping to reduce CO<sub>2</sub> emissions, but although EVs are equipped with large-capacity batteries compared to household storage batteries, the energy density is lower than that of gasoline, so in general the cruising distance tends to be shorter. Therefore, to perform at the same level as before while increasing the CO<sub>2</sub> emissions reduction effect, it is necessary to further enhance transport and delivery efficiency by measures such as high-precision estimates of energy needs for travel and route optimization.

In addition, interest in environment, social, and governance (ESG) in management is increasing and environmental management indexes are said to be directly connected to corporate value. RE100 is a global initiative in which companies aim to supply 100% of the electricity used in their businesses through renewable energy<sup>(3),(4)</sup>. Clean electricity can be generated by installing photovoltaics (PV), one type of renewable energy, on buildings. However, as

this is affected by the weather, management of the generated power is needed for more effective use. An example of this is introduction of PV, stationary storage batteries, and an energy management system (EMS). Storage batteries are expensive, however, so introduction of such batteries capable of storing the amount of electricity generated by PV incurs a large cost burden<sup>(5)</sup>. It was therefore thought that by using the batteries of EVs, there would be no need to purchase stationary storage batteries, which may reduce the introduction cost burden.

In order to use EVs both for transportation and as storage batteries for buildings, the challenge is not only to optimize operation routes, but also to optimize vehicle dispatch planning, including the power management of on-board batteries.

## 2. Development Goals

For some time Honda has been developing a Home Energy Management System (HEMS) that uses EVs<sup>(6)</sup>. HEMS realize the utilization of EVs as home storage batteries by predicting household electricity demand, PV power generation, and the periods during which the EV is at home.

In order to provide similar value as HEMS to businesses, differences in the base electric utility rate setting and the larger number of EVs used compared to ordinary

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<sup>1</sup> Innovative Research Excellence Power Unit & Energy

E-mail: tatsuya\_01\_ide@jp.honda

households make it necessary to address the complexity of managing the use of EVs with destinations that change on a daily basis. A new EMS using EVs based on the Honda-developed HEMS was therefore developed as shown in Fig. 1.

In the electric utility rate plan for businesses, the base rate is set according to peak power<sup>(7)</sup>, so the goal of this development is a system that minimizes peak power as shown on the left side of Fig. 1.

Next, regarding the increase in the number of EVs, it is necessary to consider the shorter cruising distance of EVs compared to gasoline vehicles and develop a fleet management system that matches the ways each business use EVs, as shown on the right side of Fig. 1.

Furthermore, when linking the EMS and fleet management system and using the EV batteries for peak power shaving, as the number of vehicles and the EV battery capacity are limited, there will be cases when EVs cannot be simultaneously used for both transportation and peak power shaving. To address this issue, it is necessary to develop a function to judge whether to prioritize EV use or peak power shaving as shown in the center of Fig. 1.

The above contents were organized, and the following three functions were developed.

- (1) A fleet management system that efficiently uses multiple EVs
- (2) An EMS with the purpose of helping reduce the base electric utility rate
- (3) A battery sharing management system that enables both the EMS and fleet management systems to work together in a time- and energy-efficient manner

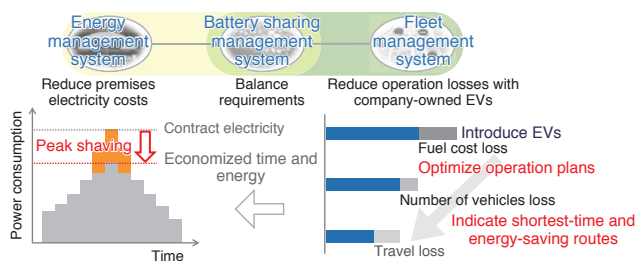


Fig. 1 System schematic and aim

### 3. Overview of Developed System

Figure 2 shows the function layout of the developed system. The flow from left to right in the figure when the three functions of this system operate is as follows: users enter the times that EVs will be used and the destinations the day prior to use; then the fleet management system calculates the optimal routes to the destinations and the electricity consumption needed to travel those routes.

In parallel, the EMS predicts the building's electricity

demand and PV power generation for the next day, and the purchased electricity prediction results are calculated by subtracting the predicted PV power generation from the building's predicted electricity demand. The battery sharing management system calculates the number of vehicles and the time needed for peak shaving from the building's purchased electricity prediction information predicted by the EMS and the building's target contract electricity. The plan arbitration function then allocates the vehicle plan for peak shaving, adjusts to achieve both use as transportation and use for peak shaving, and completes the creation of a dispatch plan.

On the day, when a user utilizes an EV as transportation, the route with the lowest energy consumption calculated by the fleet management system is displayed on the navigation system, as shown on the right side of Fig. 2. In addition, EVs secured for peak shaving use can help reduce peak power by having the EMS perform charge and discharge control. The details of the fleet management system, EMS, and battery sharing management system are explained in order below.

#### 3.1. Fleet Management System

The fleet management system has the two functions of predicting energy consumption for travel in use as transportation and managing vehicle reservations. Prediction of energy consumption for travel is explained here. Energy consumption prediction determines the route that uses the least energy and takes the shortest time in consideration of traffic and weather information to the destination and calculates the amount of energy needed.

To calculate the amount of energy needed for travel, a physical calculation model was constructed by dividing the model into four components: (a) vehicle-specific running resistance and power train efficiency; (b) a speed model created by linking with the navigation system information; (c) an auxiliary load prediction model; and (d) a regenerative model.

#### 3.2. EMS

The EMS is equipped with three functions: predicting the electricity a building will purchase, and controlling

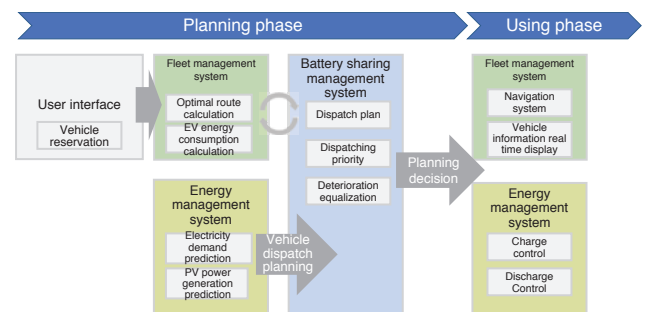


Fig. 2 System function layout

discharge to the building and EV charging on the day. An overview of each function is described below.

#### (1) Purchased electricity prediction function

It is necessary to dispatch EVs for peak shaving if the purchased electricity is quantitatively predicted to exceed the contract electricity. Particularly in the case of PV power generation, it is necessary to predict not only the amount of power used but also the amount of power generated by PV, and to calculate the purchased electricity as the difference. This system trains prediction models using feature values extracted from past statistical data such as weather information, actual electricity usage, and actual PV power generation as input information. When actually predicting the purchased electricity, a fully trained prediction model is used, and the purchased electricity prediction is calculated by inputting the weather forecast results for the day, as shown in Fig. 3.

#### (2) Discharge control (peak shaving control)

EVs are parked at the building and connected to charge/discharge stations for peak shaving based on the dispatch plan created by the battery sharing management system. In the EMS, the EVs are charged/discharged based on instructions given by the controller (EMS controller) that controls charging/discharging.

The contract electricity is determined by the peak power value in 30-minute increments, so the EMS controller obtains the power at 1-minute intervals and calculates the average value over a 30-minute period. If this average value exceeds the target contract electricity, the pre-dispatched EVs will discharge.

In addition, to increase the peak shaving success rate, the EMS controller implements discharge control that takes into account the delay in the control response from the time the EMS controller issues an instruction until the charge/discharge station is controlled.

#### (3) Charge control

The EMS controller controls multiple charge/discharge stations while calculating the 30-minute cumulative electricity demand in order to charge the EVs so that the electricity demand does not exceed the target contract electricity.

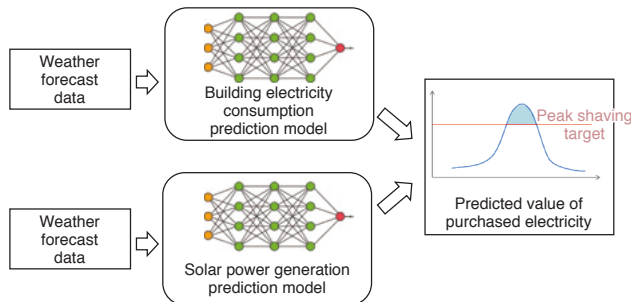


Fig. 3 Model for predicting purchased electricity

### 3.3. Battery Sharing Management System

Figure 4 shows a schematic of battery sharing management system operation. The upper portion of the figure shows the vehicle reservation status prior to system activation, with users having reserved arbitrary vehicles. The lower portion of the figure shows the vehicle reservation status after applying the peak shaving reservations made by the EMS. The original operation reservations have been assigned to different vehicles, and the plan has been rearranged to realize both the operation reservations and peak shaving reservations. In addition, prioritization has been carried out in consideration of optimization of the dispatch plan according to the reservation conditions, battery deterioration, etc.

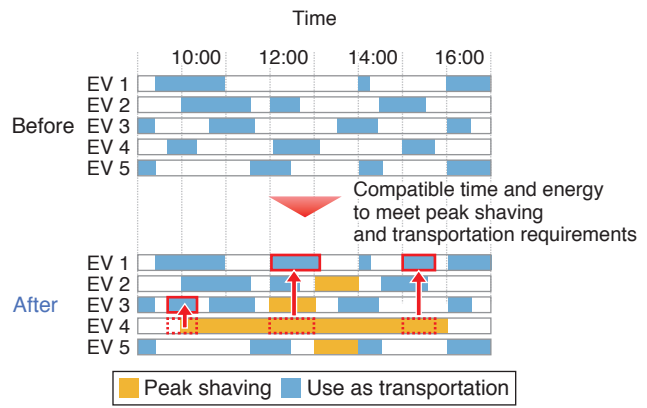


Fig. 4 Battery sharing management system

## 4. Proving Test

As shown in Fig. 5, a proving test is being conducted as of April 2023 with the cooperation of Suzuhiro Co., Ltd. (hereinafter, “Suzuhiro”) in Odawara City, Kanagawa Prefecture. As part of its environmental activities, Suzuhiro has been working for some time to introduce renewable energy equipment such as PV power generation and to establish buildings that aim to achieve an annual primary energy consumption balance of zero (Zero Energy Building: ZEB)<sup>(8)</sup>. This proving test began from an alignment of interests of Suzuhiro, which aims to realize carbon neutrality by producing and consuming energy locally, and this research, which targets practical application of energy management utilizing EVs. This proving test is focused on Suzuhiro’s head office building and uses EVs as commercial vehicles in and around Odawara City on a daily basis.

Figure 6 shows an overview of the proving test system. The originally operated five gasoline vehicles and HEVs were replaced with five Honda e EVs, and five charge/discharge stations were installed. A web application for automatically reserving dispatches and a dashboard that

displays the building power and vehicle information were developed as a user interface for the system described in Chapter 3.

Figure 7 shows the operation status of Suzuhiro's gasoline vehicles and HEVs as surveyed prior to the start of the proving test. The solid line represents the median number of EVs in use as transportation at each time, and the blue hatched area represents the range of three times the standard deviation ( $3\sigma$ ) over the median number.

The greatest vehicle usage is from around 10:00 to 15:00, and the median number in that time period is two vehicles or less but varies widely. On the other hand, the frequency of using five units as transportation at the same

time was found to be low. From this it was thought that the variation of  $3\sigma$  can be absorbed by the battery sharing management system and assumed that three vehicles can be used for peak shaving. Taking into consideration the discharge capacity of the charge/discharge stations, a target of 15 kW was set.

From this peak shaving target value, the targets for the whole system were defined as follows.

- Base electric utility rate reduction effect of 20% (20 kW), considering the amount due to cooperative control of peak shaving and air conditioning
- CO<sub>2</sub> emissions reduction effect of 60% by changing to EVs and route optimization



Fig. 5 Suzuhiro office building and EVs used for test

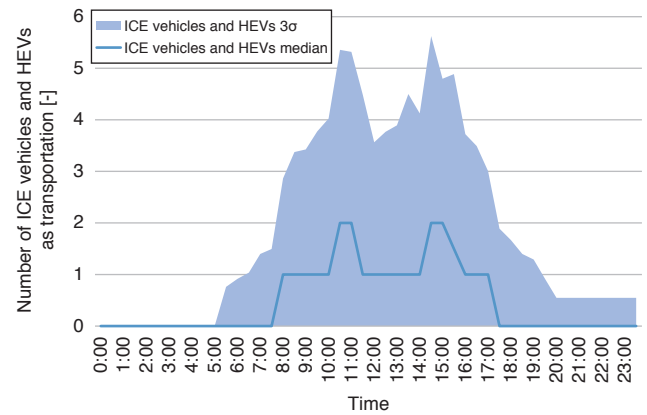


Fig. 7 Operation status of 5 ICE vehicles and HEVs as transportation before start of test

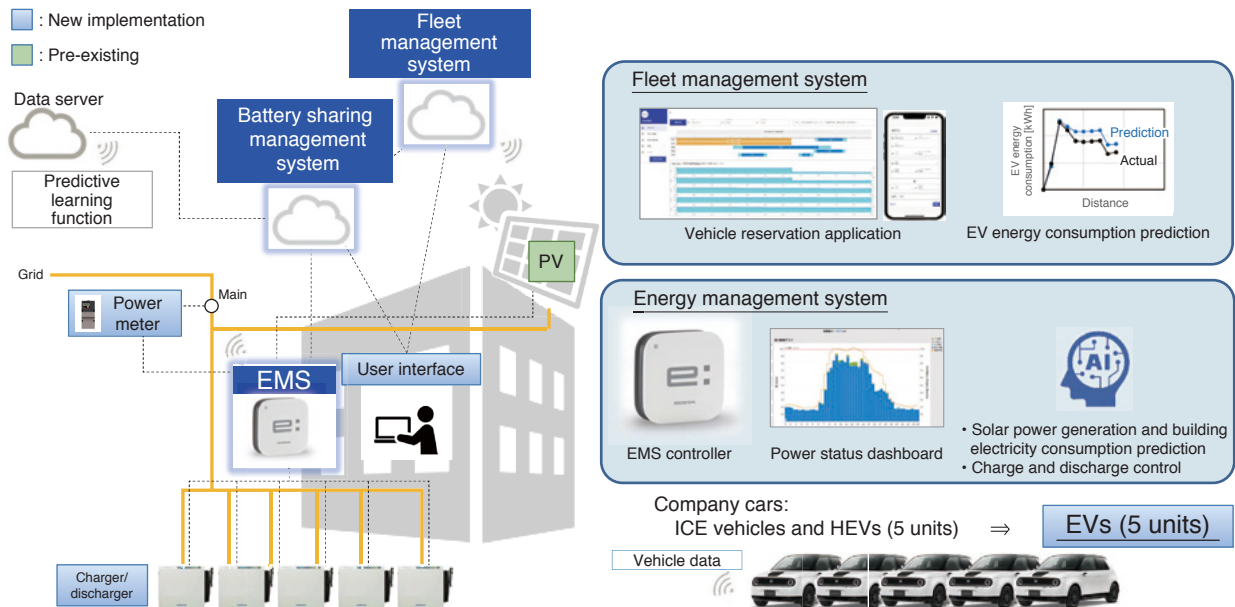


Fig. 6 System configuration of proving test

#### 4.1. System Operation

In order to illustrate the specific effects of the constructed system, Fig. 8 shows the power status of the building for one day as an example. The yellow line is the building's purchased electricity predicted by the EMS. The system calculates the number of vehicles needed for peak shaving in time slots when this predicted electricity exceeds the target contract electricity.

On this particular day, the predicted value of the purchased electricity greatly exceeded the target contract electricity, so it was calculated that three EVs would be needed for peak shaving, especially from 8:00 to 14:00, as shown in the dispatch plan in Fig. 9. On the other hand, there were six reservations for use as transportation, and the battery sharing management system formulated a plan and made reservations for use as transportation and peak shaving. The red frames in Fig. 9 show the time slots in which EVs were actually operated, and it can be seen that the vehicles are used for peak shaving in the planned time slots and as transportation in the time slots reserved for use as transportation.

Figure 8 also shows that power was discharged from the EVs (red bars in the figure) at the time of building power peaks, enabling to keep the actual purchased electricity (blue bars) to the target contract electricity (solid black line) or less.

The above results show that prediction, dispatch planning, and charge/discharge station control operated normally, and the system functioned as expected.

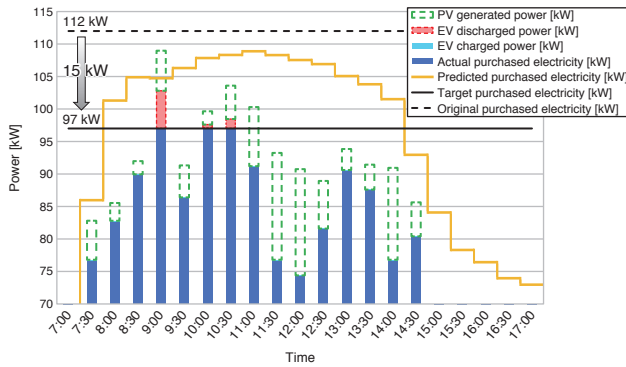


Fig. 8 Office building power status

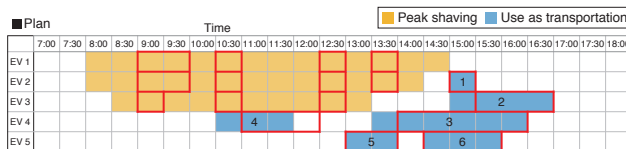


Fig. 9 Vehicle dispatch plan and actual use

#### 4.2. Confirmation of Battery Sharing Management System Effectiveness

Through the introduction of this system, the ability to coordinate five EVs for the two purposes of peak shaving and transportation was evaluated. Figure 10 shows the results for use as transportation throughout the year. The trend is similar to that found when use as transportation was investigated prior to the start of the proving test and shows that there was no substantial change in usage even when vehicles were replaced with EVs. As shown in Fig. 8, the purchased electricity also increases from 8:00 to 14:00, and it is necessary to achieve both applications of peak shaving and transportation during this time period.

Figure 11 shows the results of the highest number of dispatched vehicles per day when only days throughout the year with reservations for peak shaving are extracted. Blue indicates EV reservations for use as transportation, and yellow indicates EV reservations for peak shaving. Red indicates reservations for gasoline vehicle and HEV operation. In 82 of the 84 times during the year that peak shaving reservations were made, the battery sharing

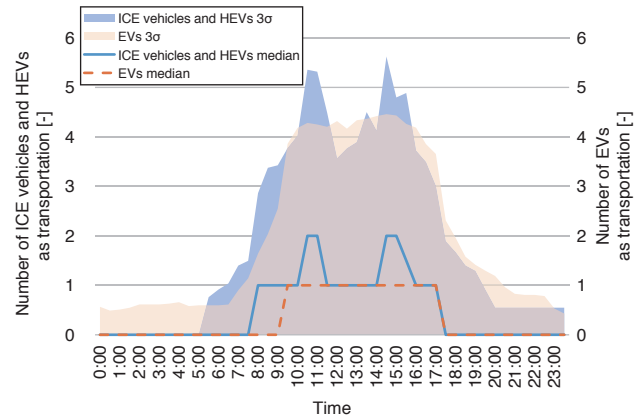


Fig. 10 Operation status of 5 EVs as transportation during test

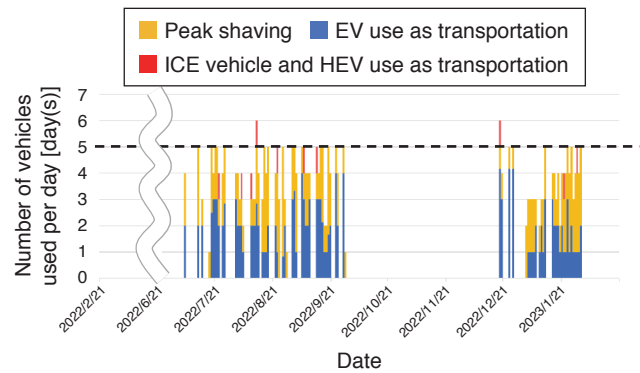


Fig. 11 Highest number of dispatched vehicles per day

management system functioned effectively, enabling achievement of use as transportation as well as peak shaving with five EVs.

#### 4.3. Electric Utility Cost Reduction Effect and CO<sub>2</sub> Emissions Reduction Effect

The effects of the introduction of this system to help reduce electric utility costs and CO<sub>2</sub> emissions were estimated under the following conditions.

- Base electric utility rate unit price: 1,470 [yen/kW]
- Energy price: Gasoline 163 [yen/L], Electricity 20.3 [yen/kWh]
- CO<sub>2</sub> emissions intensity: Gasoline 2.322 [kg/L], Electricity 0.434 [kg/kWh]

Throughout the one-year proving test, peak shaving occurred on five days in the summer and seven days in the winter for a total of 12 days. Of the 12 days when peak shaving occurred, the largest amount reduced by discharge from EVs for a single day was 7.4 kW, and a total of 51.5 kWh was reduced over the 12 days.

Based on this, the introduction of this system reduced base electric utility costs by 20% as shown in Fig. 12, achieving the target of 20%. In addition, replacing gasoline vehicles with EVs and optimizing routes reduced CO<sub>2</sub> emissions by 46%. The reason why the CO<sub>2</sub> emissions reduction target of 60% was not achieved was that, in a certain percentage of cases, a large number of passengers or objects needed to be transported and the test vehicle (Honda e) was not suitable for such tasks, so a reserve gasoline vehicle or HEV was used instead.

Suzuhiro has also estimated that adding control that selectively charges EVs with clean power generated by PV facilities can help reduce CO<sub>2</sub> emissions from company-owned vehicles by 98%.

#### 4.4. Future Initiatives

Approaches going forward include initiatives to increase the accuracy of building electricity predictions, use of real-time building electricity and vehicle data to enhance the linkage between the EMS and fleet management, further

reduction of peak shaving dispatch times, and increase of operating rates.

## 5. Conclusion

A linkage system for the fleet management system and the energy management system was developed and the following results were achieved in a year-long proving test.

- (1) Through the introduction of this system, it was proved that EVs can be used both as transportation and for building energy management.
- (2) Use of five EVs for peak shaving throughout the year reduced electric utility costs by 20%, and changing to EVs and route optimization reduced CO<sub>2</sub> emissions by 46%.

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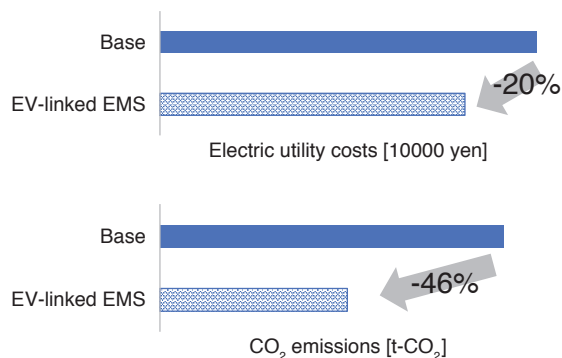


Fig. 12 Electric utility cost reduction effect and CO<sub>2</sub> emissions reduction effect

#### ■ Author ■



Tatsuya IDE



Kazumasa HONDA



Senryu OH



Yoshiya NAKAGAWA



Takuya TANAKA

# Construction of Hierarchical Scatter-band Data for Engine Specification Study in Model-based Development Realization

Yasuhiro OKURA, Ph.D.<sup>1</sup>  
Seisuke SATO<sup>3</sup>

Junya YOSHIZAWA<sup>1</sup>  
Koichi TAKASE<sup>1</sup>

Hiromitsu MATSUDA, Ph.D.<sup>2</sup>

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## ABSTRACT

Hierarchical scatter-bands were constructed to determine engine specifications in the early stages of development, and development efficiency was enhanced. The four elements of thermal efficiency and combustion stability, oil dilution, and soot, which conflict with thermal efficiency, were defined and the requirements of intermediate parameters were analyzed in order to link them to parts step by step. Using engine data, it was confirmed that the parameter linkages are generally correct. The issues of turbocharged direct injection engines and their causes were analyzed based on system characteristic analysis and requirement analysis using scatter-bands, thereby enabling efficient implement countermeasures. The in-cylinder flow was enhanced by changing the piston top to a shallow dish shape, which decreased the combustion period by 0.5 deg. and reduced the brake specific fuel consumption by approximately 0.6%. Countermeasures were also implemented for conflicting events, and the injection control was changed. This reduced the oil dilution rate by 2.6 wt% and allowed balancing of the performance demanded of the engine.

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## 1. Introduction

Automotive regulations continue to become stricter year by year against backdrops such as global warming and air pollution. The Corporate Average Fuel Economy (CAFE) method is adopted in fuel economy regulations, making it necessary to enhance the average fuel economy of not only specific models but of all vehicles sold. In addition, Real Drive Emission (RDE) regulations have been introduced in emissions (EM) regulations, necessitating compliance with EM limit values even in real environments including low temperatures. To address these issues, gasoline engines use technologies such as mitigation of knock by direct injection (DI) and reduction of soot by high fuel pressure and multi-stage injection, etc. Thus, it is necessary to design engine specifications that satisfy multiple requirements under various conditions, making engine combustion design increasingly complex.

Automobile manufacturers are continuing to promote

higher development efficiency by using the MBD-V process, which combines the V-process and Model-Based Development (MBD). The MBD-V process is a means of establishing a design and verification process hierarchy and front-loading by using models in the design stage of each level<sup>(1)</sup>. Advantages of applying MBD to development are that the accuracy of the main specifications of engines can be increased before prototyping in the early stages of development, the development period can be shortened, and the required performance can be achieved in a shorter period. Here, the models in MBD include control models such as engine control units, models of control targets, and CAE models of combustion, structural strength, sound vibration, etc.<sup>(2)</sup>

In application of CAE models to MBD, detailed and large-scale CAE entails time and cost. For this reason, CAE is repeatedly performed using engine specifications that do not meet performance target values, resulting in development reworking. The first example of reworking in engine development is the case when changing the

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<sup>1</sup> Honda Motor Co., Ltd.

E-mail: yasuihiro\_okura@jp.honda

<sup>2</sup> Innovative Research Excellence Power Unit & Energy

<sup>3</sup> Honda Racing Corporation

intake port shape to enhance the in-cylinder flow due to the relationship between Brake Specific Fuel Consumption (BSFC) and steady-state tumble ratio (T/R). The target steady-state T/R may not have sufficient effect to reduce BSFC, making it necessary to re-examine enhancement of the in-cylinder flow. This is because it is a challenge to obtain the target engine performance with only target values at the parts level, requiring design of intermediate parameters that link the two. The second example of reworking occurs when changing to DI with the goal of mitigation of knock by cooling the intake air. DI provides effects to enhance thermal efficiency by mitigation of knock but may also reduce combustion stability due to inhomogeneous fuel distribution and increase the oil dilution rate and soot due to increased fuel adhesion on the in-cylinder wall surfaces. Therefore, in order to evaluate the impact of specification changes from multiple perspectives, it is considered necessary to use the same criteria among engines with multiple requirements and differing specifications.

Attempts are being made to use scatter-bands to increase the accuracy of engine specifications in the early stages of development to avoid reworking. For example, the certainty of specifications is increased by setting target values for turbulent intensity needed for EGR combustion<sup>(3), (4)</sup>, reducing the fuel adhesion quantity to reduce the oil dilution rate<sup>(5)</sup>, and understanding the positioning of the intake port embedded in the cylinder head<sup>(6)</sup>. Here, scatter-band refers to a point cloud with a trend obtained by combining test and CFD data of engines developed in the past based on related parameters.

Conventional scatter-bands do not indicate in steps the parameters that link the performance targets demanded of engines with parts. In addition, the same criteria for comparing engines with different specifications may not be indicated. For this reason, conventional scatter-bands were considered inadequate to avoid the aforementioned reworking cases. The authors therefore constructed hierarchical scatter-band data that links engine performance and parts in steps in order to reduce reworking by increasing the certainty of engine specifications in the early stages of development. Furthermore, in order to evaluate the performance demanded of engines from multiple perspectives, the linkages of intermediate parameters between engine performance and parts were also clarified in a hierarchical manner for thermal efficiency, which is to be enhanced, and for multiple elements that conflict with thermal efficiency and thus call for confirmation. Parameter normalization was also performed in order to evaluate engines with different specifications using the same criteria. The constructed hierarchical scatter-bands were applied to promote the combustion of a turbocharged DI engine in order to verify the effectiveness, and this report describes these contents.

## 2. Examination of Hierarchical Scatter-band Data

### 2.1. Definition of Levels in V-process

Various engine phenomena such as intake and exhaust, fuel vaporization, and combustion proceed while interacting with each other, so engine performance such as power and fuel consumption is determined by many parameters. Therefore, in order to organize the parameters accumulated in scatter-bands, first the levels of the V-process in engine development were defined. Figure 1 shows the definition of the levels in the V-process. The left side of the V-process is Design, the right side is Verification, and the processes are divided into the five levels of L0: Vehicle, L1: Powertrain, L2: Engine, L3: Function, and L4: Parts. Here, L3: Function is defined as the function system (sub-system) comprising the multiple parts connecting L2: Engine and L4: Parts. For example, the combustion system consists of the cylinder head, piston, and injector (INJ), etc. Requirement parameters and target values are set in steps from L0: Vehicle to L1: Powertrain, L2: Engine, and then L4: Parts, and verification is performed by optical engines and actual engines of the same level.

Figure 2 shows a schematic diagram of scatter-band utilization in the development phase. The V-flow shown in Fig. 1 is applied to the three phases of research (hereinafter, R), pre-mass-production development (hereinafter, Pre-D), and mass-production development (hereinafter, D). The engine specifications are determined from R to the first half of Pre-D, and calibration of engine characteristics is performed from the latter half of Pre-D to D. It was thought that, since a scatter-band composed of engines already in mass production would facilitate judgment of the appropriateness of the examined specifications, data accumulation was performed in the D phase after the completion of calibration. In addition, the accumulated data is applied in the early stages of the R phase in which the next engine specifications are examined. It was assumed that scatter-bands would be used for characteristic analysis, positioning evaluation, and rough target value setting before performing large-scale CAE. To achieve this, the definitions and conditions to be accumulated as scatter-bands were examined from the following perspectives.

- Data that can be utilized in the early stages of development
- Definition and accumulation of parameters that interact with each other from L2: Engine to L3: Function and then to L4: Parts
- Evaluation can be performed using the same criteria even with different engine specifications such as displacement and natural aspiration (NA) or turbocharger (TC)

### 2.2. Examination of Engine Requirements (L2) and Operating Conditions

The engine requirements (L2) and operating conditions were examined in order to obtain data that can be utilized

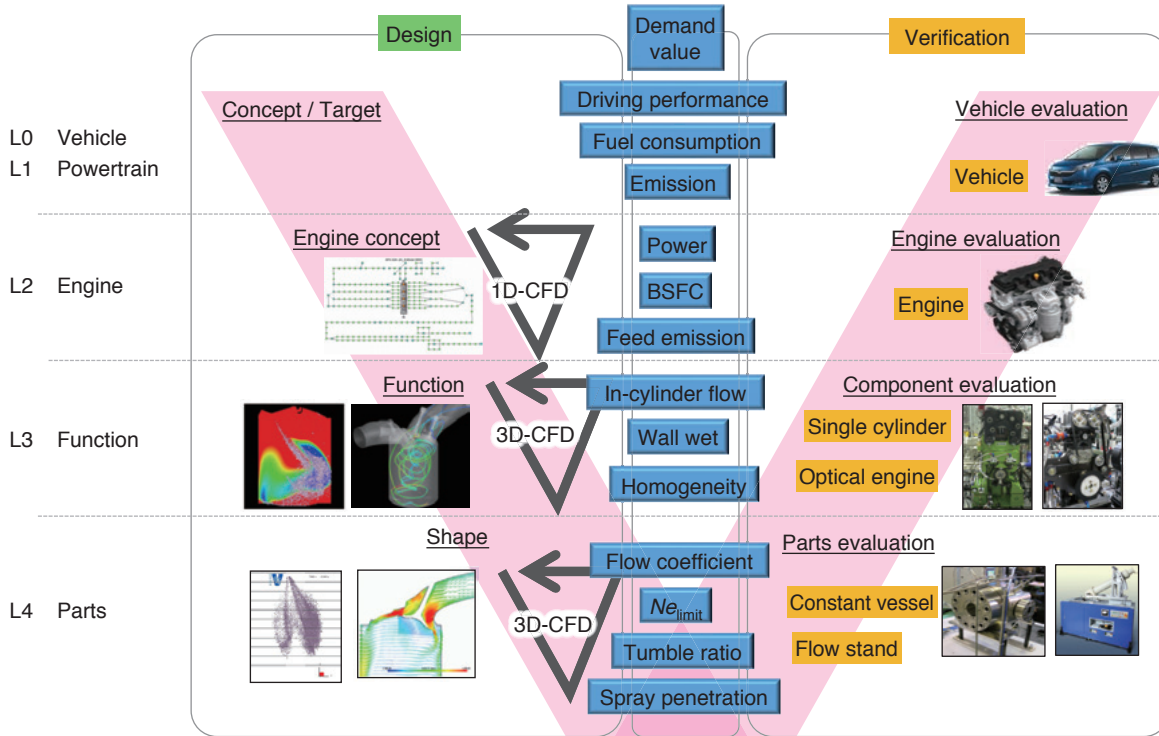


Fig. 1 Definition of each level in V-process for engine development

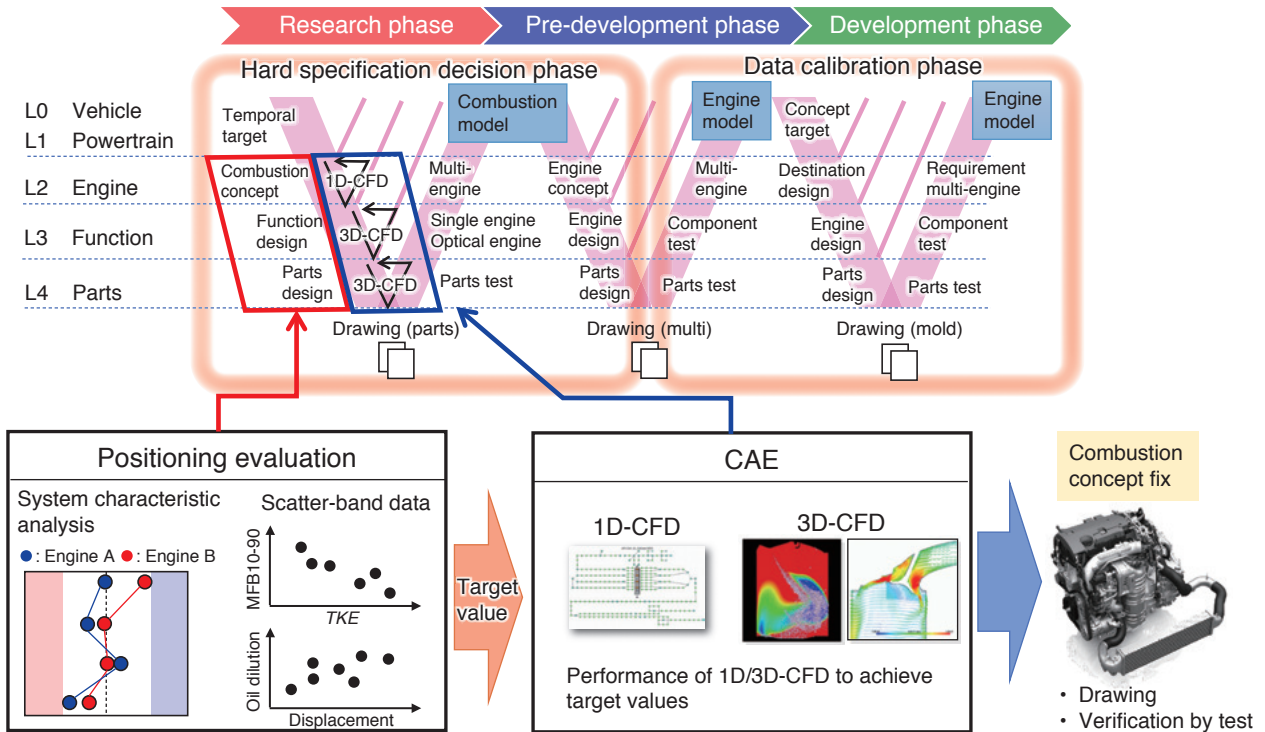


Fig. 2 Schematic diagram for utilization of scatter-band data in each development phase

in the early stages of development. The four elements of thermal efficiency, which is targeted for enhancement, and combustion stability, oil dilution, and soot, which conflict with thermal efficiency, were defined as engine requirements. In examination of operating conditions, eight types of average operating conditions were selected for engines mass-produced in the past ranging from inline 3-cylinder to V-type 6-cylinder engines with different bores, strokes, intake, and fuel supply systems. Table 1 shows the operating conditions, and Fig. 3 shows the schematic diagram. Here,  $N_e$  is the engine speed and  $T_w$  is the engine water temperature. In examination of thermal efficiency,  $N_e = 1500$  rpm, and  $T_w = 80^\circ\text{C}$  were set. Since thermal efficiency including friction is to be evaluated, the load was the Brake Mean Effective Pressure (BMEP), and three conditions were selected. In examination of combustion stability, the load was the Indicated Mean Effective Pressure (IMEP) in order to evaluate only the combustion state. From the viewpoint of vehicle drivability in the low engine speed, high-load range, IMEP was set to 1000 kPa for NA and 1600 kPa for TC. In examination of oil dilution, which tends to increase at low water temperatures,  $T_w = 50^\circ\text{C}$  was set. With regards to soot,  $N_e$ , the load, and  $T_w$  were selected according to fast idle for early warm-up in the first half and extra-high vehicle speed in the second half of the mode in the Worldwide harmonized Light vehicles Test Cycles (WLTC). The air/fuel ratio (A/F) was the stoichiometric A/F for regular gasoline (RON91), and external EGR was 0%.

Table 2 shows the engine control conditions. The exhaust valve close (EVC) and intake valve open (IVO) timings were fixed in order to make the residual gas quantity in the cylinder as similar as possible. The valve lift curves set for each engine were used. The fuel injection timing  $\theta_{inj}$  was set as the End Of Injection (EOI) for intake port injection (PI) and the Start Of Injection (SOI) for DI, and the average conditions for the aforementioned eight types of engines were selected. As the ignition timing  $\theta_{ig}$  impacts the quality of combustion, the optimal ignition timing (Minimum advance for Best Torque: MBT) was

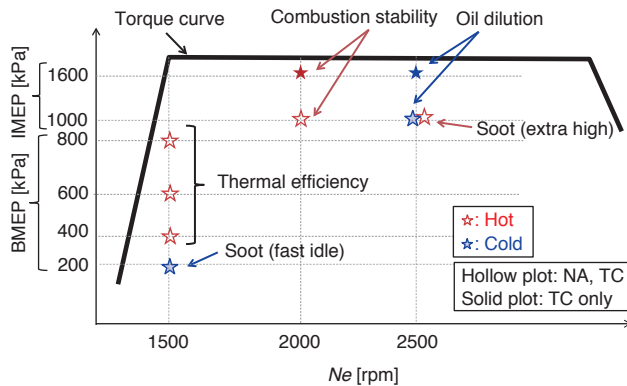


Fig. 3 Schematic diagram of engine operating condition for scatter-band

Table 1 Engine operating condition for scatter-band

| Engine requirement (L2) |            | $N_e$ [rpm] | Load [kPa]                       | $T_w$ [°C] | A/F            |
|-------------------------|------------|-------------|----------------------------------|------------|----------------|
| Thermal efficiency      |            | 1500        | BMEP 400<br>BMEP 600<br>BMEP 800 | 80         | Stoichiometric |
| Combustion stability    |            | 2000        | NA: IMEP 1000<br>TC: IMEP 1600   | 80         | Stoichiometric |
| Oil dilution            |            | 2500        | NA: IMEP 1000<br>TC: IMEP 1600   | 50         | Stoichiometric |
| Soot (PM/PN)            | Fast idle  | 1500        | BMEP 200                         | 40         | Stoichiometric |
|                         | Extra high | 2500        | IMEP 1000                        | 80         | Stoichiometric |

Table 2 Engine control conditions for scatter-band

|                |                                                    |
|----------------|----------------------------------------------------|
| Valve timing   | IVO: -10 deg. BTDC<br>EVC: -10 deg. ATDC           |
| $P_f$          | PI: 0.4 MPa<br>DI: 12 Mpa                          |
| $\theta_{inj}$ | PI: -30 deg. BTDC (EOI)<br>DI: -60 deg. BTDC (SOI) |
| $\theta_{ig}$  | MBT<br>10 deg. BTDC (fast idle)                    |

used and  $\theta_{ig}$  was fixed to -10 deg. Before Top Dead Center (BTDC) for fast idle. This control condition was applied to all the operating conditions shown in Table 1.

### 2.3. Definition of Intermediate Parameters (L3)

In order to construct scatter-bands with parameters that interact between each level from Engine (L2) to Function (L3) and then to Parts (L4), Function (L3) is divided into four parts as shown in Fig. 4. L3-1 is assigned factors to be enhanced such as indicated thermal efficiency  $\eta_i$  and volumetric efficiency  $\eta_v$  as well as factors to be reduced such as time loss. L3-2 is assigned factors that determine combustion characteristic such as in-cylinder pressure, and L3-3 is assigned factors just before combustion that realize combustion characteristics (L3-2) such as turbulent kinetic energy ( $TKE$ )<sup>(7)</sup>. L3-4 is assigned factors determined by combinations of multiple parts such as the surface/volume ratio (S/V) in the combustion chamber, and L4 is assigned single-part specifications and control parameters such as  $\theta_{ig}$  and  $\theta_{inj}$ .

Requirement analysis was performed to extract parameters step by step according to the definitions in Fig. 4. When performing requirement analysis, in order to emphasize simplicity and ease of intuitive comprehension, a method that links parameters considered to be empirically sensitive was selected. Figure 5(a) shows the requirement analysis for thermal efficiency.

The BSFC which is the requirement for engines is linked to the indicated thermal efficiency  $\eta_i$  and various losses such as time loss. Time loss is linked to the crank angle MFB50 with a mass fraction burnt (MFB) of 50% and then to the crank angle MFB10-90 with an MFB of 10% to 90%. Here, as MFB50 results in the highest thermal efficiency around 368 deg. ATDC, it is used to evaluate the

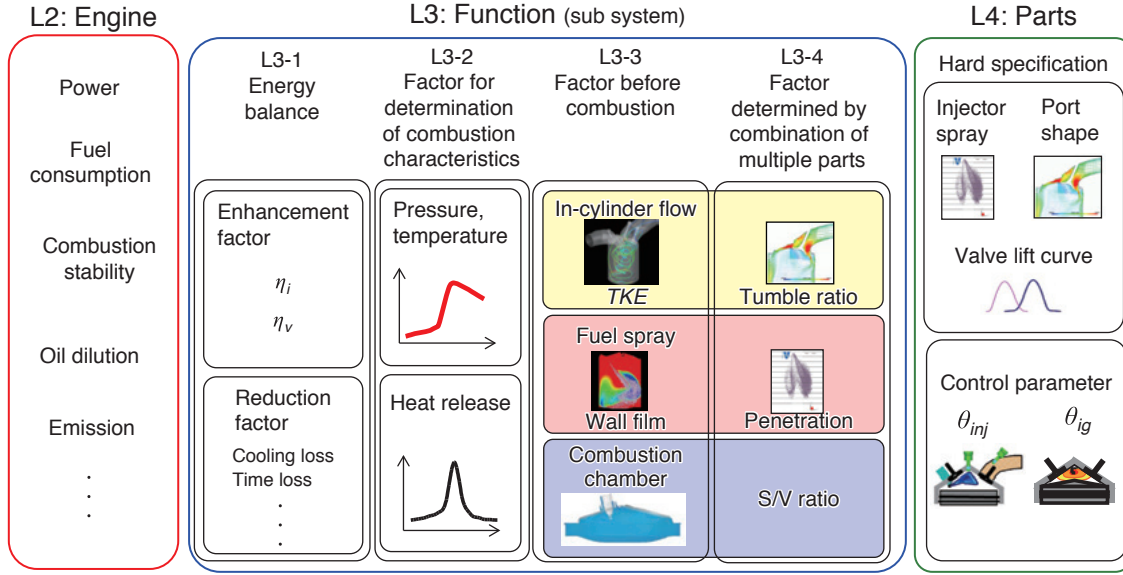


Fig. 4 Definition of parameters in L2: Engine; L3: Function (Sub system); L4: Parts

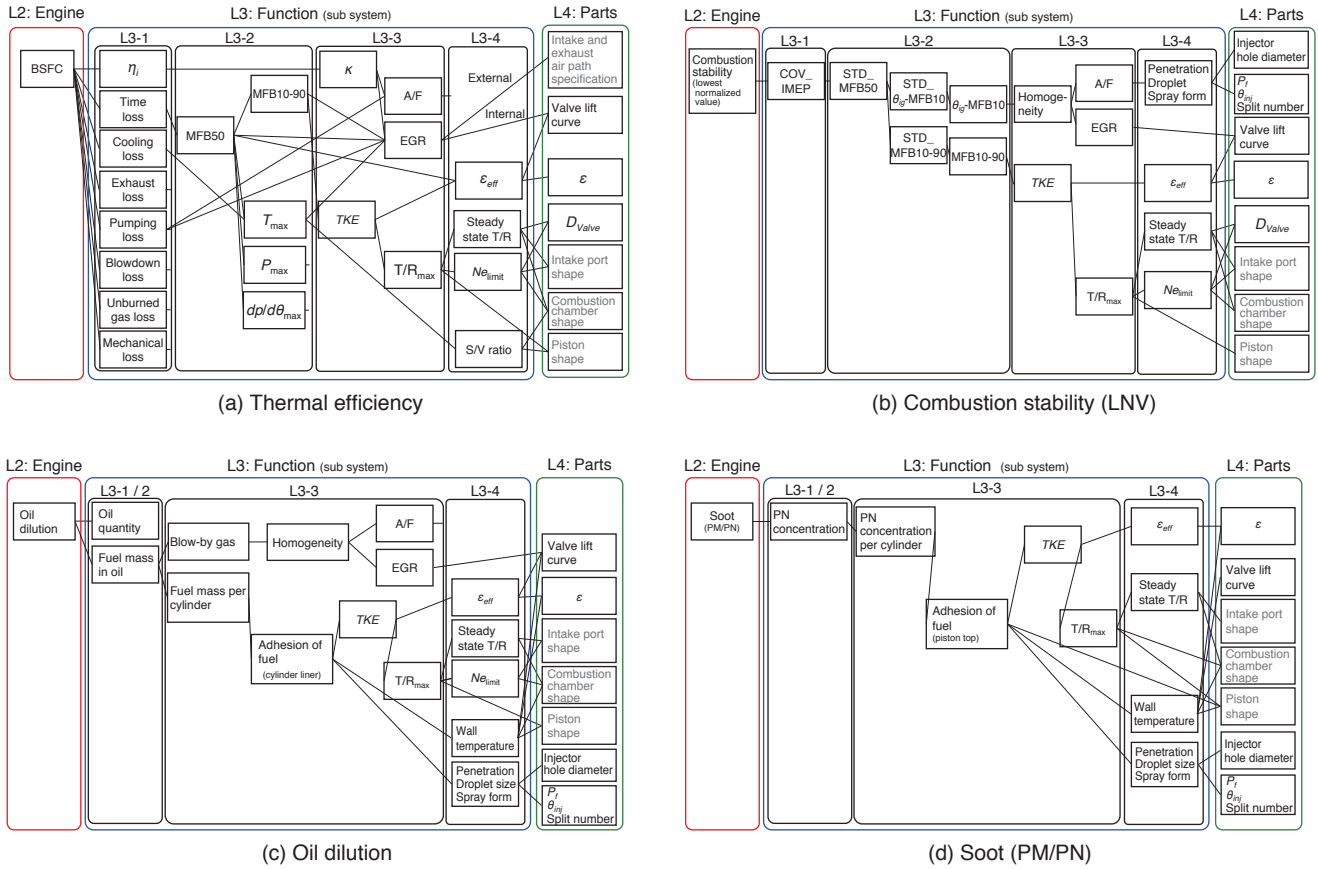


Fig. 5 Requirement analysis which were empirically linked with parameters

knock mitigation effect<sup>(8)</sup>. MFB10-90 is linked to  $TKE$ , T/R, and steady-state T/R in that order. Note that although data on parameters indicated in gray in the figure, such as intake port, has not been accumulated, however the need to change specifications and the direction of countermeasures can be determined based on the relationships shown.

Figure 5(b) shows the requirement analysis for combustion stability. The lowest normalized value (LNV) obtained by dividing the smallest IMEP in the cycle by its mean is linked to IMEP coefficient of variation (COV), STD\_MFB50, which is the standard deviation of MFB50, and then to STD\_θ<sub>ig</sub>-MFB10, which is the standard deviation of the crank angle θ<sub>ig</sub>-MFB10 at which the MFB from θ<sub>ig</sub> is 10%. It is then further linked to the A/F homogeneity, the spray penetration and droplet size, and the INJ hole diameter and fuel injection pressure  $P_p$  etc., showing that the A/F homogeneity impacts combustion stability. On the other hand, STD\_MFB50 is also linked to  $TKE$ , and the flow also impacts combustion stability.

Figure 5(c) shows the requirement analysis for oil dilution. Oil dilution is linked to fuel in the blow-by gas that escapes from the combustion chamber to the oil pan, and to fuel adhesion to the cylinder liner. Adhesion of fuel on the cylinder liner wall surface is linked to penetration and  $P_p$  etc. On the other hand, it is also linked to flow-related parameters such as T/R<sub>max</sub>, showing that the in-cylinder flow impacts oil dilution.

Soot requirement analysis is performed for the Particle Number (PN) shown in Fig. 5(d), but the same trend is also seen for the Particulate Matter (PM) mass. The PN per cylinder discharged from each cylinder is mainly linked to fuel adhesion to the piston top, and then further connected to the spray penetration, etc.

The reworking cases described in Chapter 1 were analyzed as a method of utilizing factor analysis. The requirement analysis in Fig. 5(a) shows that combustion design of  $TKE$  is needed for the main intermediate parameters of BSFC and steady-state T/R in the first reworking case. In the second reworking case, Fig. 5(b) confirmed that INJ specifications (L4) impact combustion stability via A/F homogeneity (L3-3).

## 2.4. Examination Related to Normalization of Accumulated Parameters

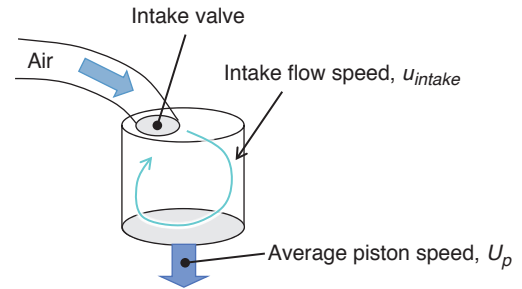
Normalization is needed in order to evaluate different engine specifications using the same criteria. For example, BMEP and  $\eta_v$  are normalized by displacement, enabling comparison of different engine specifications. This section describes normalization of  $TKE$  as an example. The flame structure in an engine in-cylinder is considered to be classified as a wrinkled laminar flame regime, and enhancement of the turbulence is known to increase the burning velocity<sup>(9)</sup>. Here, even if the specifications impacting the in-cylinder flow such as the intake port shape are the same, the burning velocity increases together with  $Ne$ <sup>(10)</sup>. Also, even if the turbulent intensity is the same,

if the bore diameter differs, the combustion period will not be the same due to the different flame propagation distance. An attempt was therefore made to correct  $TKE$  so that even data obtained with different  $Ne$  and bore diameters can be compared using the same criteria. Figure 6 shows the approach to corrected  $TKE$ . First, correction by engine speed  $Ne$  was examined. In an engine with the same intake system specifications, the average piston speed  $U_p$  is obtained from the stroke  $L_s$  and the engine speed  $Ne$  as shown in Eq. (1). As shown in Fig. 6(a), when  $U_p$  increases, the difference between the intake port pressure and the in-cylinder pressure increases, also increasing the intake flow speed  $u_{intake}$ . The in-cylinder flow is enhanced by the increase in intake flow speed  $u_{intake}$ , also increasing turbulent intensity  $u'$ . Note that  $TKE$  can be obtained from  $u'$  by Eq. (2).

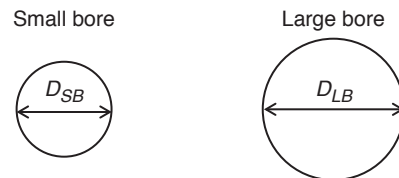
$$U_p = \frac{L_s}{60 / (Ne \times 2)} \propto u_{intake} \quad (1)$$

$$u_{intake} \propto u' = \sqrt{\frac{2}{3} TKE} \quad (2)$$

As  $U_p$  is proportional to  $Ne$ , it is thought that the turbulent intensity can be corrected by the ratio of  $Ne$ . Next, correction by bore diameter was examined. On the left side of Eq. (3), the combustion characteristic time is calculated by dividing MFB10-90 by  $Ne/60$ . It is thought that when the spark plug is positioned in the center of the bore, this characteristic time is equivalent to the time for the flame



(a) Correction by engine speed



(b) Correction by bore diameter

Fig. 6 Method of corrected turbulent kinetic energy,  $TKE_{corr}$

kernel generated near the spark plug to propagate over the bore radius  $D/2$ . The time for the flame to propagate varies according to turbulent intensity  $u'$ , so the combustion characteristic time on the left side of Eq. (3) is assumed to correlate with the value obtained by dividing the  $D/2$  shown in the center of Eq. (3) by  $u'$ . Next, in order to make the combustion characteristic time obtained by dividing the small-diameter bore  $D_{SB}$  shown in the center of Eq. (3) by  $u'_{SB}$  and the combustion characteristic time of the large-diameter bore  $D_{LB}$  shown on the right side of Eq. (3) the same, it is necessary to increase  $u'_{LB}$  as the bore diameter increases.

$$\frac{MFB_{10-90}}{Ne/60} \sim \frac{D_{SB}/2}{u'_{SB}} \approx \frac{D_{LB}/2}{u'_{LB}} \quad (3)$$

Here, the subscript SB indicates the small-diameter bore, and the subscript LB indicates the large-diameter bore. The corrected  $TKE_{corr}$  based on the above concept is shown in Eq. (4).

$$TKE_{corr} = TKE \times \left( \frac{Ne_{ref}}{Ne} \right)^2 \left( \frac{D_{B_{ref}}}{D_B} \right)^2 \quad (4)$$

The numerators of the second and third terms on the right side are respectively the reference engine speed  $Ne_{ref}$  and the reference bore diameter  $D_{B_{ref}}$ , and were set to  $Ne_{ref} = 2000$  rpm and  $D_{B_{ref}} = 73$  mm, which correspond to the intermediate positions, according to Table 1 and Table 3 described hereinafter. Also, in consideration of the turbulent intensity unit m/s and the  $TKE$  unit  $m^2/s^2$ , the second and third terms on the right side were each squared. For example, for a bore diameter of 91 mm, the third term on the right side of Eq. (4) becomes approximately 0.64, and the corrected  $TKE$  exhibits a smaller value than the original  $TKE$ . Therefore, it can be estimated that in order to obtain the same combustion period as that of a bore diameter of 73 mm, a  $TKE$  approximately 1.55 times (inverse of 0.64) that of a 73 mm bore is needed.

In order to verify the effect of  $TKE$  correction, Fig. 7 shows the correlation between  $TKE$  and MFB10-90. The horizontal axis of Fig. 7(a) shows the uncorrected  $TKE$  at the compression TDC, and Fig. 7(b) shows the  $TKE_{corr}$  corrected by Eq. (4). When  $TKE$  and MFB10-90 are approximated by a quadratic function, the coefficient of determination  $R^2$  is  $R^2 = 0.56$  without correction and  $R^2 = 0.86$  with correction.  $R^2$  is enhanced, confirming the effect of the  $TKE$  correction method.

## 2.5. Engine Specifications and Analysis Method

Testing and CFD analysis were performed using the scatter-band conditions defined in Table 1 and Table 2 in order to construct scatter-bands. Table 3 shows the main engine specifications. A total of nine inline 3-cylinder,

Table 3 Engine specifications for scatter-band validation test

| Engine type        | In-line 3-cylinder |      |      | In-line 4-cylinder |      |      |      |      | V6    |
|--------------------|--------------------|------|------|--------------------|------|------|------|------|-------|
| Engine No.         | 1                  | 2    | 3    | 4                  | 5    | 6    | 7    | 8    | 9     |
| Displacement [L]   | 0.66               | 0.66 | 0.66 | 1.5                | 1.5  | 1.5  | 2.0  | 2.4  | 3.5   |
| Bore [mm]          | 64                 | 64   | 60   | 73                 | 73   | 73   | 86   | 87   | 91    |
| Stroke [mm]        | 68.3               | 68.3 | 77.6 | 89.4               | 89.4 | 89.4 | 85.9 | 99.1 | 89.5  |
| Intake system      | NA                 | TC   | NA   | NA                 | NA   | TC   | TC   | NA   | TC    |
| Fuel supply system | PI                 | PI   | PI   | PI                 | DI   | DI   | DI   | DI   | PI/DI |

inline 4-cylinder, and V-type 6-cylinder engines were used. Engines with differing specifications were selected, such as displacement from 0.66 L to 3.5 L, NA and TC intake systems, and PI and DI fuel supply systems. The in-cylinder pressure and the intake and exhaust pressure pulsation were measured, and the obtained in-cylinder pressure was subjected to combustion analysis with the first model of thermodynamics.

In-cylinder 3D CFD analysis was performed to obtain parameters such as  $TKE$  and the quantity of fuel adhering to the wall surface, which cannot be obtained from actual engine test results. The commercial 3D fluid analysis software VECTIS (Ricardo PLC) was used, and the standard  $k-\varepsilon$  model was applied as the turbulence model. Also, in order to calculate the boundary conditions of 3D CFD, the commercial 1D engine analysis software GT-SUITE (Gamma Technologies, LLC) was used to calculate the mass flow rate of the intake and exhaust. In construction of the scatter-band, the obtained actual engine test data was applied from L2 to L3-2 and the CFD data was applied from L3-3 to L3-4.

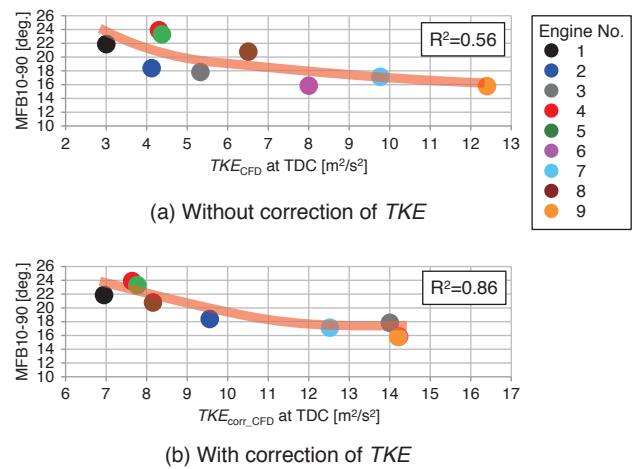


Fig. 7 Effect of correlation between combustion duration (MFB10-90) and  $TKE$  at  $Ne=1500$  rpm,  $BMEP=800$  kPa,  $T_w=80^\circ\text{C}$

### 3. Validation of Hierarchical Scatter-bands

#### 3.1. Scatter-band for Thermal Efficiency

Figure 8 shows the scatter-band data for thermal efficiency. The operating conditions are  $N_e = 1500$  rpm, BMEP = 800 kPa, and  $T_w = 80^\circ\text{C}$ . Figure 8(a) shows the relationship between BSFC and indicated thermal efficiency  $\eta_i$  in L3-1. Overall, BSFC tends to decrease as  $\eta_i$  increases. Here, engine No. 6 exhibits an  $\eta_i$  of 35.8%, which is a higher value than the 33.6% of engine No. 8, but BSFC is roughly the same value of approximately 244 g/kWh. Engine No. 6 is TC and was confirmed to have higher friction due to increased strength in order to withstand high in-cylinder pressure. Next, Fig. 8(b) shows the energy balance. Engine No. 6 exhibits a time loss of 3.1%, which is a lower value than the 3.7% of engine No. 8. This confirmed that engine No. 6 promotes more rapid combustion by the enhanced in-cylinder flow. As described above, the magnitude of the various losses can be perceived from the energy balance. In addition, by understanding the positioning based on the system characteristic analysis described in Section 4.1., the data can be used to set rough target values before performing large-scale CAE.

Figure 9 shows an example of a scatter-band for time loss. This shows that time loss is generally correlated with MFB50 [Fig. 9(a)]. From there, MFB50 is correlated with MFB10-90 [Fig. 9(b)], MFB10-90 is correlated with  $TKE_{\text{corr}}$  [Fig. 9(c)],  $TKE_{\text{corr}}$  is correlated with the maximum value of the transient tumble ratio  $T/R_{\text{max}}$  [Fig. 9(d)], and then  $T/R_{\text{max}}$  is correlated with the steady-state T/R. For example, at a time loss of 4%, MFB50 is approximately 377 deg. ATDC, and MFB10-90 at that time is approximately

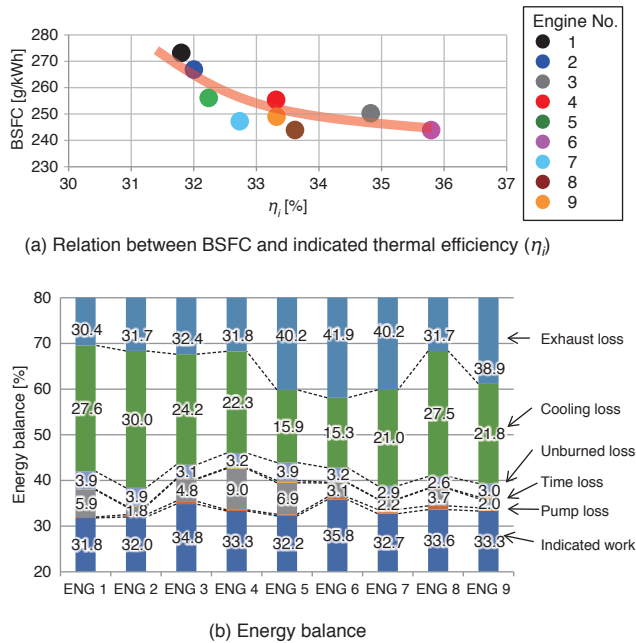


Fig. 8 Scatter-band data in L3-1 at  $N_e=1500$  rpm, BMEP=800 kPa,  $T_w=80^\circ\text{C}$

20 deg. In this way, the levels can be followed downward to eventually arrive at a steady-state T/R of approximately 0.8. The parameter shown on each vertical axis is the same as that shown on the horizontal axis of the upper level. This confirmed that if the steady-state T/R of the cylinder head can be obtained by testing or CFD, the approximate combustion period can be predicted without actual engine testing by advancing and replacing the parameters in order from the lower levels.

#### 3.2. Scatter-band for Combustion Stability

Figure 10 shows the scatter-band data for combustion stability, demonstrating that LNV, which indicates combustion stability, is correlated with combustion fluctuation COV\_IMEP [Fig. 10(a)]. From there, COV\_IMEP is correlated with the MFB50 cycle variation STD\_MFB50 [Fig. 10(b)], STD\_MFB50 is correlated with the MFB10-90 cycle variation STD\_MFB10-90 [Fig. 10(c)],

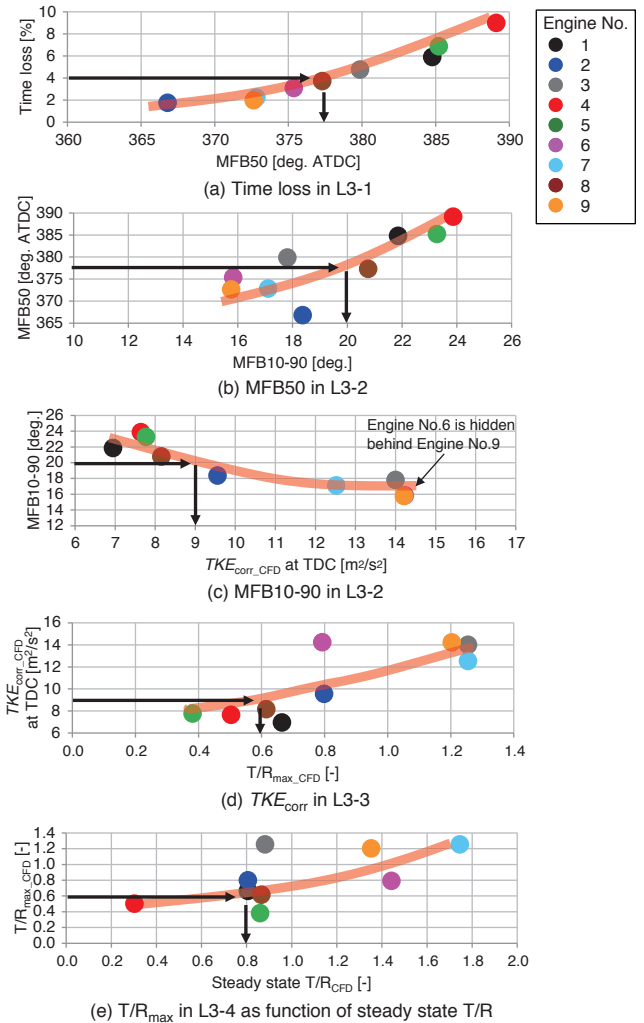


Fig. 9 Scatter-band data related time loss for thermal efficiency at  $N_e=1500$  rpm, BMEP=800 kPa,  $T_w=80^\circ\text{C}$

STD\_MFB10-90 is correlated with MFB10-90 [Fig. 10(d)], and then MFB10-90 is correlated with  $TKE_{corr}$  [Fig. 10(e)]. This confirmed that combustion fluctuation can be reduced by enhancement of the turbulent flow to promote combustion.

### 3.3. Scatter-band for Oil Dilution

Figure 11 shows the scatter-band data for oil dilution. The oil dilution rate is correlated with the oil dilution quantity divided by the oil quantity [Fig. 11(a)]. From there, the oil dilution quantity is correlated with the oil dilution quantity per cylinder [Fig. 11(b)], and the oil dilution quantity per cylinder is correlated with the highest fuel adhesion quantity on the cylinder liner [Fig. 11(c)]. Here, the highest fuel adhesion quantity was the highest value of the fuel adhering to the cylinder liner in one cycle obtained by CFD. This confirmed that the oil dilution rate can be reduced by reducing fuel adhesion to the cylinder liner.

The linkages between the parameters of the scatter-

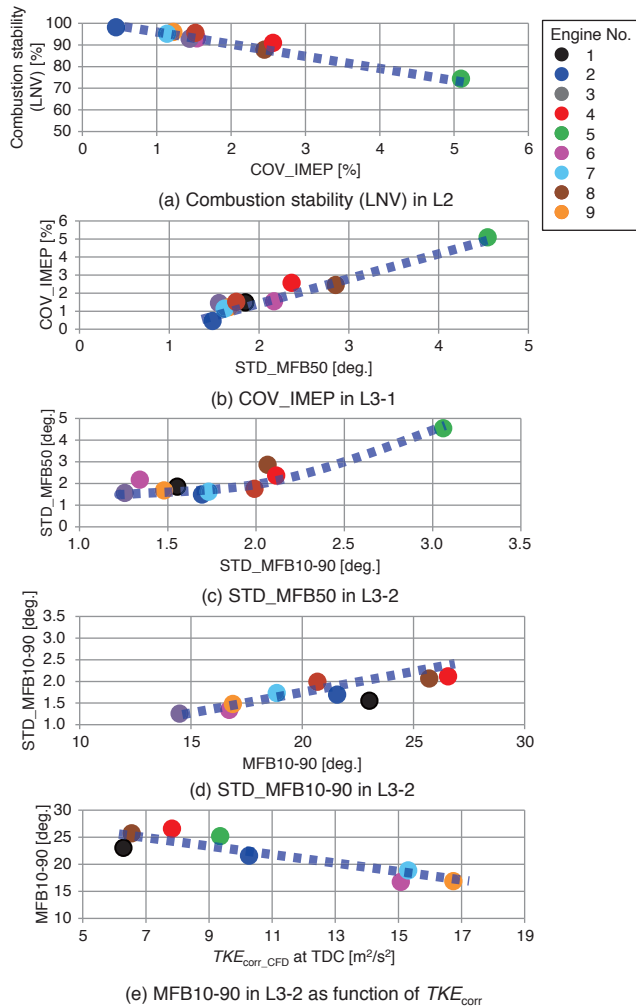


Fig. 10 Scatter-band data for combustion stability at  $N_e=2000$  rpm, IMEP=1000 kPa,  $T_w=80^\circ\text{C}$

bands for thermal efficiency, combustion stability, and oil dilution were confirmed in order to verify the validity of the constructed scatter-bands. The results confirmed that the parameter linkages examined in Fig. 5 are generally correct.

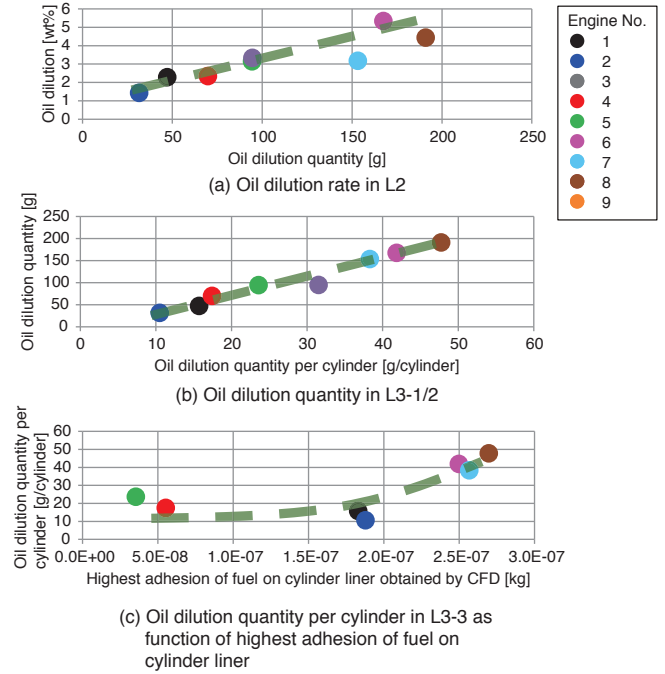


Fig. 11 Scatter-band data for oil dilution at  $N_e=2500$  rpm, IMEP=1000 kPa,  $T_w=50^\circ\text{C}$

## 4. Application to Study of Engine Specifications

In this chapter, the hierarchical scatter-bands constructed in Chapter 3 are applied to promote the combustion of a 2.0 L TC DI engine in order to verify the validity. First, Section 4.1. describes analysis of the current situation and the causes of issues and examination of countermeasures by system characteristic analysis that analyzes the positioning of the parameters in each level from an overall viewpoint. Next, Section 4.2. describes enhancement of the in-cylinder flow by the piston top shape in order to address the issues. Lastly, Section 4.3. describes examination of injection control to decrease the oil dilution rate, which calls for confirmation as a conflicting element.

### 4.1. Analysis of Current Situation by System Characteristic Analysis

Figure 12 shows the results of comparing the thermal efficiency of the 2.0 L TC DI engine No. 7 with that of the similar 1.5 L TC engine No. 6 as base engines for examining specifications. System characteristic analysis here shows the positioning of the parameters to be analyzed

in the range from -1 to 1, where the upper limit value of each parameter is 1 and the lower limit value is -1<sup>(6)</sup>. For example, as a higher indicated thermal efficiency  $\eta_i$  is better, the highest value of  $\eta_i$  in the accumulated data is expressed as 1 and the lowest value as -1. Conversely, as a lower time loss is better, here the lowest value is expressed as 1 and the highest value as -1. Note that the magnitude of the various losses relative to  $\eta_i$  differs as shown in Fig. 8(b), so misjudgment of enhancement methods may occur. Therefore, the ratio of the mean value of each loss to the mean value of  $\eta_i$  was obtained and weighting was performed by multiplying each loss by that ratio. The  $\eta_i$  of the base engine No. 7 was approximately -0.7, which was a low position overall. One factor for this is thought to be that the exhaust loss is large according to the energy balance.

Next, MFB50 and MFB10-90 are positioned well and  $TKE_{corr}$  and T/R occupy high positions, demonstrating that the engines promote combustion by enhancement of the in-cylinder flow. The  $\eta_i$  of engine No. 6 is near the scatter-band upper limit, and there was also no large difference in MFB10-90 between the engines. However,  $TKE_{corr}$  was positioned low even though the T/R of engine No. 7 is larger than that of engine No. 6.

The intake port performance of engines No. 7 and No. 6 in the steady-state condition was compared in order to analyze the relationship between T/R and  $TKE_{corr}$ . Figure 13(a) shows the velocity distribution of the cylinder liner cross-section at the position of half the bore diameter from the gasket surface as measured by particle

image velocimetry (PIV). Comparison with the velocity distribution of engine No. 6 confirmed that in engine No. 7, the flow from the intake side is suppressed and the intake port is designed so that air flows to the exhaust side [red circles in Fig. 13(a)]. Figure 13(b) shows the steady-state T/R and the limit engine speed  $Ne_{limit}^{(11)}$ . Here,  $Ne_{limit}$  is a characteristic value obtained from the average flow coefficient of the intake port, and the larger the value, the more air that can be sucked into the cylinder. Compared to engine No. 6, the  $Ne_{limit}$  of engine No. 7 was roughly the same at approximately 4000 rpm, but the steady-state T/R exhibited a higher value of approximately 2.4. The above results confirmed that, although the intake port provides adequate flow performance, flow formation is poor due to the piston shape. In addition, use of factor analysis and scatter-bands enabled efficient analysis of causes and implementation of countermeasures.

#### 4.2. Enhancement of In-Cylinder Flow by Piston Top Shape

Figure 14(a) shows the piston top bowl shape and the in-cylinder velocity distribution obtained by CFD, and Fig. 14(b) shows the relationship between MFB10-90 and

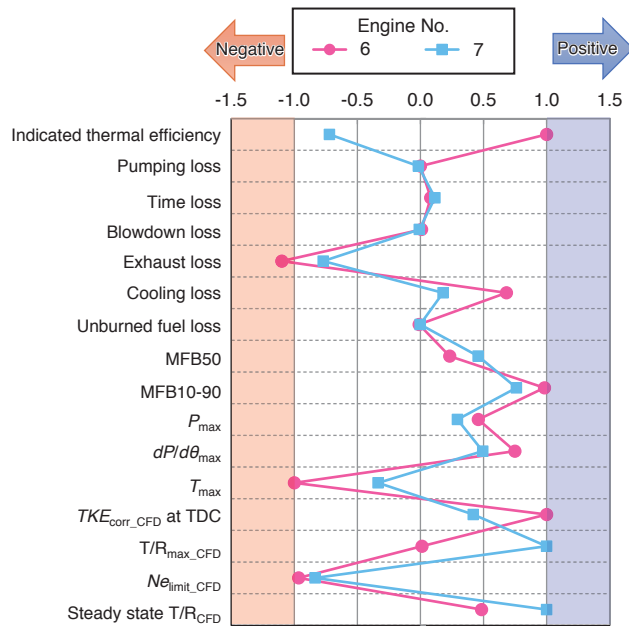
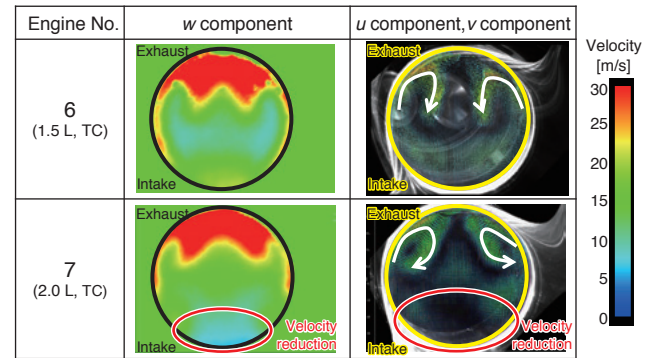
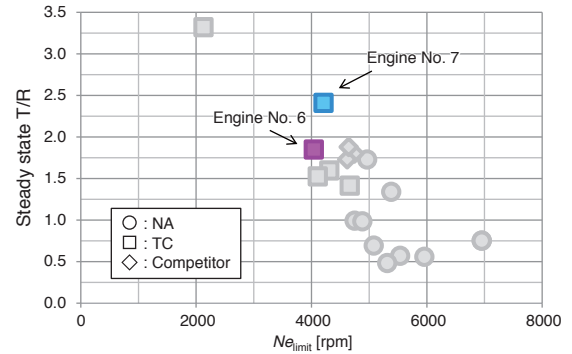


Fig. 12 System characteristic analysis for thermal efficiency by comparison of base engine, No. 7 (2.0 L, TC) with similar specification engine, No. 6 (1.5 L, TC) at  $Ne=1500$  rpm, BMEP=800 kPa,  $T_w=80^\circ\text{C}$



(a) Velocity distribution of cylinder liner cross section at 1/2 bore diameter position from gasket surface obtained by stereo-PIV



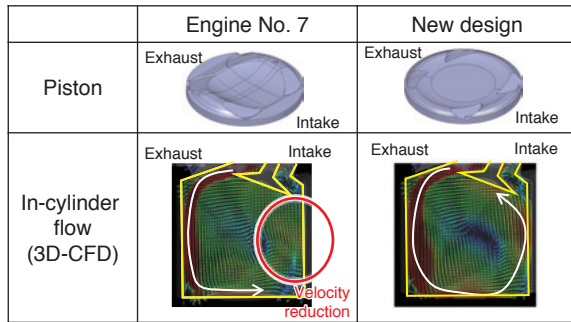
(b) Relation between steady state T/R and  $Ne_{limit}$

Fig. 13 Comparison of intake port performance of Engine No. 7 (2.0 L, TC) with Engine No. 6 (1.5 L, TC) in steady state flow

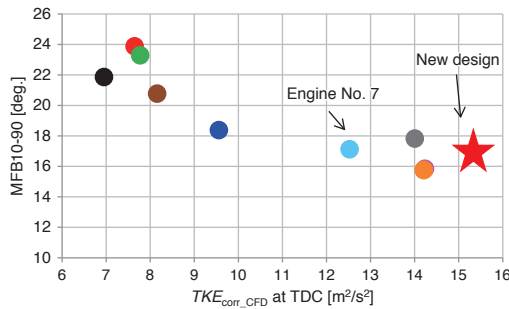
$TKE_{corr}$ . Here, the velocity distribution is the 2D distribution of the bore center cross-section. From Fig. 9(a), the time loss of engine No. 7 was 2.2% and MFB50 = 373 deg. ATDC. Assuming a tentative goal of reducing time loss by 1%, it is sufficient to design combustion so that MFB50 is 370 deg. ATDC and MFB10-90 is 15 to 16 deg. Thus, the tentative target for flow is  $TKE_{corr} = 14$  to  $15 \text{ m}^2/\text{s}^2$ . With the base shape of engine No. 7, while the flow from the intake port was converted to an upward flow by the piston bowl, a decrease in velocity was observed [Fig. 14(a) left figure]. This is consistent with the tendency to judge quality by the system characteristic analysis in Fig. 12. As shown in the right figure of Fig. 14(a), the bowl shape of the piston top was changed to a shallow dish shape in order to smoothly convert the flow into the cylinder to an upward flow, enabling increase of the rising velocity on the exhaust side. As shown in Fig. 14(b), changing from the base shape to a shallow dish shape resulted in a  $TKE_{corr}$  of approximately  $15.2 \text{ m}^2/\text{s}^2$ , so the flow could be enhanced by the bowl shape of the piston top. In addition, when a piston of the same shape was confirmed in an actual engine, MFB10-90 decreased by 0.5 deg. from 17.1 deg. to 16.6 deg. and was generally positioned on the extension of the trend, enhancing BSFC by approximately 0.6%.

#### 4.3. Reduction of Oil Dilution Rate by Injection Control

Figure 15(a) shows the oil dilution rate as a function of the engine displacement  $V_s$ , indicating that the oil dilution



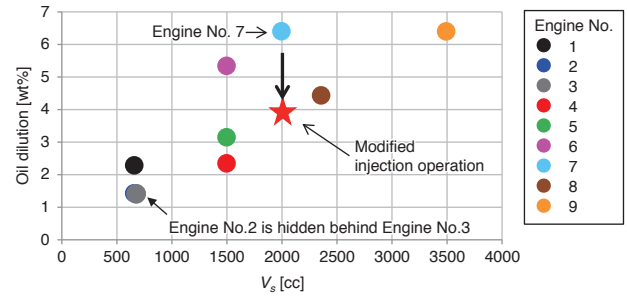
(a) Comparison of in-cylinder flow by piston top bowl shape



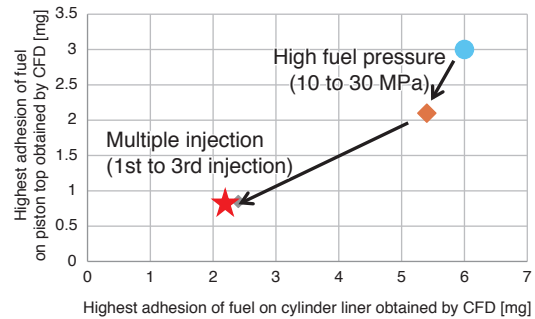
(b) Relation between MFB10-90 and  $TKE_{corr}$  of Engine No. 7 (2.0 L, TC)

Fig. 14 Effect of piston top bowl shape at scatter-band condition,  $N_e=1500 \text{ rpm}$ , BMEP=800 kPa,  $T_w=80^\circ\text{C}$

rate tends to increase together with engine displacement. The fuel injection quantity increases in accordance with the displacement at the same IMEP, so the relative increase in the quantity of fuel adhering to the in-cylinder wall surfaces, such as the cylinder liner, is thought to be a factor. The oil dilution rate of engine No. 7 is positioned near the upper limit of the trend due to the aforementioned increase in displacement. There was a concern that enhancement of the in-cylinder flow would increase the oil dilution rate, so an attempt was made to reduce the oil dilution rate by injection control. Figure 15(b) shows the highest fuel adhesion quantity on the cylinder liner and piston obtained by CFD. By increasing the fuel injection pressure  $P_f$  from the base condition of 10 MPa to 30 MPa and increasing the number of injections from one time to three times, the quantity of fuel adhering to the wall surfaces of both the cylinder liner and the piston were reduced. This is due to atomization of the fuel droplets and reduction of the spray penetration by high fuel pressure and multiple injection. As a result, the oil dilution rate of engine No. 7 could be reduced by 2.6 wt%, from 6.4 wt% to 3.8 wt% [Fig. 15(a)].



(a) Comparison of oil dilution as function of engine displacement



(b) Comparison of highest adhesion of fuel on cylinder liner and piston top

Fig. 15 Effect of injection operation at  $N_e=2500 \text{ rpm}$ , IMEP=1000 kPa,  $T_w=50^\circ\text{C}$

## 5. Systemization of Data Accumulation and Utilization

Figure 16 shows the trend in the yearly accumulation of engine and steady-state flow intake port test data. The

amount of engine data when constructing the scatter-bands was equivalent to that for nine engines. By continuously accumulating data and incorporating data from the benchmarking project of the Research Association of Automotive Internal Combustion Engines (AICE), data equivalent to 26 engines had been accumulated as of 2022. As examples of utilization, scatter-bands have been applied to set target values for in-cylinder flow and to examine the combustion chamber S/V ratio to reduce cooling loss. It is thought that utilization in the early stages of development has enabled smooth transition to combustion design and CAE analysis and reduced reworking in engine development.

From the above, the original goal of applying scatter-bands in the initial examination stage of engine development and indicating the direction of development was achieved. However, as the engine control conditions were fixed as shown in Table 2, the optimal control conditions for each engine may differ. Going forward, it is also necessary to accumulate data under the optimal control conditions for each engine, and to expand the range of utilization to understand the sensitivity of control parameters and examine the optimal values. It is also necessary to increase the number of parameters to be controlled in order to further enhance the environmental performance of engines.

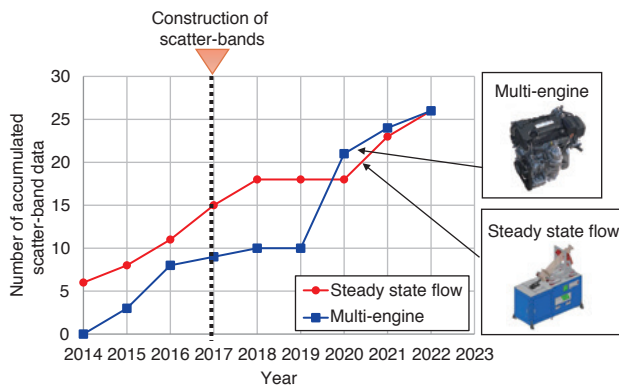


Fig. 16 Yearly accumulation of engine and steady flow test data

## 6. Conclusion

Hierarchical scatter-bands were constructed in order to determine engine specifications in the early stages of development with the goal of increasing development efficiency by reducing reworking. The constructed scatter-bands were applied to promote the combustion of a TC DI engine, the validity was verified, and the following conclusions were obtained.

- (1) The four elements of thermal efficiency and combustion stability, oil dilution, and soot, which conflict with thermal efficiency, were defined in the engine requirements (Level 2), and requirement analysis was performed for the intermediate parameters (Level 3) in order to link them hierarchically to Parts (Level 4). The

results of verification using the data of nine engines confirmed that the parameter linkages are generally correct.

- (2) Parameter normalization was performed in order to evaluate different engine specifications using the same criteria. As an example, when the turbulent kinetic energy was normalized by engine speed and bore diameter, the correlation with the combustion period was enhanced.
- (3) The issues of a TC DI engine were analyzed using scatter-bands. System characteristic analysis and requirement analysis found that in-cylinder flow formation was not good due to the piston shape and enabled efficient analysis of causes and implementation of countermeasures.
- (4) In order to reduce the oil dilution rate, which is given as a conflicting event with enhancement of the in-cylinder flow, the quantity of fuel adhering to the in-cylinder wall surfaces was reduced by injection control. High fuel pressure and multiple injections enabled reduction of fuel adhesion and balancing of the performance required of the engine.
- (5) It is thought that the continuing accumulation and utilization of scatter-band data can reduce reworking in engine development. Going forward, it will be necessary to increase the number of parameters to be controlled in order to further enhance the environmental performance of engines.

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|      |                                                     |
|------|-----------------------------------------------------|
| DI   | Direct Injection                                    |
| EGR  | Exhaust Gas Recirculation                           |
| EM   | Emission                                            |
| EOI  | End Of Injection                                    |
| EVC  | Exhaust Valve Close                                 |
| IMEP | Indicated Mean Effective Pressure                   |
| INJ  | Injector                                            |
| IVO  | Intake Valve Open                                   |
| LNV  | Lowest Normalized Value                             |
| MBD  | Model-Based Development                             |
| MBT  | Minimum advance for Best Torque                     |
| MFB  | Mass Fraction Burnt                                 |
| NA   | Natural Aspiration                                  |
| PI   | Port Injection                                      |
| PIV  | Particle Image Velocimetry                          |
| PM   | Particulate Matter                                  |
| PN   | Particle Number                                     |
| RDE  | Real Drive Emission                                 |
| SOI  | Start Of Injection                                  |
| STD  | Standard deviation                                  |
| T/R  | Tumble Ratio                                        |
| TC   | Turbocharger                                        |
| TDC  | Top Dead Center (BTDC: Before TDC, ATDC: After TDC) |
| WLTC | Worldwide harmonized Light duty vehicles Test Cycle |

### List of Symbols

|                |                                        |
|----------------|----------------------------------------|
| $A/F$          | Air/Fuel ratio [-]                     |
| $D$            | Bore diameter [mm]                     |
| $N_e$          | Engine speed [rpm]                     |
| $P_f$          | Pressure of fuel [MPa]                 |
| $L_s$          | Stroke [mm]                            |
| $S/V$          | Surface/Volume ratio [ $m^2/m^3$ ]     |
| $T_w$          | Temperature of water [ $^{\circ}C$ ]   |
| $TKE$          | Turbulent Kinetic Energy [ $m^2/s^2$ ] |
| $U_p$          | Mean piston speed [m/s]                |
| $u_{intake}$   | Velocity of intake flow [m/s]          |
| $u'$           | Turbulent intensity [m/s]              |
| $V_s$          | Displacement [L]                       |
| $\theta_{ig}$  | Ignition timing [deg. BTDC]            |
| $\theta_{inj}$ | Injection timing [deg. BTDC]           |
| $\eta_i$       | Indicated thermal efficiency [%]       |
| $\eta_v$       | Volumetric efficiency [%]              |

### List of Abbreviations

|      |                                                                    |
|------|--------------------------------------------------------------------|
| AICE | the research association of Automotive Internal Combustion Engines |
| BMEP | Brake Mean Effective Pressure                                      |
| BSFC | Brake Specific Fuel Consumption                                    |
| CAE  | Computer Aided Engineering                                         |
| CAFE | Corporate Average Fuel Efficiency                                  |
| CFD  | Computational Fluid Dynamics                                       |
| COV  | Coefficient Of Variation                                           |

### ■ Author ■



Yasuhiro OKURA



Junya YOSHIZAWA



Hiromitsu MATSUDA



Seisuke SATO



Koichi TAKASE

# Performance of Polymer Additively Manufactured Tooling for Low-volume High Strength Steel Sheet Metal Parts

Ryan HAHNLEN, Ph.D.<sup>1</sup> Ben HOFFMAN<sup>1</sup> Madhura ATHALE<sup>2</sup>  
Taejoon PARK, Ph.D.<sup>2</sup> Farhang POURBOGHRAT, Ph.D.<sup>2</sup>

## ABSTRACT

Low-volume prototype tooling is a large expense in vehicle development. Often, these tools cost a similar amount to mass-production tooling despite the much shorter useful life. Much of this cost is associated with the precision machining needed to create the tool geometry. Additive manufacturing brings with it the ability to create complex geometries at or near the final part shape. When applied to metal forming tools, additive manufacturing has the potential to reduce the cost and lead time of tooling by reducing the machining time required for traditionally manufactured tools. This study investigates the performance of sheet metal forming tools made from different polymer additive manufacturing materials and processes through forming trials on 1.6 mm thick 590 MPa high-strength steel, comparing the tools and their manufactured parts to traditional hard steel tooling and parts produced thereon. Physical die trials show success in forming mass-production materials accurately and tool life adequate to support low-volume production. A modeling framework has also been developed to rapidly iterate on new materials for tool design and application to other sheet metal grades and gauges.

## 1. Introduction

The development of automobiles is an iterative process, involving design, analysis, and prototyping phases before new models enter into mass-production. The majority of mass-production vehicle structures consist of many individually formed sheet metal components, each formed by unique die sets. These mass-production die sets are typically made from hardened steel for longevity, allowing for 1,000-10,000's of parts before refurbishment. However, before mass-production tooling can be made, validation needs to be performed on prototype parts made on prototype tooling. Depending upon the grade and gauge of sheet metal used to make the stamped component, tooling used for prototyping these parts is typically made from machined steel or cast and machined zinc-aluminum alloys such as Kirksite or Zamak. Where the cost of mass-production die sets is amortized over the production volume of the vehicle, often consisting of multiple 100,000's of parts, the useful life of prototype tooling, which has a cost similar to that of mass-production tooling, may be less than 100 parts due to

the small quantity of parts needed for development. Despite similar robustness and cost, prototype tooling has a much shorter useful life than mass-production tooling and is one of the largest contributors to vehicle development cost.

This study investigates the ability to use Additive Manufacturing (AM) to create sheet metal forming tools that can create formed components equivalent to the same components formed on hard tooling with the ultimate objective of reducing the cost and lead time as compared to traditional hard tooling manufacturing methods.

## 2. Methods

### 2.1. Approach

This study endeavors to create parts of relevant sheet metal grade and gauge on AM tooling that match the forming strain and geometry of the same components formed using traditional hard tooling while understanding the toolset life as determined by deformation of the tools themselves. In order to obtain a common basis for comparison, the parts formed on the AM toolset are

<sup>1</sup> Honda Development and Manufacturing of America, LLC

E-mail: rhahnlen@na.honda.com

<sup>2</sup> The Ohio State University

compared to parts formed on a steel toolset of identical geometry that was manufactured using traditional machining methods.

While metal AM processes are an obvious first choice for forming tools from a tool longevity perspective, material cost, process cost, post-processing time, and size envelopes inherent in current metal AM technology preclude metal AM as a viable alternative to traditional hard tooling manufacturing processes due to the required size of stamping dies and associated cost of the die sets. Instead, polymer AM processes are the focus of this research due to the lower overall cost of the parts they produce. Key challenges in successfully using polymer AM die sets for forming sheet metal components are managing the inherently lower yield strength and elastic modulus of the materials which impact part accuracy and tool longevity. If the tools are limited to low-volume production, as in prototype and service part production, tool longevity of polymer tools has been shown to be sufficient for thin gauge and/or low-grade alloys<sup>(1)-(6)</sup>, but little research to date has investigated application to automotive-relevant gauges and grades.

Simulation is a key step in developing metal forming tools. A common assumption in metal forming simulation is the use of rigid tooling, which holds well when forming thin sheets of metal with steel dies. However, in switching from steel to polymer-based tooling, assumptions on negligible tool deflection and wear are no longer accurate. This study extends the authors' work<sup>(7)</sup> on development of a modeling methodology that accounts for the elastic and plastic response of AM tooling during sheet metal stamping. The models not only accurately recreate tool behavior but serve as a basis for further exploration in using new AM materials and forming other grades and gauges of sheet metal.

## 2.2. Material Grade

All parts formed in this study were made from 1.6 mm

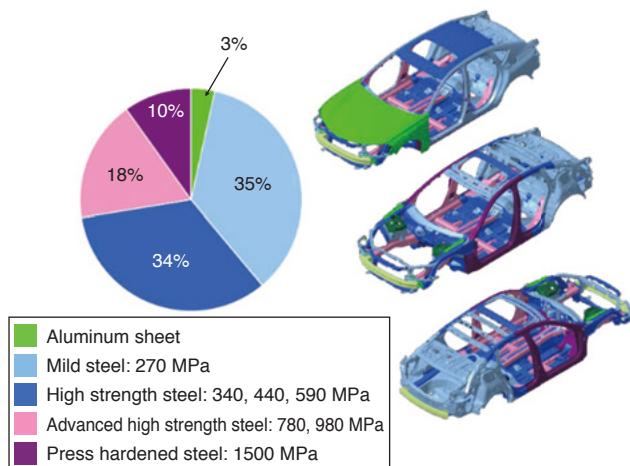


Fig. 1 Body-in-White sheet metal composition for 2021 Acura TLX

thick High-Strength Steel 590 (HSS 590), a commonly used material for structural components in automobile designs. This material and gauge were selected because they represent a large portion of the Body-in-White (BIW) structure in modern unibody automotive construction while a majority of the remainder of a typical BIW consists of lower grade steel and aluminum sheet metals. For example, Fig. 1 shows the BIW composition of a 2021 Acura TLX<sup>(8)</sup>. HSS 590 comprises 35% of the BIW and when combined with lower grade steel and aluminum alloys, accounts for 90% of the BIW composition. If AM tools are capable of forming HSS 590 parts accurately and consistently, it is likely that such AM tools will also successfully form the lower-strength and thinner-gauge alloys as well.

## 2.3. AM Processes and Materials

This study investigates two different AM processes using two different materials to create a sheet metal forming toolset. The two processes are Big Area Additive Manufacturing (BAAM), developed by Cincinnati Incorporated and Oak Ridge National Lab, and Fused Deposition Modeling (FDM) on a Stratasys F900 system. Both systems provide unique capabilities that make them attractive for printing forming tools.

The BAAM system has a large build volume, up to  $2.4 \times 6.1 \times 1.8$  m, and a deposition rate of approximately 45 kg/hour<sup>(9)</sup> which makes it attractive for printing toolsets for large automotive components in a single build. However, the BAAM system requires a finish machining process to achieve the final tool geometry due to its low print resolution. While BAAM does not eliminate the machining step, finish machining of a net-shape polymer is faster than machining the same geometry from a billet of steel, as done for traditional tool manufacturing. In comparison, the FDM system has a smaller build envelop, up to  $914 \times 610 \times 914$  mm<sup>(10)</sup>, but much finer resolution, allowing for the use of printed components directly from the machine.

Both the BAAM and FDM systems have a wide variety of available polymer feedstock, allowing a tool designer to select a material that has sufficient mechanical properties and wear characteristics while minimizing the cost of the print. For this study, glass fiber filled polycarbonate (GF-PC) was selected for use in the BAAM systems due to its strength, stiffness, and toughness. For FDM tooling, Nylon 12CF, a carbon fiber filled nylon (CF-Nylon), was selected for its high strength and stiffness.

## 2.4. AM Material Characterization

AM materials exhibit high anisotropy in material properties due to the presence of reinforcement fibers and layer-wise fabrication which results in the formation of voids inside the material as well as inhomogeneous temperature histories. In FDM fabrication processes, the reinforcement fibers get aligned along the direction of material deposition due to extrusion forces. This results in the material having tetragonal symmetry, with every

Table 1 Elastic modulus and yield strength of tested AM materials

| Material | Direction | E [GPa] | YS [MPa] |
|----------|-----------|---------|----------|
| CF-Nylon | X         | 2.7     | 26.4     |
|          | Y         | 2.6     | 28.5     |
|          | Z         | 2.2     | 30.0     |
|          | XY        | 7.0     | 67.9     |
|          | XZ        | 1.6     | 20.2     |
|          | YZ        | 1.8     | 17.1     |
| GF-PC    | X         | 4.0     | 56.6     |
|          | Y         | 3.9     | 58.3     |
|          | Z         | 2.8     | 57.7     |
|          | XY        | 3.6     | 54.4     |
|          | XZ        | 3.0     | 44.1     |
|          | YZ        | 2.7     | 47.7     |

layer orientation being orthogonal to the previous layer. In tetragonal materials, the directions X and Y, as well as XZ and YZ are equivalent due to the internal symmetry<sup>(7), (11)-(15)</sup>. Since BAAM is a similar AM technology as FDM but at a larger scale, these same observations are assumed to apply. Here, the X-Y plane is considered as the printing plane and Z is the build direction. Due to the complex properties of AM materials, it is important to characterize them properly to make accurate models during the die design process.

The AM materials were characterized using uniaxial tension test along three principal and three diagonal material directions. Table 1 shows the results of mechanical characterization of the CF-Nylon and GF-PC materials. High anisotropy is observed in both elastic modulus and yield strength in BAAM and FDM materials due to the presence and orientation of reinforcement fibers and voids from printing.

## 2.5. Forming Trial Procedure

Draw forming, in which a flat blank is held between a blank holder and die while a punch is used to draw the material into the die, is a common forming process in automotive mass-production. In this process, the blank holder force can be varied to adjust how material flows into the die and the amount of plastic deformation the blank undergoes during the forming process. A common draw forming tool geometry, the Universal Formability Testing (UFT) tool seen in Fig. 2, was used as a basis for comparison between the baseline steel tooling and different AM materials to evaluate formed part accuracy, die life, and tool cost. The UFT tool consists of four parts: the die insert, primary die, blank holder, and punch.

For this study, the full steel toolset was used to make 100 formed parts to serve as a component baseline, then an initial pilot study replaced the steel die insert with a 3D printed solid CF-Nylon insert. Upon successful completion of the pilot study, an additional forming trial was completed with a solid GF-PC AM toolset consisting of the UFT punch and combined primary die and insert.

All forming trials utilized a 300 ton servo press

programmed with a crank slide motion. The blank holder force was maintained at 200 kN for the duration of the draw phase and the total draw depth was set at 65 mm with a speed of 14 strokes per minute. These parameters were chosen based on prior experience with the sheet metal material and relevance to mass-production manufacturing. For all trials, the HSS 590 blanks were lubricated with the same mass-production relevant water-based lubricant and a subset of blanks was etched through an electrochemical process for post-forming strain analysis. The etching process applies a regular pattern on the surface of the sheet metal with known spacing. By measuring the pattern spacing after forming, a discrete strain map can be generated. An example of the etch pattern used is shown in Fig. 3(b).

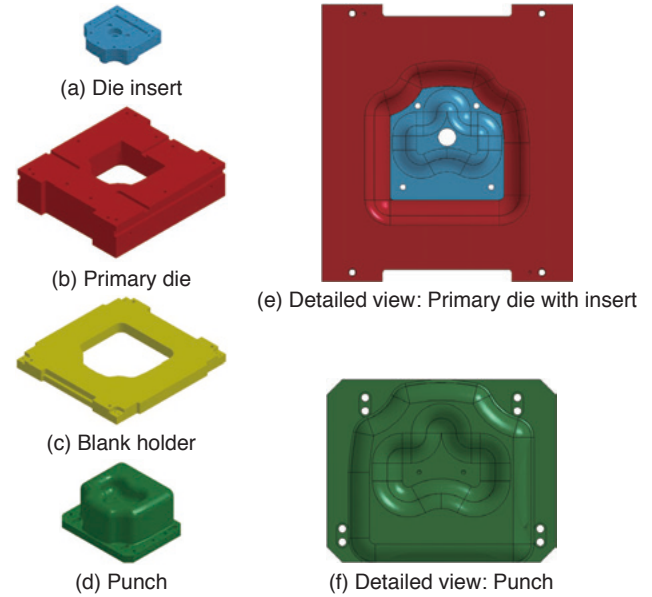


Fig. 2 Universal formability testing tool components

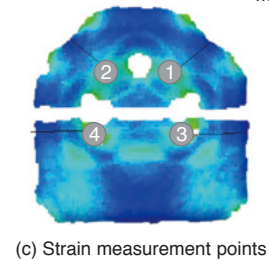
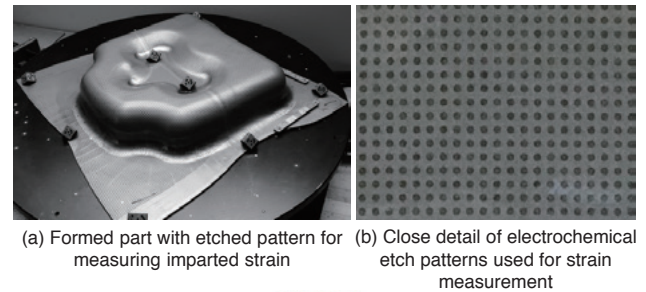


Fig. 3 Strain measurement of a steel tool-formed component

Components with etched patterns were scanned with an ARGUS system to quantify and compare post-forming strain at up to five locations on final components for comparison across all forming trials. The geometric accuracy of the parts was also measured using an ATOS 3D scanner. Both strain measurements and geometric measurements were compared to parts formed on the steel baseline toolset. Each toolset was also scanned using an ATOS 3D scanner before and after the forming trial to quantify tool change due to wear or deformation.

## 2.6. Modeling and Simulations

FEA simulations of the stamping process described in Section 2.5. were performed on the commercial software ABAQUS/Explicit. For stamping with the steel toolset, all the tools were modeled as rigid parts. The blank was meshed with 3 mm shell elements having 7 Gauss integration points through thickness. Element type and size were decided based on a mesh sensitivity analysis considering parameters such as the stresses and strains at critical locations. The die was fixed while the punch was given a displacement boundary condition with the same profile as in experiments. Preliminary forming simulations were first validated on the baseline trial. Stamped part strains and part thickness from simulations were compared with that from experiments to validate the simulation parameters.

For stamping simulations with polymer AM tools, the AM parts were modeled with 3 mm deformable linear tetrahedral elements as they are much softer than conventional steel tooling. To account for the tetragonal symmetry of AM materials with orthogonal printing orientation, orthotropic elastic material model along with von Mises yield function and isotropic hardening was used. Experimental testing data from Table 1 was used to calibrate the model coefficients<sup>(16)</sup>.

In all simulations in this study, a linear elasticity model, von Mises yield function, and isotropic hardening model were assumed for HSS 590 blank sheet. Hardening properties were obtained from uniaxial tension tests used for initial sheet metal characterization. Friction coefficient between the blank and tools was calibrated for steel tools as well as polymer tools by comparing the punch force vs. displacement data from experiments and simulations. A friction coefficient of 0.15 was found to be ideal for both steel and polymer tools.

Progressive plastic deformation of the AM tool parts due to repeated stamping was estimated through FEA simulations by a geometry update scheme. After each stamping simulation using ABAQUS/Explicit, an unloading simulation using ABAQUS/Standard was performed on the AM tooling to obtain the plastic deformation. The deformed tool shape along with the material state was used as the starting point for the next stamping simulation. This process was repeated until the plastic deformation reached saturation, and the additional plastic deformation was less than 5% from the previous stamping simulation.

Springback simulations were also performed on the formed part using ABAQUS/Standard. Final part shape after springback was compared with experiments as well as that from stamping simulation with steel tooling. Tool geometry after springback was also compared with experimental tool scans showing the plastic deformation of AM tooling post-stamping.

## 3. Experimental Results and Discussion

### 3.1. Steel Tool Baseline Trials

The steel toolset, including the punch, blank holder, primary die, and die insert were installed in the stamping press and formed a full 100-part trial using the HSS 590 material and the press parameters described in Section 2.4. Blanks #1, #15, #30, #40, #50, #60, #70, #80, #91, and #100 were etched for strain analysis. For brevity, only the top side average major strains and their standard deviations are shown in Table 2.

#### 3.1.1. Formed part strain measurements

A formed part ready for strain analysis is shown in Fig. 3(a). Due to the high forces and friction inherent in the forming process, the etched pattern in some regions of some parts was worn off of the blank and unable to provide strain data. However, all etched blanks did provide strain measurements in multiple key locations. Four key locations were selected from the strain maps of the baseline tool-formed components and used as points of comparison for parts formed using AM toolsets. An example of a strain map and regions of comparison are shown in Fig. 3(c). Strain comparison results are shown in Table 2 for the top side of the formed component. As exhibited by the standard deviation, a maximum of 1.41% at strain region 2, strain was consistent across the entire 100-part trial for the steel tool-formed parts. To compare the accuracy of the AM toolsets, the same strain regions are investigated and compared to the range of strain values within  $\pm 3$  standard deviations ( $\pm 3\sigma$ ) of the average strain of a particular region on the steel tool-formed baseline components. If the average strain of a part formed on an AM tool falls within this region, it indicates that it is within the expected variation of strain induced by a traditionally made toolset.

Since the steel die is considered the baseline for comparison of AM die sets, ATOS scans of the formed parts are compared to AM tool-formed parts in forthcoming sections. The ATOS scan gives a 3D measurement of the final part and is used to compare draw depth and overall shape profile in the drawn portion of the components.

#### 3.1.2. Simulation and comparison

Stamped part strains and part thickness from simulations were compared with that from experiments as shown in Table 2 to validate the simulation parameters. Strains for all four regions match the average experimental values within 2.2%, indicating that the baseline simulation has

Table 2 Comparison of experimental part strain and simulated strain for the steel baseline UFT toolset

| Strain             | Strain region |       |       |       |
|--------------------|---------------|-------|-------|-------|
|                    | 1             | 2     | 3     | 4     |
| Exp. average       | 16.5%         | 14.7% | 12.4% | 13.7% |
| Standard deviation | 0.07%         | 1.41% | 0.42% | 0.92% |
| Simulation         | 18.1%         | 15.9% | 10.4% | 11.5% |

sufficient accuracy for examining the effects of changing the properties of the forming tools. This maximum deviation of the baseline tool simulation will be used as a point of comparison for the accuracy of simulated AM toolsets.

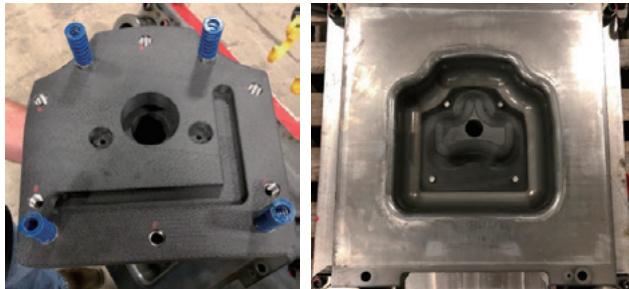
### 3.2. CF-Nylon Tool Trials

Prior to printing a full AM die set, the insert portion of the UFT die was printed from CF-Nylon to prove concept viability. The insert was printed fully-dense to maximize part strength as shown in Fig. 4. Aside from the insert, the punch, blank holder, and primary die were all the same steel UFT components used in the baseline trial.

The steel tool components and the CF-Nylon die insert were installed in the stamping press and formed a full 100-part trial using the HSS 590 material and the press parameters described in Section 2.5. Blanks #5, #40, #99, and #100 were etched for strain analysis.

#### 3.2.1. CF-Nylon part accuracy

Part #5 and #100 were oriented such that the etching patterns and strain analysis was performed on the top surface. The strain measurements are summarized in Table 3. For measurement regions 1-4, the average strain data are within 2.3% of the same regions on the steel tool-formed baseline components. For strain regions 1, 2, and 4, these fall within  $\pm 3\sigma$  of the baseline components, indicating that parts formed with the CF-Nylon insert are comparable to the parts formed on a complete steel die set. The consistency of strain measurements over the 100-part forming trial is also comparable to that of the measurements of the steel tool-formed components, with standard deviations between 0.14% and 0.37%, similar to the range of standard deviation observed in the baseline components, 0.07% to 1.41%. The



(a) Solid CF-Nylon printed die insert (b) CF-Nylon insert installed in primary die

Fig. 4 CF-Nylon die insert

Table 3 Comparison of experimental part strain and simulated strain for the CF-Nylon insert with steel primary die

| Strain             | Strain region |       |       |       |
|--------------------|---------------|-------|-------|-------|
|                    | 1             | 2     | 3     | 4     |
| Exp. average       | 16.6%         | 17.0% | 10.6% | 12.8% |
| Standard deviation | 0.14%         | 0.37% | 0.32% | 0.18% |
| Simulation         | 15.8%         | 16.3% | 11.8% | 12.3% |

similar strain levels and similar consistency of the parts as compared with those formed on the steel toolset indicate that a solid CF-Nylon insert is an acceptable choice from a part accuracy perspective.

Since the CF-Nylon insert was intended as a quick verification of the viability of AM forming tools, individual parts were not scanned via ATOS for a geometry comparison with the baseline steel tool-formed parts.

#### 3.2.2. CF-Nylon tool geometry

The CF-Nylon insert performed well on the full 100-part forming trial and a second geometry scan was completed to quantify the overall deformation of the tool. Figure 5 shows the comparison of the pre- and post-trial geometry scans. Deformation is concentrated at the corners of the insert with the maximum occurring at the front protrusion, or “nose,” of the insert with the maximum deformation of 0.259 mm. Due to the lack of plastic debris observed during the forming trial and absence of scratches on the insert, this deformation is believed to be due solely to plastic deformation due to the compressive forces from contact with the blanks during forming.

#### 3.2.3. CF-Nylon simulation and comparison

Figure 6 shows the cumulative plastic deformation from simulation compared with experiment. It is observed that the highest amount of tool deformation occurs in the very first stamping pass and the cumulative deformation reaches a steady state value within the first 5 passes. Additionally, the simulated part strain closely matches that measured from the experimental trials as seen in Table 3.

Simulated part strain of components formed using the CF-Nylon insert have a maximum absolute deviation of 1.20% from the average measured strain in region 3, as shown in Table 3. This is less than the simulation deviation of the rigid tool simulation used in the baseline analysis, indicating that the model is accurately capturing the key behaviors relevant for using deformable AM tools.

### 3.3. GF-PC Tool Trials

A BAAM system was utilized to print a solid UFT die with integrated insert and a matching punch from GF-PC. Due to the size of the tools relative to the BAAM system, solid blocks were printed and machined to final dimensions as seen in Fig. 7. The insert and punch were installed with

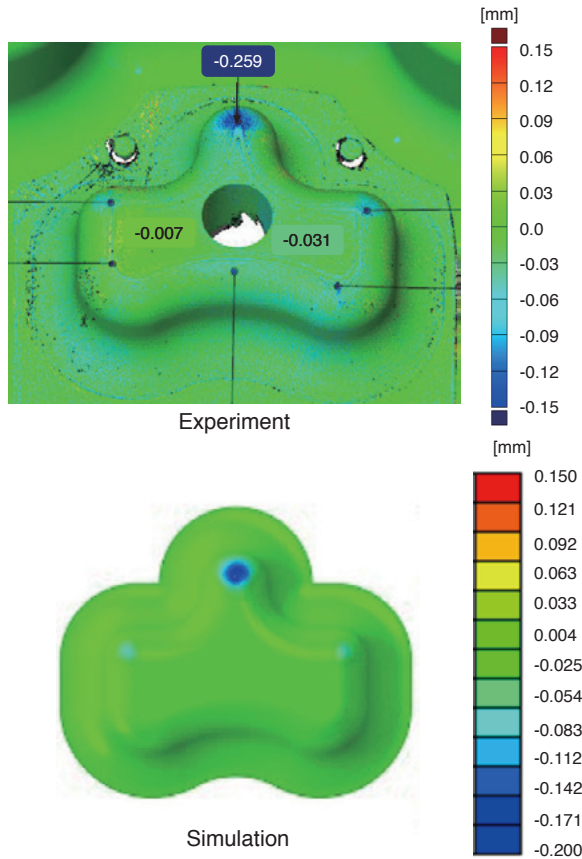


Fig. 5 Experimentally determined and simulated deformation in the CF-Nylon insert

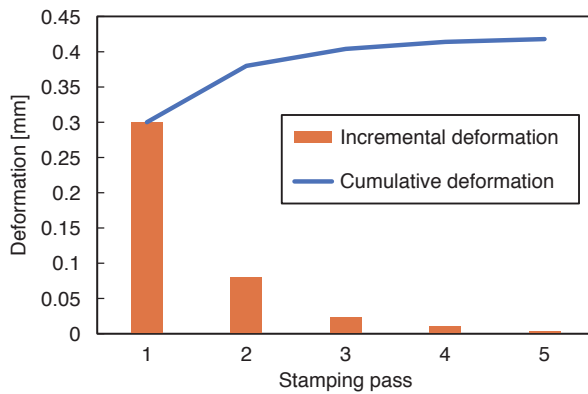


Fig. 6 Cumulative deformation from FEA of CF-Nylon insert over repeated part stampings

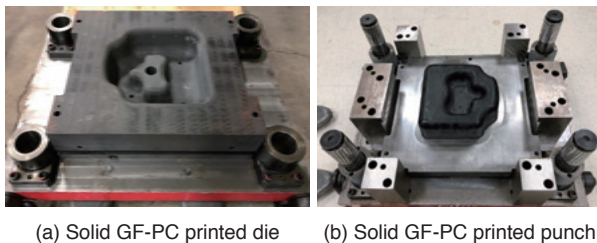


Fig. 7 Solid GF-PC die and punch

Table 4 Comparison of experimental part strain and simulated strain for the GF-PC UFT toolset

| Strain             | Strain region |       |       |       |
|--------------------|---------------|-------|-------|-------|
|                    | 1             | 2     | 3     | 4     |
| Exp. average       | 11.7%         | 11.8% | 10.9% | 10.8% |
| Standard deviation | 0.61%         | 0.64% | 1.61% | 0.15% |
| Simulation         | 12.8%         | 13.7% | 10.7% | 10.6% |

the steel blank holder for the UFT toolset in preparation for the forming trials. Similar to the previous forming trials, 100 sheet metal parts were formed using the GF-PC BAAM printed tool. Parts #1, #15, #30, #40, #50, #60, #70, #80, #90, and #100 were etched for strain analysis and were also scanned for geometry measurements.

### 3.3.1. GF-PC part accuracy

The etched patterns on the GF-PC formed components on regions 1-4 provide strain values seen in Table 4. These strains are lower than the strains exhibited by the same regions on both the steel baseline tool and CF-Nylon insert formed components. The maximum absolute deviation between the GF-PC average strain and that of the baseline components is 4.8% at region 1 while the strains at both regions 2 and 4 are 2.9% lower than their respective average values on the baseline components. This indicates that the material was not stretched as much during the forming operation with the GF-PC toolset as it was when using the other toolsets. Despite the reduced draw depth and resulting reduced strain levels, the standard deviation over the forming trial is 1.61%, similar to that of the baseline and CF-Nylon insert trials, showing that the GF-PC toolset does produce consistent components.

The difference between the parts from GF-PC tool compared to the steel tool baseline showed a much greater deviation than the part-to-part change during the GF-PC trial. A difference of approximately 1.5 to 2.2 mm was observed in the GF-PC part #1 vs. steel tool part #1 within the body of the part, as seen in Fig. 8. This is believed to be due to increased deflection of the AM tools due to the lower elastic modulus of the GF-PC material as compared to steel. The reduced draw depth is believed to be the cause of the lower strains, as compared to the steel baseline formed parts, measured in the formed parts, shown in Table 4.

### 3.3.2. GF-PC tool geometry

The GF-PC die and punch were ATOS scanned before and after the forming trials. The pre- and post-trial scans were compared to each other to determine the amount of deformation incurred over the trial. The comparison shows a maximum deviation of 0.158 mm in the pre- to post-trial comparison occurring at the tool nose where maximum load occurs, as seen in Fig. 9. This is approximately half of the deformation observed in the CF-Nylon insert in the same

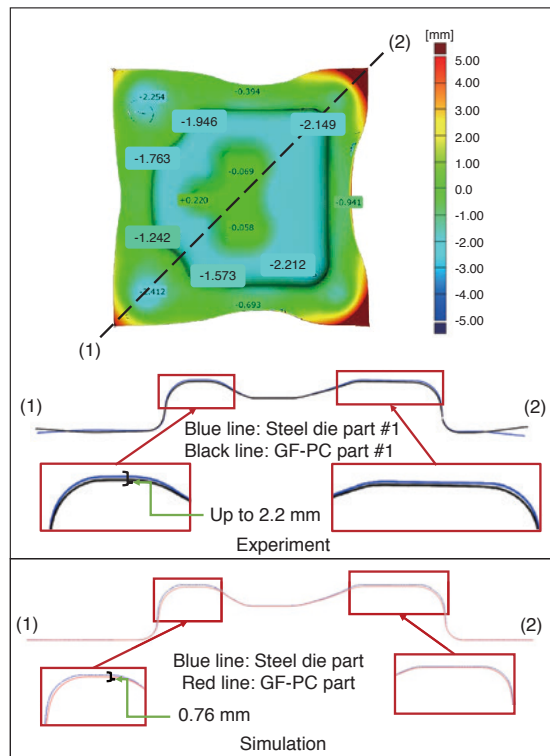


Fig. 8 Draw deviation between steel tool-formed part #1 and GF-PC tool formed-part #1

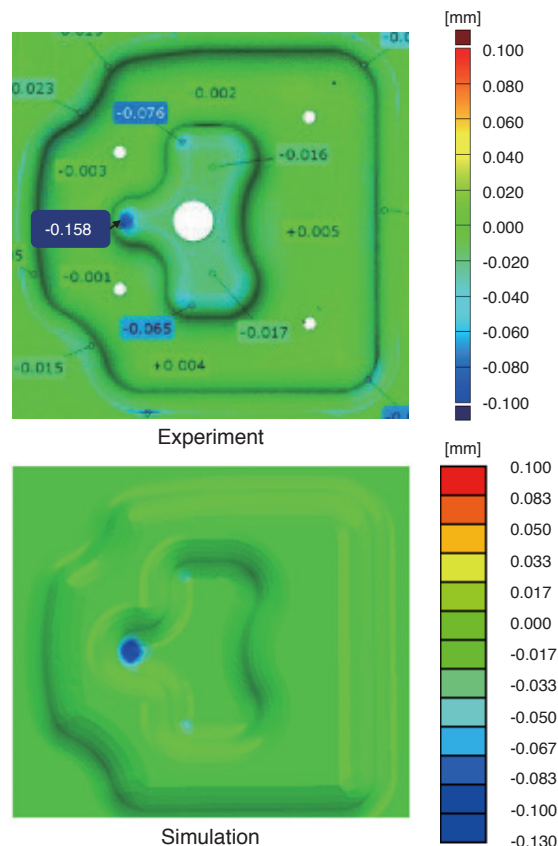


Fig. 9 Measured and simulated deformation comparison for GF-PC die

region, indicating that this toolset could likely form many more components.

### 3.3.3. GF-PC simulation and comparison

As seen in Table 4, simulated part strains match well with those from experiments, with a maximum deviation of -1.90% at region 2. The model also captures the generally reduced strain in the key regions of the GF-PC formed components as compared to baseline parts. This indicates that, like the CF-Nylon insert simulation, the model has sufficient detail to account for the role of a deformable tool in the forming process.

Maximum deviation of 0.76 mm was found between parts stamped using steel vs. GF-PC tools after the springback simulation on the blank, shown in Fig. 8. This deviation is smaller than that found experimentally, up to 2.2 mm, which could be due to the lack of a sophisticated blank material model which would require additional testing to calibrate. Accurate prediction of springback was not considered to be a major goal of this study.

The simulation was also able to accurately capture the deformation of the GF-PC toolset. As shown in Fig. 9, the simulated die exhibits a deformation of 0.130 mm in the nose region of the insert, the same region in which the GF-PC tool exhibited a 0.158 mm deviation from its pre-trial geometry. This indicates that the yield criteria used for the AM material and the stresses generated in the model accurately reflect those experienced during the forming trials.

## 4. Performance Comparison

By comparing the performance of the AM die sets to each other, a viable approach for using polymer AM tooling for low-volume applications can be developed. In terms of overall durability, the solid CF-Nylon insert and solid GF-PC tools set are still usable forming tools after the initial 100-part trial. The maximum deformations of 0.26 mm and 0.16 mm exhibited by the CF-Nylon insert and GF-PC die, respectively, are not substantial enough to merit refurbishment or reprinting of the tool before forming additional components. Further, FEA simulations indicate that both tools accumulate a majority of their deformation while forming the first few parts. This is also consistent with findings in the broader literature<sup>(4)</sup>, indicating that both tools are able to accurately form several more parts beyond the initial 100-part trial. The observed lack of plastic particles during the trials and accuracy of the FEA model deformation indicate that plastic deformation of the AM material is the dominate mode as opposed to wear, the physical removal of the polymer surface by abrasion by or adhesion to the sheet metal. These findings indicate that the polymers used in these two AM tools are sufficiently strong and durable, thus further suggesting that non-reinforced polymers may also be viable options for AM tools, another avenue for cost reduction potential.

While AM material strength may be reduced, there is a limitation on minimum ductility. A low strain to failure for a given AM material may lead to tool fracture if the yield stress is locally exceeded where a more ductile material may be able to withstand minor deformation. With this in mind, when selecting an AM material for a sheet metal tool, strain to failure is a more critical material property than overall strength. Since each forming application will have unique stress and strain demands on the tools due to their unique geometry and grade and gauge of sheet metal, specific values for these properties cannot be provided from this study, however, this research shows that an FEA forming simulation that accounts for deformable tools provides a good indication of the stresses and strains that the tool will ultimately experience and can be used as a starting point in material selection.

In comparing the formed parts to those formed by the baseline steel UFT tool, the primary metric is the overall draw depth. The GF-PC toolset showed a global draw reduction of approximately 2 mm in the finished parts. Since the press stroke was the same in all trials, this draw depth deficit is due to elastic deformation of the punch and die themselves. This is a consequence of the lower elastic modulus of the GF-PC material ( $\leq 4$  GPa) as compared to the steel UFT tool (200 GPa). This deviation is consistent across the entire GF-PC part run. One approach to remedy this would be to program a deeper draw into the press to account for elastic die deformation.

The imparted strain for finished sheet metal parts is compared for the AM tool-formed parts and baseline steel tool-formed parts. Where Tables 2, 3, and 4 compare the individual strain points for each tool, a higher-level analysis is performed by considering the average of strain over multiple parts for points 1-4 and determining if they fall within  $\pm 3\sigma$  of the respective points on the baseline steel tool-formed parts. The average part strains for all measured regions are compared in Fig. 10 with error bars defined by  $\pm 3\sigma$  for each region of each toolset's respective parts. As shown in Tables 2 and 3 and Fig. 10, parts formed with

the CF-Nylon insert exhibit average strains falling within  $\pm 3\sigma$  of the average strain in the steel-formed parts for all four locations. The solid GF-PC toolset exhibits average strains falling within  $\pm 3\sigma$  of the average strain in the steel-formed parts for three out of four locations. This deviation is likely due to the reduced global draw depth; increasing the draw depth to better match that of the baseline components would likely bring the average strain measurements of all four regions within the standard deviations measured for the baseline components.

## 5. Conclusions

The die trials in this study have shown that polymer AM tools are capable of forming relevant grades and gauges of automotive sheet metal at volumes appropriate for prototyping. Part strains are consistent across the entire run for both AM toolsets and deviate less than 3% from those on the baseline components for all of the strain comparison regions on the CF-Nylon toolset-formed components and three out of four regions on the GF-PC toolset-formed components. Solid AM polymer tools perform well in terms of tool longevity and part accuracy. Both CF-Nylon and GF-PC materials have sufficient strength for forming applications as demonstrated by the minimal wear accumulated over the forming trials. It is noted that the lower stiffness of polymer dies does result in an effectively reduced draw depth in the finished parts, though this can likely be remedied through increasing the draw depth of the press stroke or increasing the stiffness of the AM toolset itself.

The modeling methodologies developed to incorporate deformable die geometries accurately model the strains induced in the formed parts, predict final part deviation due to reduced tool stiffness, and predict the deformation accumulated in the toolsets. The demonstrated simulations will serve as useful framework in designing future AM die sets and performing virtual investigations on the suitability of AM for applications with more demanding geometries, different sheet metal grades, or thicker gauge materials. Whether the ultimate application for polymer AM tooling is in full die sets or inserts in larger traditionally constructed tools, there are large cost savings in low-volume tooling enabled by this agile tooling concept.

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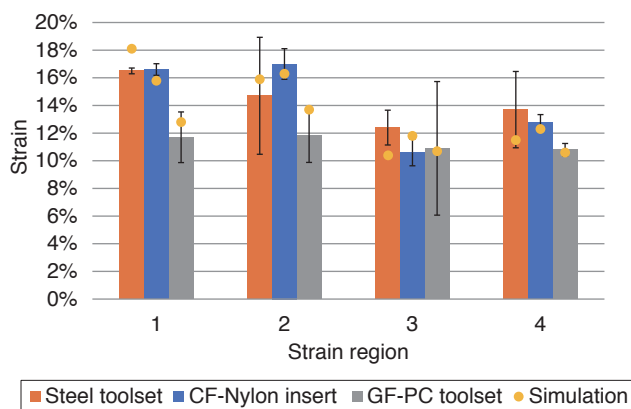


Fig. 10 Strain comparisons of parts formed on AM toolsets and their respective simulated strains

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#### ■ Author ■



Ryan HAHNLEN



Ben HOFFMAN



Madhura ATHALE



Taejoon PARK



Farhang POURBOGHRAHAT

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Editorial Afterword

Thank you for reading to the end of this edition of the Technical Review. I am grateful to all the associates who contributed manuscripts. With your support and assistance, the Technical Review has successfully reached volume 36.

Two years have passed since I became involved in the production of the Technical Review. Initially I felt confused by the differences between the Technical Review, academic journals, and technical reports from other companies as mentioned below.

The first point of difference was that the Technical Review does not reject any submitted manuscripts unlike academic journals. In the event that a submitted manuscript is not quite up to the level required for publication, the referee works with the authors to brush up the text. I imagine that it is a heavy burden, particularly for those who have never written a paper for submission before, but as long as the writer themselves does not give up, members of the referee panel and editors will continue to provide them with support aimed at realizing publication.

The second point is that there are no restrictions on the field of technology. It is usual for only manuscripts related to the academic field specified by the collection to be accepted. By comparison, the technical reports of other companies tend to focus on specific technologies or products, and it seems that in many cases special features are created for which the officer in charge of that field acts as the person responsible for editing. The Technical Review is different.

Provided that the author shows their willingness to share their ideas, irrespective of the field, the author, referee panel, and editors will continue to work together as one until publication is finally achieved, which makes the Technical Review unlike any other publication. From the perspective of those involved in the task of publishing, this may consume enormous amounts of time and effort, which is frankly inefficient.

So why do we do it? After two years, the best answer I have been able to come up with is: "Because this is the way Honda does things."

As I understand it, this booklet published by Honda is needed as a place for anybody who has the materials and the will to share their own ideas, irrespective of rank or position, and based on the Honda Philosophy fundamental belief of "respect for the individual," with the result being the approach to editing that we have today. It has been nearly 25 years since the first edition was published. While protecting the originality of Honda's Technical Review, I hope to see it evolve further in response to the needs of a new era.

Eijiro KITAMURA

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