A new process to develop a hydraulic system adapted to biodegradable hydraulic oil for construction machinery

—Case study integrating component analyses and SysML description in failure analyses—

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[Translation from *Synthesiology*, Vol.12, No.2, p.57–74 (2019)]

Causes and countermeasures for various kinds of hydraulic system failures in construction machinery generated by biodegradable hydraulic oil (bio-oil) are discussed. Previous component analytical methods can prevent all kinds of failures except hydraulic system malfunction, which requires a holistic approach for analysis. Using the Systems Modeling Language (SysML), the cause of malfunctions can be understood, and the most effective countermeasure can be obtained. Integration of a component analysis method and a holistic analysis method for system development is proposed.

Keywords : Hydraulic system, construction machinery, biodegradable hydraulic oil, malfunction, countermeasure, SysML

1 Introduction

A vehicle type construction machinery can travel by rotating crawlers (or tires) and can excavate using a bucket, as shown in the example of a hydraulic excavator of Fig. 1. The mechanisms for motion and excavation are driven by high-pressure oil (34–45 MPa), and the operator performs complex maneuvers by operating multiple hydraulic pilot valves. Concerning such construction machinery, environmental pollution becomes an issue if the oil is released into the environment when hydraulic oil in the hydraulic system is changed on site or when the hose is damaged by hitting rocks during the operation. Specifically, damages include contamination by oil film of drinking water, death of fish, or withering of plants in forests or agricultural fields.

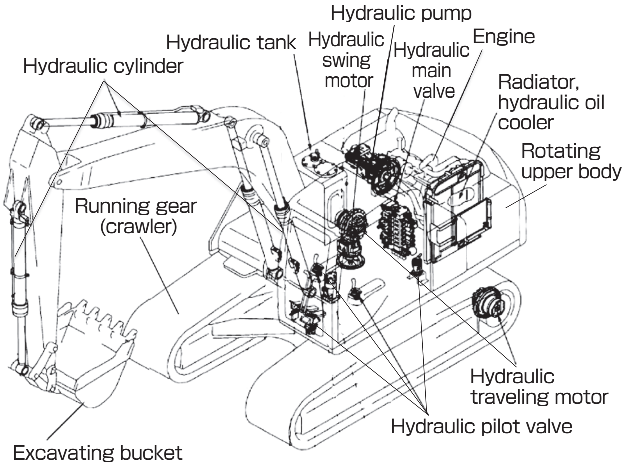

Fig. 1 Exterior of construction machinery and arrangement of hydraulic devices[1]

Therefore, in the 1990s, Germany, Switzerland, and Austria required the use of biodegradable hydraulic oil (hereinafter called bio-oil) in construction machinery, as such oil is broken down in a short period into carbon gas and water by natural microorganisms.[2][3] This was enforced through administrative actions of local governments[5] based on Germany's Federal Water Act.[4] The mandatory use of bio-oil in construction machinery has affected the entire EU regions and spread throughout the environmental protection areas.[3] In 2002, the ISO standard was set for the quality standard of bio-oil.[3][6][7] In 2011, the EU eco-label, which is equivalent to the Japanese eco-mark, was given only to bio-oil products that passed over 40 items of environmental toxicity tests.[8]

Figure 2 is a schematic diagram of the relationships of stakeholders and the environment in which construction machinery is used in Europe. With stringent demands for use of bio-oil from the environmental protection authorities and pressure from neighborhoods, the users pressed the construction machinery manufacturers for a quick response. One of the authors was a lubricants researcher who responded by starting up a company project for bio-oil at Komatsu Ltd. The project team included people from the service, design, testing, factory, and purchasing divisions, and the countermeasures were also proposed with the cooperation of parts manufacturers. As a short-term measure, it was decided that an operation manual for handling bio-oil would be created within half a year, and as a long-term measure, that the hydraulic system would be improved in four to five years.

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Original manuscript received December 18, 2018, Revisions received February 15, 2019, Accepted February 18, 2019

The operation manual on bio-oil for service persons and users was prepared with consideration for the EU competition law[9] (equivalent to the antimonopoly or antitrust laws of Japan). Operating conditions of construction machinery are difficult due to rocky ground, forests, and water sources in the environmental protection areas, and oil leakages are likely to occur during maintenance work in poor conditions and the backwoods. The users had to determine the use or non-use of bio-oil according to the instruction of the environmental protection authorities, and selection of bio-oil, operation, and maintenance would be conducted based on the operation manual and guidance of service persons.

For bio-oil, rapeseed oil (glycerol fatty acid ester) and synthetic polyol esters (hereinafter, synthetic esters) are used as main ingredients (base oil). The base oil is decomposed by enzymatic reaction by microorganisms and is taken in as a nutrient (biological constituents) of microorganism (this process is called assimilation).[10] Rapeseed oil and some synthetic esters containing unsaturated fatty acids have low oxidation stability due to the presence of double bonds. Even commercial bio-oil that adopts synthetic esters of saturated fatty acids with high oxidation stability as base oil, the oxidation stability is lower compared to petroleum hydraulic oil. This is due to prohibition of additives by stringent environmental regulations,[1] and antioxidants of hindered phenol and aromatic amines that are generally used in petroleum hydraulic oil, or antioxidants and anti-seize agents of zinc dialkyldithiophosphate (ZDTP)[1] cannot be used from the perspective of aquatic environmental toxicity.[11] That is, the premise is that there is absolutely no oil leakage for petroleum hydraulic oil, while bio-oil is developed with the assumption that it may leak into the natural environmental such as rivers and marshes.

Depending on the type of synthetic ester base oil, some of

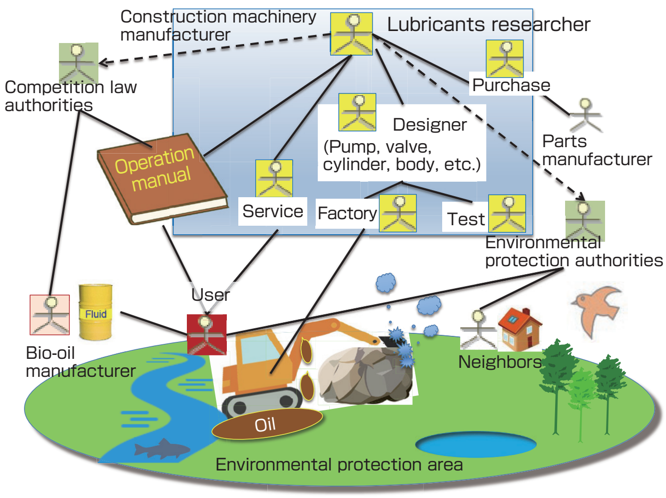

Fig. 2 Schematic diagram of stakeholders and environment in which construction machinery is used in Europe (solid line: direct relationship, dashed line: information gathering)

the synthetic ester bio-oil shows lower viscosity increase against pressure rise (high-pressure viscosity[12]) compared to petroleum base oil.[13][14] Therefore, its oil film is thinner, and there is a disadvantage of causing seizure in the bearing metal of hydraulic motors and hydraulic pumps. Anti-seize agents such as ZDTP that compensate the thin oil film cannot be added due to the aforementioned reason. From such reasons, the commercial bio-oil has various issues such as low oxidation stability, rubber compatibility, a thin oil film and so on.[3][15][16][17] Failures are predicted if bio-oil is used without any measures taken to construction machinery that has complex hydraulic systems.

To develop a hydraulic system to which all bio-oils can be applied, the use of component analysis methods such as fishbone diagrams, fault tree analysis (FTA),[18] failure mode and effect analysis (FMEA)[19] were considered. Based on these analyses, we set out to develop equipment of the hydraulic system (hereinafter, subsystems) that comprises construction machinery that are compatible to bio-oil. FTA is a method for analyzing causes and conditions under which a phenomenon occurs by extracting the causes and factors of the established top events,[18] while FMEA is a method for clarifying the potential failure mode of system performance and its cause and effect.[19] These component analysis methods have been widely used by the automobile and construction machinery manufacturers since around 1980. In general, FTA is used to analyze the cause of failures, while FMEA is used to prevent failures during designing.

2 Scenario for development of construction machinery compatible with bio-oil

The development scenario of this study is shown in Fig. 3. There are several issues in terms of the quality of bio-oil. In the development of the operation manual as a short-term measure, directions for usage of bio-oil in construction machinery for each quality issue were determined, and brands of commercial bio-oil were categorized by quality. The short-term measures were terminated at the point when long-term measures were completed. The subjects of the long-term measures were mostly technologies of the hydraulic system of construction machinery. In relation to the production of construction machinery, there was a problem that bio-oil may mix with hydraulic oil added at the factory. For these issues, the factors of failures caused by bio-oil were analyzed by conventional FTA or FMEA to investigate and derive countermeasures. However, for failures that involve chemical properties (oxidation stability) of the bio-oil, in addition to the complexity of the hydraulic system comprised of multiple subsystems, the cause investigation was difficult using the conventional methods. Also, there was no appropriate method for creating and validating countermeasures for a failure. Therefore, in this paper, we attempted the analysis of this unsolved

Table 1. Problems in quality of bio-oil, and short-term and long-term measures implemented by the construction machinery manufacturers using component analysis method

No.	Required lubricant's qualities	Current bio-oil's quality	Field failure	Failure cause	Countermeasures implemented and content (○: Yes, ×: No)		Remarks
					Short-term measures	Long-term measures	
1	Oil-film strength	Low	Bearing metal seizure	· Low viscosity at high-pressure · Low content of extreme-pressure additive	○*1	Expand bearing width	*1: Machinery operation manual for bio-oil *2: Recommendation for bio-oil brand
2	Rubber compatibility	Low	· Oil leak at seal · Hose breakage	Strong affinity of ester base oil with rubber	○*1	Change rubber material	
3	Antirust	Low	Rust forming in hydraulic oil tank	Lack of antirust additive	○*1	Antirust treatment	
4	Anticorrosion for bronze	Low	Abnormal wear of bearing metal	Addition of active sulfur additive	○*1,*2	Improve bronze alloy	
5	Friction coefficient	Extremely low	Poor performance of parking break	Property of ester base oil	○*1	Improve brake material	
6	Compatibility with petroleum hydraulic oil	Precipitation	Filter plugging	Precipitation of calcium carbonate and calcium soap due to the reaction between ester base oil and petroleum hydraulic oil additives	○*1	Bio-oil filling at factory	

problem and the derivation of countermeasures from the perspective of systems engineering[21] of a multidisciplinary approach using the System Modeling Language (hereinafter, SysML),[20] which is a graphical modeling language that supports analysis, specification setting, design, verification and validation of a complex system.

3 Failure analysis and countermeasures using component analyses (FTA and FMEA) for each subsystem of hydraulic system

Table 1 is a summary of the problems No. 1–6 on bio-oil quality, the short-term measures and the long-term measures to develop subsystems compatible to bio-oil. The operation manual was prepared using the component analysis method based on a survey[17][22] of bio-oil quality through chemical analysis and laboratory tests and also investigation results of field failure. Prohibition of use of low-quality bio-oil brands was considered as an short-term measure, but this was not done because it may have led to local bio-oil companies suing the authorities for violation of competition laws. Therefore, as shown in Table 2, the operation manual outlined limitations of oil temperature and pressure during operation, shortening of oil change interval, and recommended brands for each quality level, and it was left up to the users to make the selections.[17] Since the users have come to select brands with

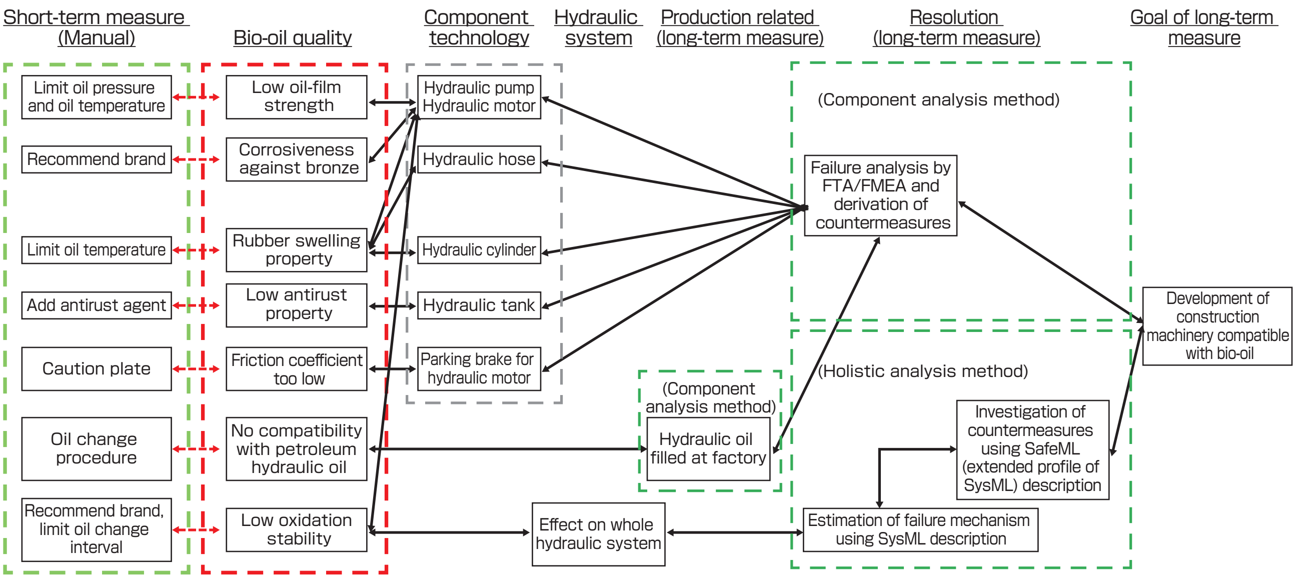

Fig. 3 Scenario for development of construction machinery compatible with bio-oil

Table 2. Bio-oil classification and recommended operating condition[17]

Quality grade	Base oil	Oil temperature ℃	Oil pressure MPa	Oil change interval h	Parking brake
1	Rapeseed oil	-10+80	32 or less	1,500 or less	Attach caution plate, or replace to improved brake material
2	Rapeseed oil or synthetic ester		35 or less	3,000 or less	
3	Synthetic ester	-30+100			
4			42 or less	5,000 or less	Continue use as is

Table 3. Cause of bio-oil oxidation and short-term measures

Possible field failures	Causes of failure occurrence	Short-term measure
Discoloration of oil	・Unsaturated ester base oil ・Lack of anti-oxidant	Shortening of oil change interval in Table 2
Lead dissolving from bronze bearing	Corrosion and dissolution of lead by oxidation product	

quality grade 3 based on the recommendations, the operation manual was effective.

For the development of subsystems that allow the use of bio-oil, the long-term measures were planned and conducted using the component analysis method as shown in Table 1. For problem No. 1, low oil-film strength, we conducted design change of expanding the width (surface area) of bearing metal to eliminate complex verifications. For No. 2, rubber compatibility with bio-oil, it was found that the strengths of nitrile rubber (NBR) with low nitrile content and chloroprene rubber (CR) decrease significantly.[16] Therefore, these rubber parts were replaced to materials of hydrogenated NBR (HNBR) or NBR with high nitrile content for high oil resistance. For No. 3, poor antirust property of bio-oil, an antirust coating was applied inside the hydraulic oil tank. For No. 4, corrosion of bronze, an improved bearing material, which has anticorrosive property against hydrogen sulfide, was developed maintaining the bearing property by adding zinc to the metal composition.[23] For No. 5, excessive low torque of multi-disk wet parking brakes, a new brake material was developed and was adopted for producing high torque in bio-oil in collaboration with a brake material manufacturer. For No. 6, filter plugging caused by a chemical reaction between bio-oil and petroleum hydraulic oil additives, we took measures to prevent mixing with petroleum hydraulic oil by shipping the machinery with factory filled bio-oil to users who requested bio-oil.

For the low oxidation stability of bio-oil, only the discoloration (darkening) of the rapeseed oil was the failure encountered in the field, as seen in Table 3. Although the possibility of lead dissolving from the lead bronze bearing was considered, there were no failures in the market. Therefore, the authors determined that there was no problem other than instructing the proper oil change interval to the users. As a long-term measure, a new bio-oil with high oxidation stability with the goal of achieving quality grade 4 could be developed,[15][17] but it was unable to clear the European environmental toxicity regulation[8] and was not introduced to the European market.

The following problem occurred after the aforementioned series of countermeasures. In construction machinery operated in the field, malfunctions of hydraulic valves caused by bio-oil occurred, and lack of pressure in the hydraulic pumps and malfunctions of hydraulic cylinders and hydraulic motors became problems. From the surveys of these matters, the cause was suspected to be abnormal wear and sticking of the hydraulic valves due to wear debris produced inside and sand dust that entered from outside (hereinafter, oil dust), but the direct relationship to bio-oil was unclear. It was thought that because of low oxidation stability of bio-oil, oil-insoluble oxidative polycondensation products[1] (hereinafter, lacquer) were formed, which then adhered to the hydraulic valve to cause malfunctions. However, there was no lacquer adhesion upon inspection of the malfunctioned hydraulic valve. It seemed that the malfunction phenomenon subsided, but the cause of hydraulic valve malfunction was never clarified. Due to this fact, we were unable to complete the development of the construction machinery that was compatible with bio-oil.

4 Application of holistic analysis method using system model for cause investigation and countermeasure for the whole system

As described earlier, it was necessary to newly conduct a holistic analysis using a system model described by SysML for the failures involving oxidation stability of bio-oil, in addition to the complex hydraulic system. Since SysML was a modeling language that enabled graphic description of system requirements, structure, and behaviors, and supported verification and validation, we thought it would be effective to combine system models described by SysML and SafeML (extended profile of SysML, details will be explained later) for cause investigation and countermeasures, as shown in Table 4. It is difficult to apply the conventional component analysis method to the analysis of the whole system in cases in which the cause is particularly complex, and the mechanism cannot be graphically rendered. The component analysis method has the disadvantage that the descriptive technical terms cannot be understood or reviewed unless one is an expert. In contrast, SysML allows description even if the cause is complex, and simple descriptions can be used for technical terms (for example, a “hydraulic valve” is described as “a subsystem to control the flow of oil”), and it can be easily understood in graphical form even by multidisciplinary team members. Although SysML allows validation of a countermeasure, it cannot create or verify

Table 4. Comparison of previous methods of analyses and countermeasure and a new holistic method using system model (○: Possible, △: Partially possible, ×: Impossible)

No.	Previous methods or modeling language		Cause investigation			Countermeasures			Multidiscipline discussion
			Case study of cause investigation for failures	Application to complex systems and causes	Visualization of failure mechanism (behavior)	Resolution planning	Verification	Validation	
1	Fishbone diagram		Yes	×	×	×	×	×	×
2	FTA		Yes	×	×	×	×	○	×
3	FMEA		Yes	×	×	×	×	○	×
4	SysML	SysML	No	○	○	○	×	○	○
5		SafeML	Yes	△	×	△	○	○	○

the countermeasure. SafeML is a language that defines the combination of hazards, hazardous context, and harm as risks and can clearly describe defense (countermeasure) methods. However, SafeML cannot illustrate in detail the failure mechanism. SysML and SafeML allows multidisciplinary investigation by a team even with some people who are not engineers.

Figure 4 shows the integrated methods of both analysis and development on the hydraulic subsystem and system against bio-oil using the conventional component analysis method and the holistic analysis method. While the component analysis is effective for cause investigation and countermeasure planning focusing on individual subsystems, it cannot handle complex problems like a malfunction of a hydraulic valve that needs to be solved observing the state of bio-oil, while looking at the whole hydraulic system.

In this paper, the action of the hydraulic system is described and understood as a systems model using SysML. Next, the mechanism of a hydraulic system that leads to failure (hereinafter, behavior) is described, the relationship with the bio-oil state transitions is grasped, and the cause is assumed.

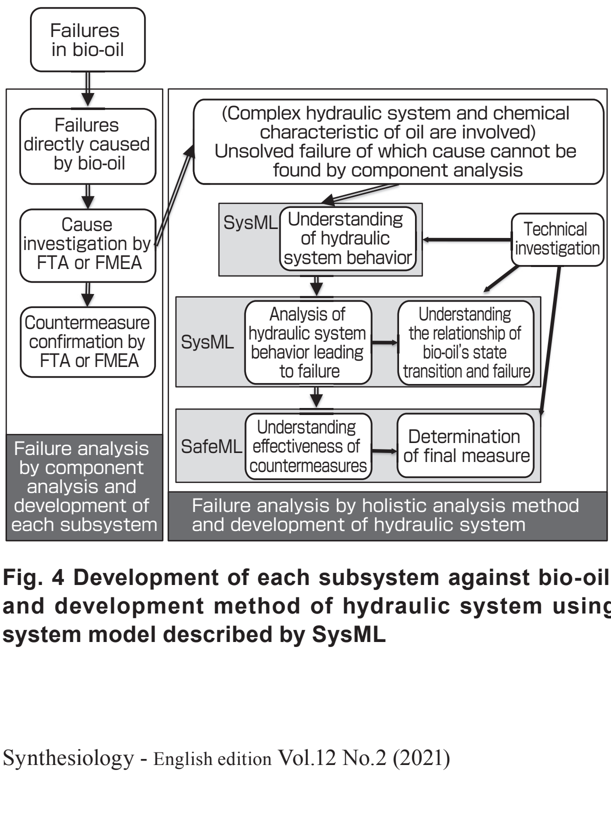

Fig. 4 Development of each subsystem against bio-oil, and development method of hydraulic system using system model described by SysML

Also, the relationship with failure is understood from the bio-oil state transitions.

Although there are several attempts to integrate SysML with safety analysis,[24]–[27] SafeML proposed by Biggs *et al*.[27] is the most practical. SafeML is an extended profile of SysML specific to safety information, and can clearly describe system risks, countermeasures taken for the risks, and risk management results.[28] Using this SafeML, the countermeasures are created for the situation in which a failure occurs, and the effect of such countermeasures, validation, and also countermeasure costs are considered. The safety score (will be explained later) is calculated according to the items pertaining to the safety of system behavior that is clarified here. In this system model, descriptions are written at the parts level of the hydraulic system, to allow easy understanding by the parts manufacturers of the subsystem.

5 Understanding of hydraulic system by holistic analysis method using system model and result of technical investigation of failure factor

5.1 System model description using SysML

Behavior of the whole construction machinery is shown in the activity diagram of Fig. 5. The activity diagram shows behavior using input flow, output flow, control flow (dashed line), object flow (solid line), and action blocks.[20] The "Engine" drives the "Hydraulic System" by output of "Generate Power" action. The operator controls the hydraulic system by "operator command force" flow, and transfers hydraulic pressure into force or rotational torque to the "Work Component" partition by the "Provide Hydraulic Force" action. The work components are set in motion to perform actions such as "Excavate Earth," "Rotate Excavating Direction," or "Run Machinery." To adjust air pressure of the hydraulic system, a small amount of "Air" is taken in a "discrete" manner.

Similarly, the context of the hydraulic system is shown in the internal block diagram of Fig. 6. The hydraulic pump "block1 pump: Oil Press Generation Subsystem" is driven by the "Engine Power," and high-pressure (35 MPa) oil "HP_oil" and middle-pressure (3 MPa) pilot oil "Pilot_ oil" are produced. The operator adjusts the pressure of the hydraulic pump and controls the main valve "block2.2 main-valve: Actuator Moving Device," through the pilot valve "block2.1 pilot valve: Pilot Valve Device" in the hydraulic valve "block2 valve: Oil Flow Control Subsystem." The main valve is composed of multiple units that control the flow direction, flow rate, and oil pressure of the high-pressure oil. The controlled high-pressure oil "CHP_oil" actuates the hydraulic motor device and hydraulic cylinder device in the subsystem that moves the work component "block3 actuator: Work Component Actuation Subsystem." The high-pressure oil after the actuation returns to the main valve and becomes low-pressure (0.1 MPa) oil "LP_oil," and enters the oil feed subsystem "block4: Oil Feed Subsystem." Since the oil temperature increases due to heat release as high-pressure oil becomes low-pressure oil, as well as due to friction of various parts and heat generation by viscous resistance, oil cooling is provided by "Oil Cooler Device." Oil dust in the low-pressure oil is eliminated by the filter "block4.1.1 filter: Dust Eliminating Unit" and returns to the "Oil Tank Unit."

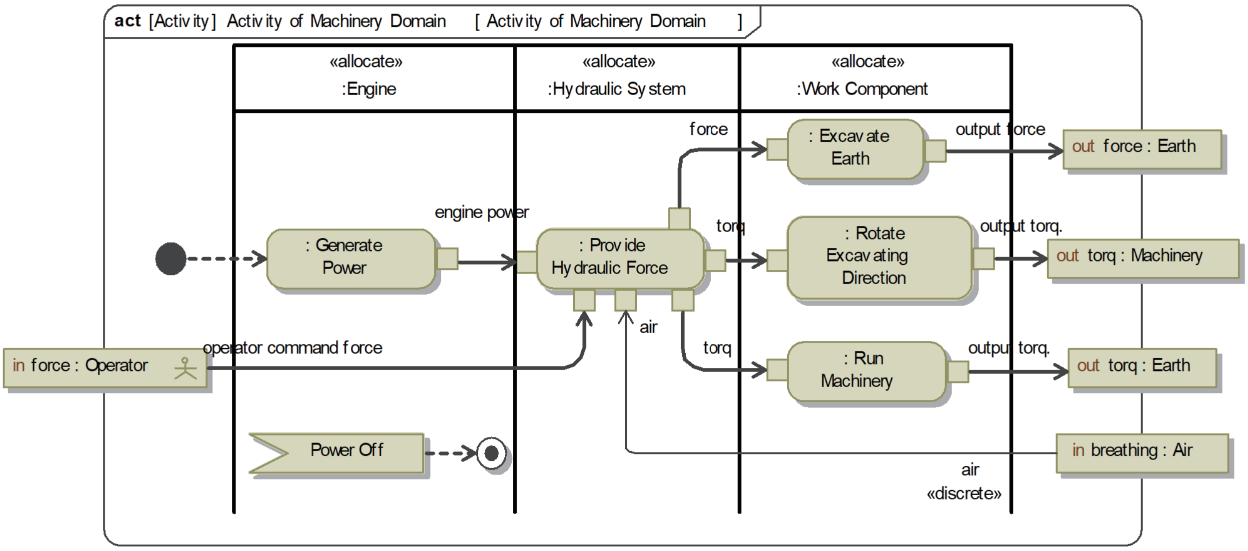

Fig. 5 Activity diagram of construction machinery domain

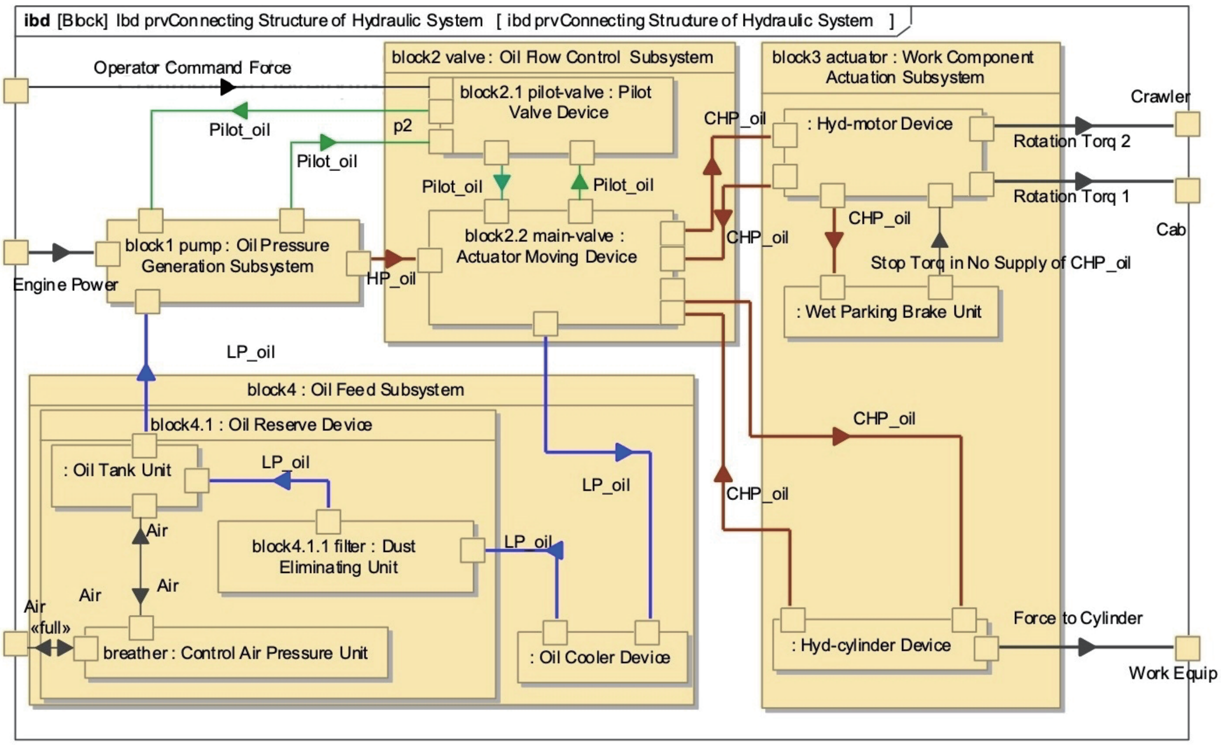

Fig. 6 Internal block diagram of hydraulic system of construction machinery

5.2 Technological investigation on failure factor

5.2.1 Consideration of subsystem (pump and valve) that causes oxidation of bio-oil

There was no long-term countermeasure for the poor oxidation stability of the bio-oil, and it was thought that the oxidation stability had something to do with hydraulic valve malfunctions. Therefore, to understand the cause of hydraulic system malfunctions, it was necessary to clarify in which subsystem the bio-oil underwent oxidation. In Fig. 6, the subsystem in which oxidation is most likely to occur is the hydraulic pump with high load and temperature, but no investigation has been done on the possibility of oxidation in the hydraulic motor, the hydraulic cylinder in "block3 actuator" and in the main valve "block2.2 main-valve." Kazama *et al.*[29] conducted temperature measurement of the swash-plate-type axial piston hydraulic pump (21 MPa) used in construction machinery, and observed a temperature increase of 30 ºC or higher at the cylinder block (increase to 110 ºC when oil temperature was 80 ºC). In cases in which there were bubbles in the oil, hot spots of 1,400 ºC or higher (in cases of 35 MPa) were produced due to adiabatic compression, and the surrounding bio-oil became heated.[30] It could be assumed that the bio-oil underwent oxidation to become lacquer.

The energy loss of all subsystems during the operation of construction machinery may reach 60–75 %,[31][32] and according to the authors' study, it was about 15 % at the hydraulic pump, and about 25 % at the main valve. Since energy loss leads to increased oil temperature, it can be assumed that the oil temperature inside the main valve becomes higher than the hydraulic pump. There is a relief valve that releases high-pressure oil into a low-pressure circuit in the main valve. When the motion of the hydraulic cylinder or the hydraulic motor is stopped when there is excessive load on the hydraulic system, as when construction machinery is removing a large rock with an excavating bucket, excess high-pressure oil is released into the LP_oil circuit of the Oil Feed Subsystem from the relief valve in "block2.2 main-valve," and the kinetic energy is converted to heat. When the heat value at the relief valve is calculated according to Equation (1),[33] the oil temperature reaches about 100 ºC (from oil temperature 80 ºC), and this is equivalent to the oil temperature of the hydraulic pump.

$$H = p \cdot Q \qquad (1)$$

Here, H is the heat value (KJ/min) from the relief valve, p is relief pressure (MPa), and Q is relief flow rate (L/min).

Imanishi *et al.*[34] conducted simulations of the action of the main valve "block2.2 main-valve," and showed that the energy loss is large, equivalent to the relief valve unit, even at the unit that controls the direction of the flow of high-pressure oil from the main valve to the actuator "block3 actuator." The oil flows at flow rate 100 m/s or more at the unit that controls the flow direction of high-pressure oil,[1] and severe cavitation occurs. This may cause damage to the quenched or carburized steel parts.[1] In such severe cavitation, high-temperature and high-pressure (about 4,700 ºC and 100 MPa) hot spots[35] may occur due to the collapse of bubbles. In this situation, molecules may be broken down almost to the atom level or carbon bonds may be randomly split.[35]–[37] It is assumed that this causes surrounding bio-oil to become oxidized and lacquer is formed. Also, damage by cavitation may occur inside the hydraulic pump although at a smaller scale.[38] From these investigations, the authors found that lacquer was formed in the hydraulic pump and at the hydraulic valve.

Although lacquer formation may occur in the hydraulic cylinder and the hydraulic motor, the load factor is lower compared to the hydraulic pump or the main valve. In the past, problems were caused by cavitation during rotation switching from left to right in the hydraulic swing motor, but currently countermeasures are taken by improving the hydraulic valve.[31] Therefore, it is assumed that lacquer formation is minimal in the hydraulic motor and the hydraulic cylinder. The formed lacquer does not dissolve in bio-oil, is captured in the filter, and may cause plugging.

5.2.2 Consideration of oil dust and filter

Figure 7 shows the structure of the hydraulic tank, filter, and breather "block-4.1" in Fig. 6. The filter "block-4.1.1 filter" captures oil dust during by passing of low-pressure oil about 20–100 times. According to our experiments conducted by the authors using actual machinery, conventional cellulose filters (explained later) can capture 50 % or more oil dust of 5 µm or more in a few hours. The number of particles of oil dust (cleanliness level) can be kept below the upper limit required for the hydraulic system. It is designed so that when the filter is plugged and pressure increases, the filter bypass

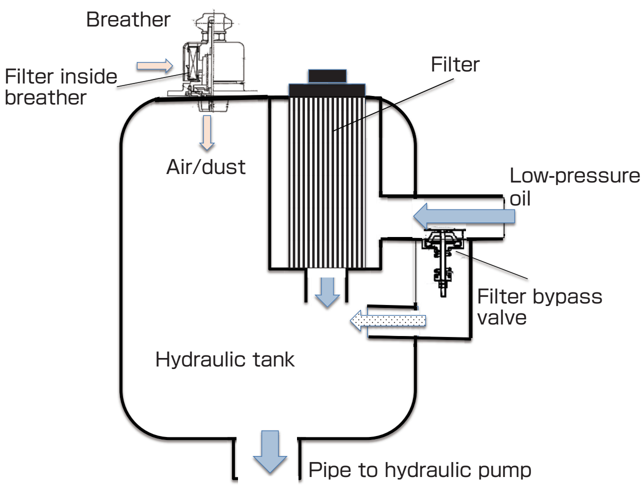

Fig. 7 Schematic diagram of hydraulic tank and filter/ breather

Table 5. Limit value of particle count (cleanliness level) for each particle diameter of oil dust, and typical particle count values in hydraulic oil where failure occurred

Particle size µm	5-15	15-25	25-50	50-100	>100
Upper limit of particle numbers mL^{-1}	500,000	32,000	4,000	1,000	100
Examples of contamination where failure occurred mL^{-1}	3,490,150	96,990	3,120	140	0

valve opens, and the low-pressure oil does not go through the filter and enters the hydraulic tank directly. The timing of filter replacement is set at 250–500 h, and this is calculated from the volume of oil dust captured.

As mentioned before, oil dust is composed of outside dust and metal wear debris from the interior. The outside dust enters as dust particles and muddy water along with air intake, from the filtered breather[39] in “block4.1” that is installed in the hydraulic tank. Since the air goes through the breather filter only once, fine dust cannot be prevented and this becomes the source of oil dust. This filter is made of a cellulose material the same as the oil filter. The outside dust may enter during oil feeding, filter exchange, hydraulic hose exchange, and subsystem repair at sites with poor conditions.

Therefore, oil dust contains hard components (Vickers hardness HV 600 or more) such as oxidized iron and steel that are metal wear debris, as well as silica sand (quartz) or feldspar from dust. Table 5 shows the cleanliness limit values[1] for oil dust that were prepared by the authors,[40] and also provides examples of typical cleanliness levels at which failures occurred. When limits are exceeded, malfunction due to abnormal wear or sticking of the hydraulic valve may occur.[33] Since the gap of the movable parts such as the main valve and the pilot valve is about several µm to 30 µm,[1] oil dust may enter the gaps even if it is within the cleanliness limit. In the case of a field pump failure, the number of oil dust reached at maximum seven times the cleanliness limit.

6 Investigation result of hydraulic system behavior leading to failure

6.1 Normal behavior of bio-oil in hydraulic system

Figure 8 shows the activity diagram of the normal behavior of the hydraulic system. The activity partitions in this figure match the subsystem blocks in Fig. 6. The hydraulic pump “block1 pump” sends high-pressure oil “HP_oil” to the hydraulic valve “block2 valve.” The operator controls the hydraulic valve to adjust the pump pressure by pilot oil and controls the direction and flow rate of the high-pressure oil. This controlled high-pressure oil “CHP_oil” moves the actuator “block3 actuator” such as the hydraulic motor and the hydraulic cylinder. This moves the “Work Component.” The high-pressure oil used in the work returns to the oil feed subsystem “block4” as low-pressure oil “LP_oil” through the hydraulic main valve, becomes cooled as “Cool LP_Oil,” filtered as “Filtrate LP_oil,” goes to the oil tank “Reserve LP_Oil” as clean low-pressure oil “clean LP_oil,” and enters the hydraulic pump to become pressurized gain. However, when the viscosity of the bio-oil is high such as during low-temperature start-up, the filter differential pressure becomes high “filtration pressure => 0.15 MPa,” and the bypass valve in the filter temporarily opens. Then, the bio-oil will not pass

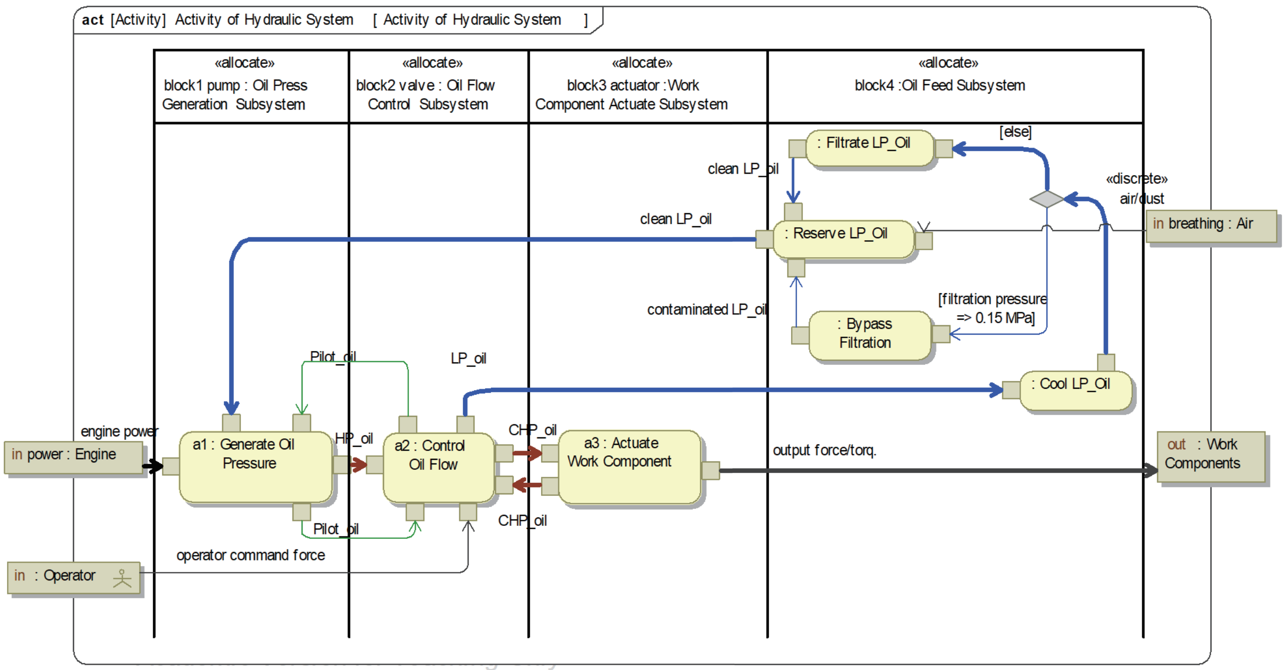

Fig. 8 Activity diagram of normal state of hydraulic system

through the filter "Bypass Filtration," and enters the oil tank while containing oil dust "contaminated LP_oil." The oil temperature increases to 60 ºC or more in about 30 min after start-up, the low-pressure oil will start passing through the filter, and the amount of oil dust decreases immediately.

6.2 Investigation result of behavior of hydraulic system malfunction by bio-oil oxidation

The activity diagram of Fig. 9 shows the formation of lacquer by oxidation of bio-oil and its behavior in the hydraulic system. (1) In the hydraulic pump with increased oil temperature, lacquer forms in the high-pressure oil due to adiabatic compression of bubbles "Generate Oil Pressure and Generate Lacquer in HP_oil." The high-pressure oil containing lacquer "HP_oil + lacquer" flows into the hydraulic valve. (2) Severe cavitation occurs at the hydraulic valve, lacquer is formed in low-pressure oil "Control Oil Flow and Generate Lacquer in LP_Oil," and this flows into the oil feed subsystem. (3) The high-pressure oil containing lacquer flows into the actuator, but the effect on the actuator may be small. (4) The lacquer is captured in the filter "Filtrate LP_oil" of the oil feed subsystem, and clean low-pressure oil returns to the hydraulic pump. However, as the lacquer gradually accumulates in the filter, the filter differential pressure becomes 0.15 MPa even at oil temperature of 60ºC or more, and the filter bypass valve remains open and the filter is plugged "plug filter with lacquer." As a result, oil dust and lacquer are not filtered and mix into the low-pressure oil as "contaminate LP_oil," and the low-pressure oil contaminated with oil dust flows.

The behavior of the contaminated bio-oil in the hydraulic system is shown in Fig. 10. The contaminated low-pressure oil is sucked into the hydraulic pump and becomes high-pressure oil and pilot oil containing oil dust and lacquer "Generate Contaminated HP_Oil and Pilot_Oil," and these are sent to the hydraulic valve. The wear debris concentrates in the contaminated high-pressure oil "contaminated HP_oil" at the actuator, the oil returns to the oil feed subsystem as low-pressure oil. In the "Reserve LP_Oil," outside dust " air/dust" is entered and is concentrated. This is repeated and when the concentration of oil dust surpasses the upper limit of cleanliness "exceed cleanliness limit" (◇ below ●), malfunction occurs "Malfunction by Valve Sticking or Wear" by sticking or abnormal wear as the oil dust enters the gap of the hydraulic valve, including both the main valve and the pilot valve. The flow ends (⊗) and repair becomes necessary. It was found that the hydraulic valve malfunction causes faulty or no movement of the hydraulic pump, the hydraulic motor, or the hydraulic cylinder.

7 Investigation result of relationship between bio-oil state transition and failure

7.1 System model description of bio-oil state transition

Figure 11 is a state machine diagram that shows the behavior of state transition pertaining to bio-oil oxidation and dust inclusion. When oxygen is dissolved in bio-oil, part of the bio-oil becomes radicals due to oxidation even at oil temperature of around 100 ºC.[41] Radicals are short-lived molecules that are activated by the break in parts of the bond in oil molecules,[42] and tend to accelerate oxidation in a chain reaction. The radicals of bio-oil cause oxidation by a reaction mechanism similar to petroleum hydraulic oil.[43]

The authors have confirmed in oxidation stability tests[44] that lacquer begins to form when bio-oil was oxidized

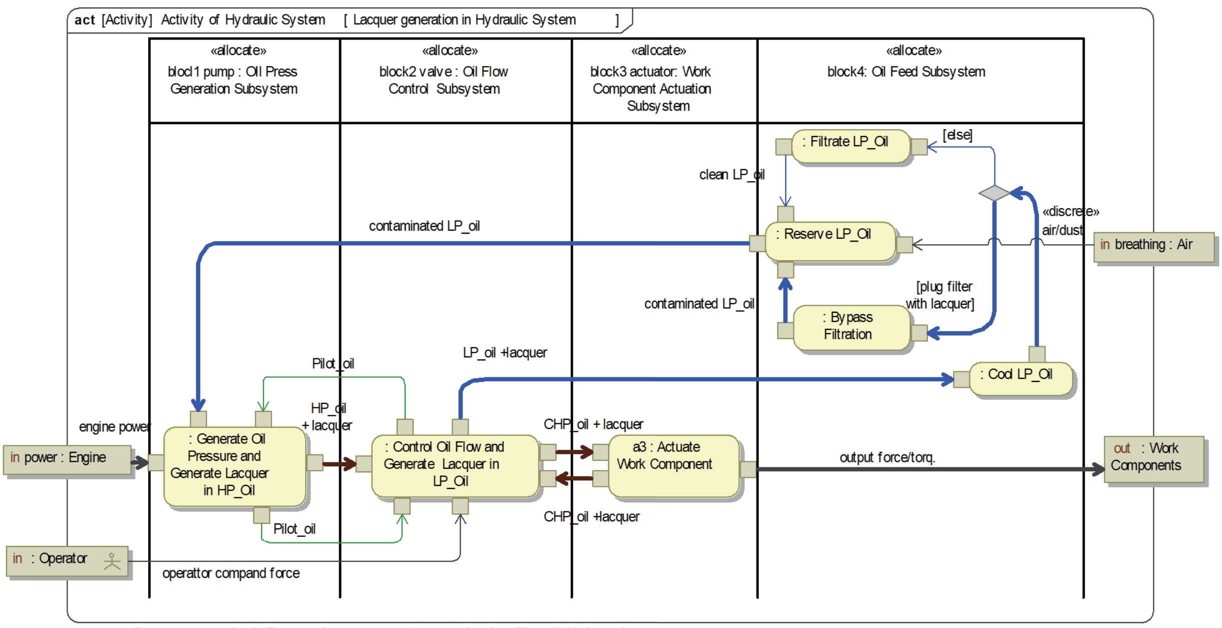

Fig. 9 Activity diagram for lacquer formation and its behavior of bio-oil in hydraulic system

in conditions of 135 °C × 500 h or more.[15][22] No lacquer formation was observed in this condition for petroleum hydraulic oil. The maximum oil temperature of the hydraulic system for construction machinery is low at 110 °C,[1] and will not reach 135 °C. Therefore, the authors assumed that rapid radical formation, oxidation, and lacquer formation occurred in bio-oil only after emergence of local high-temperature regions, or hot spots, due to adiabatic compression of bubbles[30] and cavitation[35] as mentioned earlier. Bio-oil containing lacquer is in a deteriorating state. If lacquer is removed by a filter, it is considered as a "Normal" condition. Lacquer is removed up to the upper limit of the filter capacity

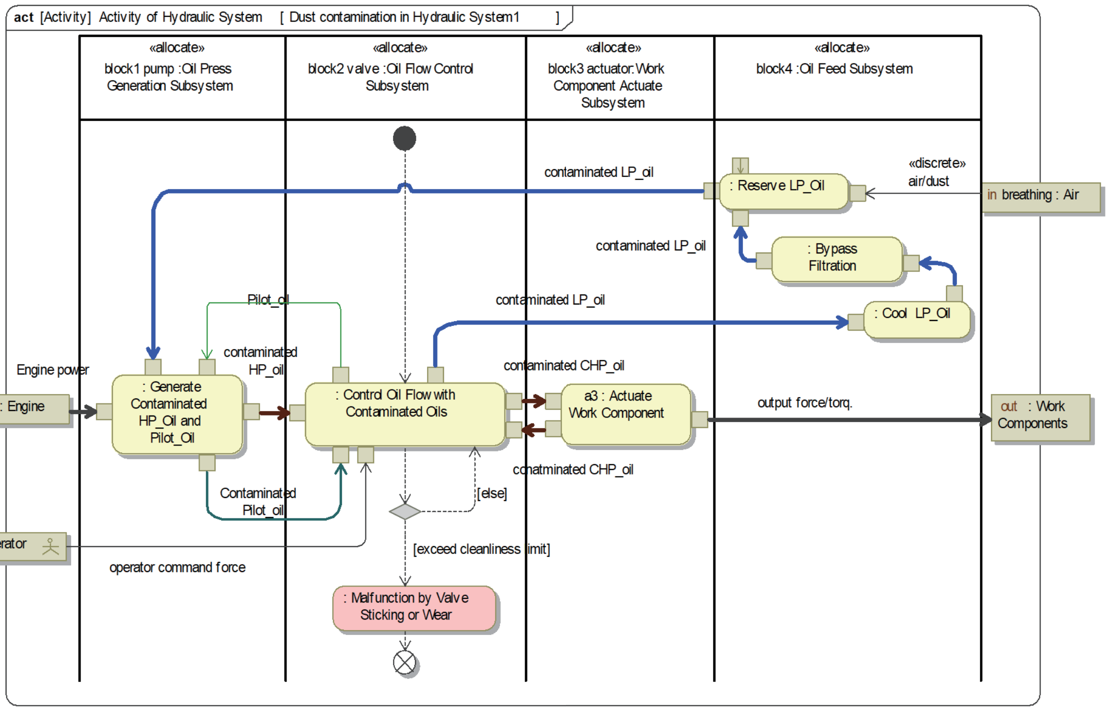

Fig. 10 Activity diagram of contaminated bio-oil and malfunction occurrence of hydraulic system

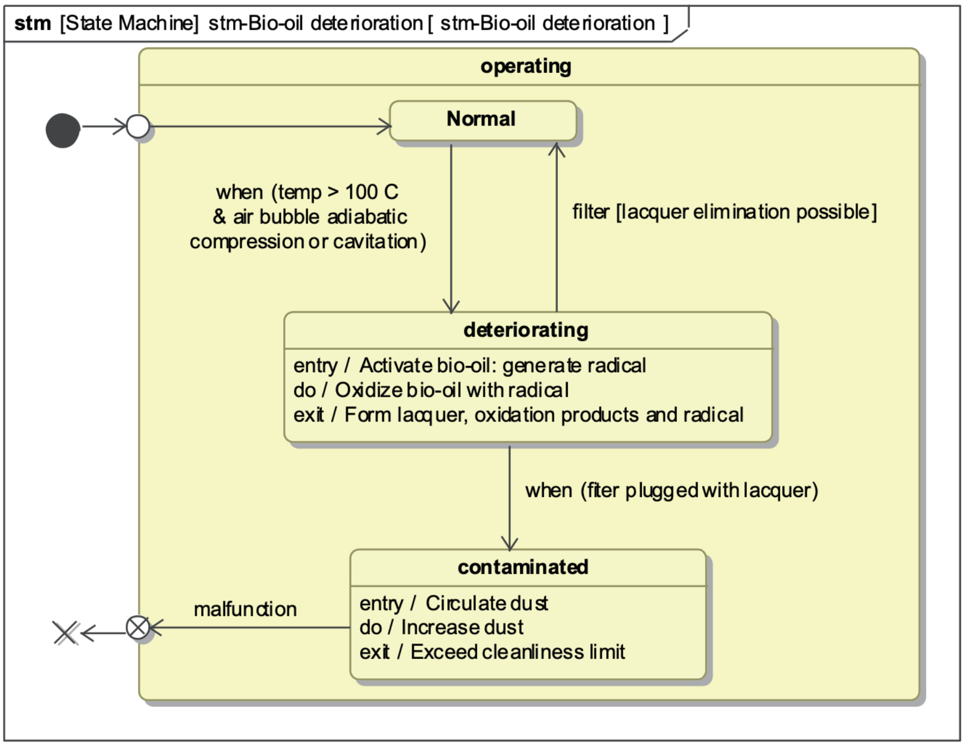

Fig. 11 State machine diagram showing state transition of bio-oil

"lacquer elimination possible." When lacquer accumulates in the filter and the filter differential pressure increases, the filter becomes plugged as "filter plugged with lacquer" in Fig. 9, and the bio-oil is contaminated with oil dust and lacquer. Ultimately, it can be derived that contamination by oil dust means to exceed the limit of cleanliness of the hydraulic system, even in the study described by the state machine diagram.

Oxidation products,[45] that are produced by oxidation reaction, and radicals dissolve in oil, move past the filter, and circulate the hydraulic system. High-reactive radicals have short lifespans (1 ns to several hours), while low-reactive radicals have lifespans of a year or more.[46][47] It is thought that not too many highly reactive radicals that may produce lacquer accumulate in oil. However, oxidation products become concentrated.

7.2 Technological investigation result of bio-oil state transition

7.2.1 Acid value increase in bio-oil field test

To study the effect of concentration of oxidation products of bio-oil on lacquer formation, we conducted a field test of construction machinery for commercial bio-oil with base oil of saturated fatty acid synthetic ester that has higher oxidation stability.[48] The result is shown as the solid line of Fig. 12. The acid value of bio-oil, which is the index for oxidation product concentration, approaches the use limit of petroleum hydraulic oil when it exceeds 3,000 h. The acid value is the index of the acidic component or the amount of free fatty acids in the lubricating oil, and it is expressed by the amount of potassium hydroxide needed for neutralization. When this limit is exceeded, the oxidation product corrodes and dissolves the lead in the bronze bearing metal, and seizure occurs.[49] Therefore, the authors set a standard that the recommended oil change interval of saturated fatty acid synthetic ester bio-oil should be every 3,000 h (Table 2) for standard European products, to maintain the acid value below the limit value. Regarding petroleum hydraulic oil, since rapid acid value increase does not occur as shown in the dashed line in the figure, the oil change interval is set at every 5,000 h. In the next section, we consider whether the increased oxidation in bio-oil is related to lacquer formation.

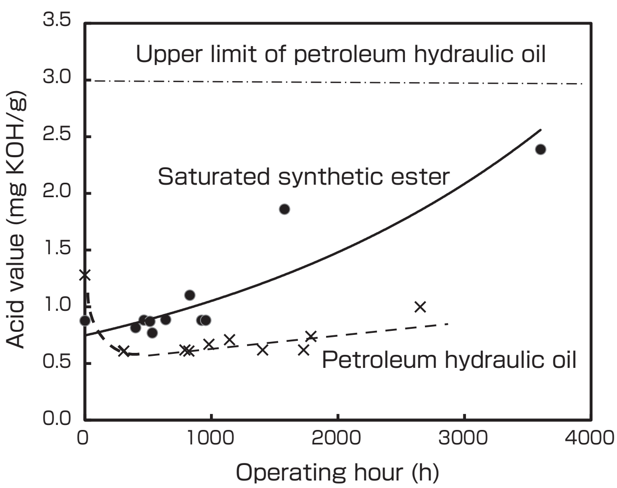

Fig. 12 Acid value change of bio-oil of saturated fatty acid synthetic ester base oil[48] and that of petroleum hydraulic oil during field test of construction machinery,

It is said that in synthetic ester bio-oil, hydrolysis occurs with a mixture of a few percent of water and the acid value increases.[50] However Totten *et al*.[38] determined that hydrolysis does not occur since water entering the hydraulic excavator is 0.1 % or less. The authors similarly obtained results that hydrolysis did not occur in the field tests,[48] and therefore, only the state transition of oxidation is shown in Fig. 10.

7.2.2 Investigation of filter plugging in cases other than bio-oil

To investigate the mechanism of lacquer formation, the authors studied lacquer formation in petroleum hydraulic oil and engine oil.

In the field tests of extending the filter change interval from 500 h to 5,000 h in large construction machinery, which was a wheel loader using petroleum hydraulic oil, significant lacquer adhesion on the filter was observed (Fig. 13). Brown lacquer adhered to the white endplate and the yellow cellulose filter material and the filter material was plugged with lacquer. Since petroleum hydraulic oil has low acid value even at 4,000 h (Fig. 12), it is thought that the increased acid value was not related to lacquer formation, but the filter was plugged by lacquer formation near the hot spots.

The authors also clarified the cause of similar failure in engines.[51] Radicals are formed in the engine oil due to nitrogen oxides (NOx) in the combustion gas, and a large amount of lacquer is formed, and excessive wear of engine parts occurs due to early filter plugging. The engine oil used in this study did not contain effective antioxidants against

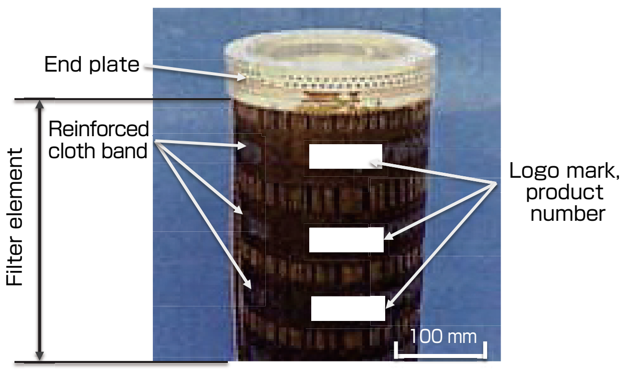

Fig. 13 Lacquer adhered on filter element in extension test (4,200 h) for filter change interval

NOx oxidation. It is the same situation as bio-oil that does not contain effective antioxidants against radicals. Such filter plugging by lacquer formation backs the assumption of the behavior in the state transition of bio-oil.

8 Proposal of countermeasures for malfunction using extended SafeML

8.1 Extension of SafeML

Hazardous situations were described using SafeML based on the behavior of malfunctions described by SysML, and countermeasures were investigated. However, conventional SafeML did not target hazard sources of failure of a product itself.[28] Therefore, the authors extended the language by adding "Short-term defence," "Long-term defence" (hereinafter, countermeasure), and market survey "Field Survey" to understand the effect of short-term measures that are shown in three purple elements as "Defence elements" of SafeML (Fig. 14). This paper will not address the short-term measures and the field survey. Biggs *et al.*[27] attempted calculation of the relative and quantitative "Safety Score" (see Appendix A) for multiple measures. Here, we attempt the application of the safety score for selecting the countermeasures.

8.2 Proposal for malfunction and countermeasures describing by extended SafeML

Three countermeasures can be proposed as described by the extended SafeML, as shown in Fig. 15. The countermeasures against the hazardous/harmful situations are described in Figs. 8–10. The use of unacceptable bio-oil, which is easy to deteriorate, that is inappropriate for construction machinery (pink element) is a "Hazard," and the malfunction of the hydraulic valve due to oil dust (red element) is "Harm." The source of the hazard is bio-oil, and it is shown in association as <<deriveHzd>>. "Harm Context" (yellow element) is the occurrence of sticking or abnormal wear of the hydraulic valve caused by oil dust as the filter is plugged prematurely due to the deterioration of the bio-oil. Since the element where the harm context occurs is in the hydraulic valve, it is shown in association as <<deriveHC>>. The long-term measures (green element <<Long-term defence>>) are proposals for preventing the harm context, and specific effects are shown in the result of long-term measures (blue element <<Defence Result>>). The five tag values are entered into the red, yellow, green, and blue elements. These include investigations of the probability of success, probability of occurrence, probability of harm, and range of harm, and severity of harm.[27] The safety requirement (light pink element <<requirement>>) that is shown in association as <<req Defence>> is described to validate long-term measures. The equipment for long-term measures associated to <<satisfy>> and the test <<test case>> associated to <<verify>> in the safety requirements can be specifically described through information sharing among the design department and the test department.

The basic countermeasures considered from malfunction behaviors are as follows: to prevent occurrence of hot spots by lowering excessive high-pressure oil, to prevent oxidation of bio-oil, and to prevent filter plugging. The specific proposals for the three long-term measures are shown below.

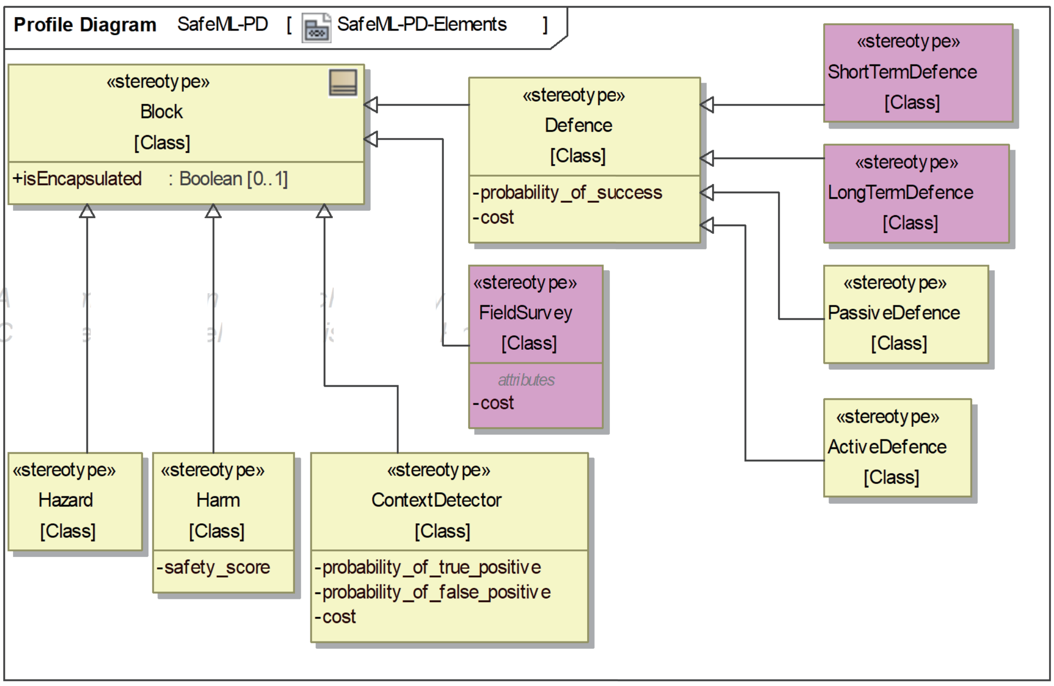

Fig. 14 Elements added to SafeML (purple element)

8.2.1 Proposal 1

The green element “(1) Auto engine controller” suppresses the release of excessive high-pressure oil from the relief valve unit of the main valve by engine control to reduce cavitation and lacquer formation. With this long-term measure proposal, a safety requirement of reducing excess oil pressure at low operating load operation (light pink element) is generated. To fulfill the requirement, it is necessary to investigate by a “Machinery Test” for the engine rotation controlling device “block, Engine Controller.” The result of the countermeasure (blue element) is the ability to reduce lacquer formation by lowering the pressure of the hydraulic valve to prevent filter plugging.

8.2.2 Proposal 2

The green element “(2) Centrifugal air bubble separator” involves the removal of air bubbles in the oil using a centrifuge,[30] and the reduction of lacquer formation by adiabatic compression at the hydraulic pump. The safety requirement is the reduction of oil oxygen content to prevent oxidation of bio-oil (light pink element). For the centrifugal air bubble separator that fulfills this safety requirement, it is necessary to conduct tests for the oil feed subsystem (yellow element). The effect of the countermeasure is to prevent bypassing of oil dust by controlling the deterioration of the bio-oil (blue element).

8.2.3 Proposal 3

The green element “(3) Improved Filter” involves the prevention of plugging by lacquer by improving the filtration performance of the filter. The safety requirement is to prevent filter plugging (light pink element). For the improved filter that uses the newly improved filter media that can fulfill this requirement, it is necessary to conduct a “Filter Bench Test.” The result of the countermeasure is to prevent the release of oil dust by increasing the capacity of the filter (blue element).

8.3 Technological investigation of countermeasure

Oil temperature decreases if pressure of high-pressure oil is reduced at low-load operation by automatic control of the engine, and release of excess high-pressure oil from the relief valve of the main valve is reduced. However, since cavitation occurs by other hydraulic valve operations, the effect is limited. For the deterioration of hydraulic oil, Sakama[30] clarified that the progress of oxidation reaction can be controlled by reducing the oxygen content in the hydraulic oil by centrifuging the air bubbles in oil. However, as mentioned before, antioxidants, which can sufficiently inhibit radical reactions, are not added to bio-oil, and it is thought that oxidation reaction occurs even in a state of reduced oxygen content. Therefore, sufficient results of oxidation prevention cannot be expected by the centrifuge method.

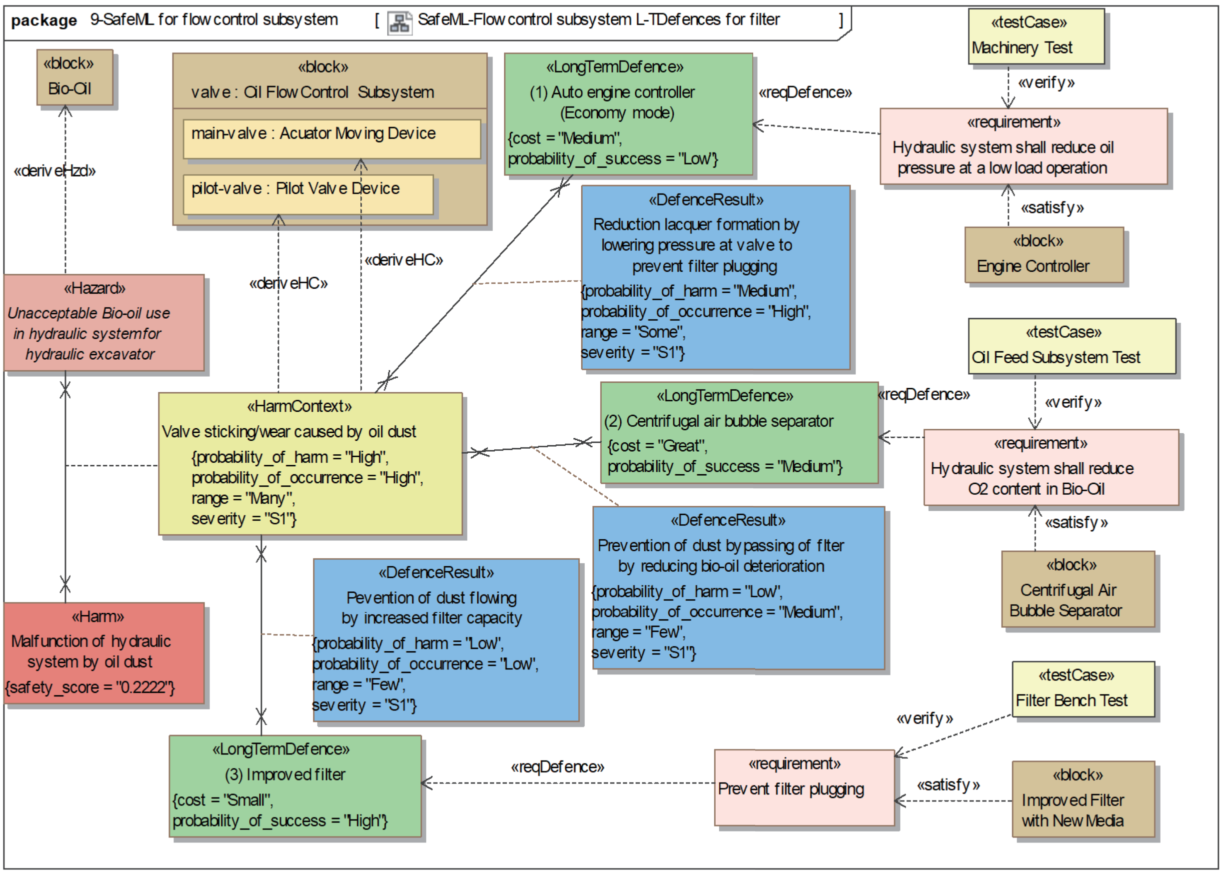

Fig. 15 SafeML diagram for three long-term measures for malfunction of hydraulic valve caused by bio-oil

Table 6. Comparison of five items tag value, safety score, and cost evaluation of cases without countermeasures and cases with three countermeasure proposals

No.	Countermeasures (defence)	Probability of defence success *S*	Probability of context occurrence of *P(Ou)* or *P(Od)*	Probability of harm occurrence *P(Hu)* or *P(Hd)*	Range of harm *Ru* or *Rd*	Severity of harm *Su* or *Sd*	Safety score *SS*	Cost evaluation
0	Undefended case	-	High (1.0000)	High (1.0000)	Many (0.7500)	S2 (0.5000)	0.3750	-
1	Automatic engine controller (economy mode)	Low (0.3333)	High (1.0000)	High (1.0000)	Some (0.5000)	S2 (0.5000)	0.3333	Small (0.5000)
2	Centrifugal air bubble separator	Medium (0.6667)	Medium (0.6667)	High (1.0000)	Few (0.2500)	S2 (0.5000)	0.0741	Great (1.0000)
3	Improved filter	High (1.0000)	Low (0.3333)	High (1.0000)	Few (0.2500)	S2 (0.5000)	0.0000	Small (0.5000)

Table 7. Occurrence of the malfunction in machinery before/after filter improvement

	Average annual occurrence of malfunction (over 2 years)
Vehicles using conventional cellulose filter	10.5
Vehicles using improved filter	Less than 1.4

For filters, improvement of filter materials has advanced recently, and the capturing performance of dust has increased and the lifespan until plugging has been extended.[52] In the measurement results of JIS hydraulic filter performance tests,[53] while a conventional cellulose filter material captures over 50 % of the dust of 20–30 μm or more, an improved filter material made by mixing glass fiber with polypropylene fiber can capture 50 % of dust of the size of 5 μm or more.[1] It is also reported that the filter lifespan using the improved filter media can be more than twice longer than the conventional material.[52] The diameter of a cellulose filter is at maximum 30 μm, while the diameter of the improved filter media is at maximum 1.0 μm. This is the reason the filter performance has improved, and it has prevented plugging of the filter by lacquer, and has enabled capture of oil dust, thus preventing sticking and abnormal wear of the hydraulic valve.

8.4 Determination of countermeasures

Table 6 shows the “Safety Score” (*SS*) and cost evaluation calculated using the equation in Appendix A, based on the tag values in the elements of Fig. 15, for a case without countermeasures (Undefended case) and cases with countermeasures. The probabilities of occurrence were categorized and quantified into three stages: low (Low: 1/3), medium (Medium: 2/3), and high (High: 1/1). The ranges of harm were set in four levels: 0.3 % or less (Few:1/4), medium level (Some: 2/4), high level (Many: 3/4), and 10 % or more (Most: 4/4). The severities of harm were set in four levels: cases that only require part replacement, cleaning, and adjustment that incur hardly any cost (S1: 1/4); cases that require replacement of parts or subsystems on site, or require disassembly and cleaning (S2: 2/4); cases that require repair of subsystems in a repair shop (S3: 3/4); and cases that require total repair of the vehicle or in which human injury has occurred (S4: 4/4). Cost evaluation was set in 4 levels: compatible and inexpensive (Minimum: 1/4), to small (Small), medium (Medium), and cases that require addition of part numbers of new subsystems and modification of the car body (Great: 4/4).

In the case of undefended case, the safety score is 0.3750, but the filter improvement plan has a safety score 0.0000 with the lowest value (highest effectiveness) and also has low cost. Therefore, we adopted the use of the improved filter. The safety score for the auto engine controller is 0.3333 and the one for the centrifugal air bubble separator is 0.0741, so the effectiveness of the countermeasures is lower than that of the improved filter. For cost evaluation, the auto engine controller was already employed in some models and its installation in all models had been decided, and the cost was evaluated as small. The centrifugal air bubble separator requires a new design of the hydraulic tank, and its installment has not been determined except in a few models,[54] and we set the cost evaluation as “great.” Since the improved filter is not compatible with the conventional filter due to the strength of the filter media, the cost was set as “small” rather than “minimum.”

8.5 Technical validation of countermeasures

Recently, the authors employed a filter with improved filter media to extend oil change interval. As a result, we found that there was no occurrence of malfunction of the hydraulic valve due to bio-oil in construction machinery as shown in Table 7. The effects expected by the use of the improved filter was to extend the oil change interval of petroleum hydraulic oil that had high oxidation stability and sufficient oil lifespan, by capturing and removing as much oil dust as possible.

The auto engine controller was already used in some machinery that also used the conventional cellulose filter, but it was assumed that there was hardly any effect on malfunction. The centrifugal air bubble separator for hydraulic oil was adopted in some machinery[54] as mentioned earlier, but the effect on bio-oil has not been observed. From these results of confirmation, it was shown that the determination of countermeasures using the safety score was appropriate.

9 Discussion

The project team was able to quickly implement short-term and long-term measures because component analysis methods had been deeply rooted in the construction machinery manufacturers. With the series of countermeasures (short-term and long-term measures), a certain degree of recognition was gained from the users and service persons, but the unsolved malfunctions of the hydraulic valve caused discontent among the users and service persons.

By analyzing the unsolved failures and proposing measures through an holistic analysis method using the system model described by SysML, we were able to complete the development of the hydraulic system of the construction machinery that allowed use of bio-oil. It was found that we were able to describe the cause and mechanism of the malfunctions based on the description in SysML, and we were able to determine the countermeasures based on the description in SafeML. Through this analysis, while only lead dissolution in bearing metal and oil discoloration were conventionally thought to be the problems caused by the low oxidation stability of bio-oil, it was newly clarified that filter plugging occurred by lacquer formation in the hydraulic oil. It was found that the filter not only captured oil dust, but also had the function of preventing oxidation and deterioration of oil by capturing lacquer produced by oxidation. In the future, development looking at the whole system using this new integrated analysis method will be possible. SafeML can graphically describe hazardous situations, countermeasures (defences), and safety requirements for failures, and these can be reviewed by a multidisciplinary team including those who are not engineers. The selection of countermeasures becomes possible from easy-to-understand indices of safety scores and cost. While the component analysis method has the disadvantage against problems that cover the whole complex system, it is an effective method for the analysis of failures in subsystems or parts as it can be done in a short time. The holistic analysis method using system models by SysML description has the disadvantage that it may take time to gain proficiency. Therefore, as shown in Fig. 4, it is recommended that the component analysis be used for the development of subsystems, while the holistic analysis be used for system development and problem solving.

10 Conclusion

In this paper, we attempted cause investigation and considered countermeasures for some problems of biodegradable hydraulic oil in construction machinery as promoted in Europe, utilizing a holistic analysis method using system models.

As a result, through the activities of the project team for bio-oil using the component analysis method, the following countermeasures were implemented.

1) As a short-term measure, a manual of bio-oil was created within half a year. This was distributed to the users through service personnel. This manual was effective until the completion of the long-term measures.

2) For long-term measures, hydraulic subsystems were improved in 4 to 5 years as scheduled, and were installed gradually to the construction machinery.

However, the cause and mechanism (behavior) of the unsolved malfunctions by bio-oil in construction machinery were not clarified since the occurrence of malfunctions ceased and no countermeasures were taken for failures.

Therefore, by analyzing the malfunctions using the new holistic analysis method and implementing countermeasures, the following results were obtained.

3) The cause and behavior of the malfunctions were clarified as follows using a system model described by SysML.
3-1 Lacquer is formed in bio-oil by adiabatic compression of air bubbles in the hydraulic pump and cavitation at the main valve.
3-2 The formed lacquer gradually accumulates and plugs the filter. Oil dust that flows without being filtered causes sticking and abnormal wear of the hydraulic valve, and this causes the malfunction of the hydraulic valve.

Based on these analysis results, countermeasures (long-term measures) were investigated using SafeML, and from evaluations of safety scores and cost, we were able to derive a countermeasure by an improved filter that is most effective and of low cost.

4) Through this analysis, we were able to complete the development of construction machinery that is compatible with bio-oil.

In the future, for development and failures that are large enough to affect business, it is expected that this holistic analysis method can be used for the cause analysis and countermeasure planning, in addition to the conventional component analysis method.

Finally, we are grateful for the advice given on SafeML by Dr. Geoffrey Biggs of AIST.

Appendix Equation for the safety score[27]

$SS = Qu(1-P(S)) + QdP(S)$ (1)

$Qu = P(Ou)P(Hu)RuSu$ (2)

$Qd = P(Od)P(Hd)RdSd$ (3)

provided

SS is safety score,

Qu is the preliminary safety score for undefended (no countermeasure) case,

Qd is the preliminary safety score for defence case,

P(S) is the probability of success of defence,

P(Ou) is the probability of context occurrence for undefended case,

P(Hu) is the probability of harm occurrence for undefended case,

Ru is the range of harm occurrence for undefended case,

Su is the severity of harm undefended case,

P(Od) is the probability of context occurrence for defence case,

P(Hd) is the probability of harm occurrence for defence case,

Rd is the range of harm for defence case, and

Sd is the severity of harm for defence case.

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Discussions with Reviewers

1 Overall

Comment (AKAMATSU Motoyuki, AIST and KOBAYASHI Naoto, Waseda University)

This paper explores the cause of failures that occur when bio-oil is used in the hydraulic system of construction machinery, and explains cases in which SysML and SafeML are used as methods to create countermeasures. Since the mechanism of failure occurrence by bio-oil is complex, analysis using accident analysis methods such as FTA is difficult in reaching a countermeasure. However, this paper shows that countermeasures can be determined using SysML that allows the description of interactions among subsystems. The paper presents a description of a scenario on how countermeasures were implemented in employing bio-oil, and this study is an example of a synthetic approach. This paper is appropriate for publication in *Synthesiology* in the points that it provides a solution to the practical issue of applying biodegradable hydraulic oil to the hydraulic system of construction machinery, contributes to the development of the hydraulic system, and shows the effectiveness of the integrated analysis method to solve complex problems through SysML and SafeML.

2 Overall picture of countermeasures

Comment (AKAMATSU Motoyuki)

I think this paper will become more appropriate for *Synthesiology* if you provide an overview showing the mutual positioning of countermeasures, short-term measures, and long-term measures for the subsystems, as well as the appeals to stakeholders (for example, a manual). I think the readers will be interested in knowing whether the countermeasures for the filter made the conventional measures no longer necessary, or the conventional measures still play important roles.

Answer (OHKAWA Satoshi)

To enhance understandability, we made corrections and additions to the diagram for the positioning of countermeasures, short-term measures, and long-term measures for the whole system, as well as measures for the subsystems. The definitions of short-term and long-term measures are explained in Chapter 1.

3 Effect on environment

Question (KOBAYASHI Naoto)

You mention that the motivation for using biodegradable hydraulic oil in the hydraulic system of construction machinery is to reduce the effect of environmental pollution when oil leakage occurs, but in reality, how often and in what amount have oil leakages occurred?

Answer (OHKAWA Satoshi)

A 30-ton class hydraulic excavator runs for an average 2,000 hours per year, and there is the possibility of about 40 L leakage during the year. Recently, instructions have been given to prevent oil leakage during work (such as placing plastic sheets when service persons provide services or removing oil with oil absorbing agents), and I think the amount of leakage has reduced. One-liter oil leakage contaminates 1 m^3 (2 ton) of soil, and the processing cost is 100,000 yen/ton. It is calculated that the processing cost of contaminated soil is 8 million yen a year. On the other hand, cases for which immediate measures must be taken are when a hydraulic hose hits a rock or reinforcing steel in concrete, the hose is broken, and oil spews out. In such cases a 350 L hydraulic tank will become empty in a minute.

4 Difference from conventional methods

Question (Kobayashi Naoto)

You clearly state the difference between the conventional component analysis methods (FTA and FMEA) and the newly employed integrated analysis methods (SysML and SafeML), but in practice, the boundary between them is not necessarily clear. Therefore, can you provide examples for the following: (1) what are your views on using different methods in various situations, such as using the new method in places where it didn't go well with the conventional method; and (2) what are the systems to which this method (SysML and SafeML) is highly applicable?

Answer (Ohkawa Satoshi)

All analyses can be done by holistic analysis methods using the system model described by SysML, without using component analysis. In fact, the author attempted cause analysis and countermeasure selection only by holistic analysis, and was able to find causes and mechanisms that could not be found with component analysis only. However, while this may depend on the skill level of the authors, holistic analysis (particularly, describing by SysML) required several times more time compared to component analysis.

(1) Since component analysis is simple and quick, it should be used on all systems. As shown in this paper, holistic analysis should be applied only to complex problems that cannot be clarified by component analysis.

(2) The holistic analysis method can be meaningfully applied to computer-controlled machine systems, machine systems affected by human behavior, and machine systems affected by complex chemical reaction.

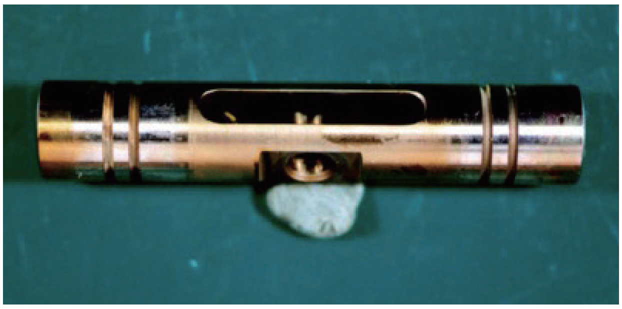
5 Lacquer formation

Question (Kobayashi Naoto)

You state that the major causes of lacquer formation, or oxidation condensate, are (1) adiabatic compression of air bubbles in the hydraulic pump and (2) cavitation at the main valve. Please provide explanation of the formation mechanism using supporting data and photographs. (It can be data from your published papers or other papers.) Lacquer has important effect on inducing plugging of the filter, but please provide typical chemical structures or names of the substance. How about other oxidation products?

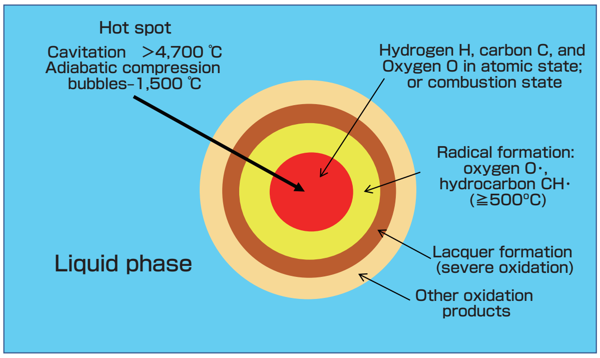
Answer (Ohkawa Satoshi)

As an example of lacquer, we added a photograph of the interior surface of a hydraulic pump part. It is assumed that the adhering lacquer was produced by adiabatic compression in the hydraulic pump. The lubricant oxidation test (JIS K 2514-1, 2018) of JIS standard provides a measurement method of the degree of lacquer formation by oxidation. The author has published a paper on a subject in which this oxidation test was conducted for biodegradable hydraulic oil [S. Ohkawa *et al.*: Oxidation and corrosion characteristics of vegetable-base biodegradable hydraulic oils, *SAE Paper*, 951038 (1995)], but did not mention lacquer as I was oblivious to its importance at the time.



Lacquer coat (brown part) on servo valve surface of hydraulic pump tester produced by commercial hydraulic oil (photo by authors).

When random oxidation is set off by radicals, the biodegradable hydraulic oil increases in viscosity (molecular weight 200–8,000; 100,000 in very high cases), as oxidation products containing alcohol (-OH), aldehydes (-CO), and acids (COOH) with complex composition and various molecular weights are formed. With severe oxidation polymerization by radicals, adhesive-like resin, or lacquer, is formed. Since lacquer is produced by such uncontrolled oxidation, there is no set chemical structure, and analysis is difficult. "Other oxidation products" are also difficult to analyze, and there is no prior research on such analysis. The author imagines that the formation of lacquer and "other oxidation products" progress as shown in the following figure.



Imagined state of oxidation of biodegradable hydraulic oil caused by cavitation and adiabatic compression bubbles (figure drawn by authors).