

Engine Dynamometers for Marine Applications

船舶用エンジンダイナモメータ

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HORIBA Automotive Test Systems (ATS) - as the name indicates - is mainly known as product and system provider for the automotive industry. Nevertheless, HORIBA Mechatronics due to its history, also has a strong footprint in the non-automotive sector by providing engine dynamometers for marine, aerospace and railway applications. This article gives an overview on different solutions for marine engine testing that were realized by HORIBA during the last 15 years in cooperation with customers all over the world.

HORIBAの自動車計測システム部門(ATS : Automotive Test Systems)は自動車産業向けの製品やシステムを提供している。加えて、メカトロニクス事業では、自動車以外の船舶、航空、鉄道分野にもエンジンダイナモメータを提供し、多くの実績を残している。本稿では、お客様との協力でHORIBAが実現した、船舶用のエンジン試験に用いたエンジンダイナモメータの最近の事例をいくつか紹介する。

Introduction

Marine transport plays a significant role in the global economy because sea freight is the most cost-effective way for goods and raw materials around the world.^[1] In 2017 the world seaborne trade reached a total volume of 10.7 billion tons.^[2] More than 90% of the world's trade is carried by sea^[1] and further growth of 3.8% per annum is expected until 2023.^[2]

This strong demand for transport vessels of all sizes is also reflected in the increasing demand for test systems for all type of ships. The International Maritime Organization (IMO) adopted in April 2018 an initial strategy to reduce the total annual greenhouse gas emissions from ships by at least 50% until 2050.^[2] It can be assumed that due to this ambitious target, the development effort for marine engines will increase as well as the demand for testing solutions for marine applications.

HORIBA's History and Experience in Engine Dynamometers

HORIBA gained a long history and tradition in the field of engine testing with the acquisition of the German company SCHENCK DTS (Development Test Systems) in 2005. Since 1960 HORIBA and SCHENCK delivered consolidated more than 10,000 units of hydraulic

dynamometers, eddy-current dynamometers, AC^{*1} and PM^{*2} (synchronous machine) dynamometers for engine and powertrain testing.

The hydraulic and eddy-current dynamometers were for a long time state-of-the-art technology and widely used as loading units for engine testing. Due to changed engine testing requirements, these dynamometers lost their dominate position and were systematically replaced by AC machines that have become the most important dynamometers during the last decades. In the meanwhile, HORIBA sold more than 1,400 load units of its well-respected Dynas3 AC dynamometer. But the "old" - and well proven - load units never lost their right to exist and are still commonly used in the marine engine testing because of some advantages compared with other solutions. In the following chapters, these dynamometer types are presented with different test bench concepts and applications.

*1: AC: Alternating Current

*2: PM: Permanent Magnet

Engine Test Stand with AC Dynamometer

We start our journey through different dynamometer concepts for marine engines with a conventional TITAN (brand name of the HORIBA system) Engine test bench that can

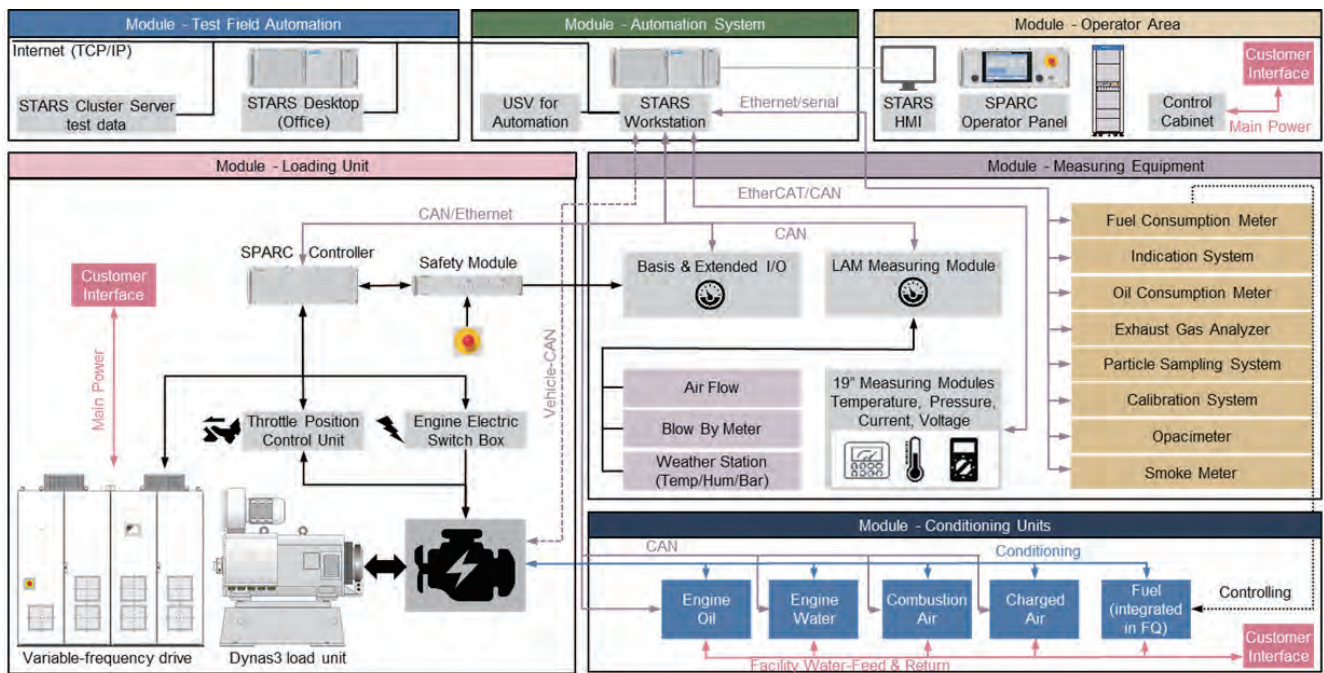


Figure 1 Block diagram TITAN engine test system

be used for all types of internal combustion engines. The TITAN Engine is mainly used for automotive engines, but in principle there is no difference from the system design between an engine test stand for automotive or marine applications. In most of the cases, the differentiation is due to the performance data of the specimen (maximum speed, torque, power, inertia etc.), the application of the test bed (stationary, transient or dynamic testing) and the measuring tasks.

In this example (Figure 1), the TITAN is equipped with a state-of-the-art AC dynamometer from the Dynas3 series. One of the reasons why AC machines are today's standard load units is that they perform in motoring (driving) and generating (absorbing) operation. While passive dynos - such as eddy-current and hydraulic dynos - only run in absorbing mode. In addition, they can be used for dynamic tests because of their dynamic response behaviour that is also not the case with passive dynos.

Figure 1 demonstrates the block diagram of the TITAN Engine Test System with its six core modules; namely, loading unit (rose), conditioning units (dark blue), measuring equipment (purple), operation's place (yellow), automation system (green) and test field automation (light blue).

The dynamometer and the SPARC Engine controller are the main components of the loading unit module (rose). The shown Dynas3 AC dynamometer is powered by a VFD (variable-frequency drive) cabinet and mechanically connected to the engine (DUT = device under test). The SPARC Engine controller is responsible for control of both the dynamometer and the DUT.

The block called Module-Conditioning Units (dark blue)

supplies fuel, oil, coolant, charged air and combustion air for the engine that are essential to run the DUT. Exact conditioning of media are needed to minimize non-systemic errors as well as to achieve accurate and reproducible measurements results.

The entire block called Module-Measuring Equipment (purple) is strongly influenced by the purpose of the test and the measuring task. The acquisition of temperature, pressure, current and voltage are done with standardized measuring modules. The ambient test cell conditions (temperature, humidity and pressure), which are important for the evaluation of the measurement results, are measured by a weather station. In addition, there are many engine-specific measuring systems that are used for specific measuring tasks (such as fuel flow, air flow, blow-by, oil consumption, smoke meter etc.).

Outside of the test cell is the block called Module-Operation's Place (yellow) where the user spends most of the time. It includes HMIs (human machine interfaces) of the SPARC controller as well as the STARS automation system and the measuring cabinet.

The STARS Engine automation system, shown in the block Module-Automation System (green) is a flexible high-performance automation platform with integrated automation, data acquisition and control functions. For larger test fields with a higher number of test stands, an additional block called Module-Test Field Automation (light blue) is beneficial for central data management.

The test cell of a TITAN Engine with an AC dynamometer Dynas3 HT 350 (350 kW rated power, 1,006 Nm rated torque and 9,000 rpm maximum speed) can be seen in Figure 2. The most important parts of the system are



Figure 2 Test cell with TITAN engine test system (HORIBA test center Oberursel, Germany)

marked with numbers as follows: operator area (1), test cell (2), base plate with air damper system (3), AC dynamometer with base frame (4), and DUT mounted on engine pallet (5).

The TITAN Engine covers the needs of development and production test. Development tasks can be performance testing, functional testing, endurance testing, calibration testing and emission certification. Production tasks are quality control or end-of-line testing.^[3]

The Dynas3 standard portfolio reaches from Dynas3 LI 145 (145 kW/308 Nm absorbing) to Dynas3 HD 1000 (1,000 kW/5,001 Nm absorbing). HORIBA provides dynamic test stand solutions for engines between 20 and close to 1,000 kW.

Test Stand with Hydraulic Dynamometer for Large Engines

Ship's power plants and propulsion systems are mainly constant speed diesel engines with high power and high torque. For stationary testing of engines above 500 kW, hydraulic dynamometers are the first choice because of their high power density and unbeatable price/performance ratio.

Main differentiation between hydraulic and AC dynamometers is that hydraulic load units can only perform in absorbing mode while AC machines are capable for absorbing plus driving operation. Hydraulic dynamometers work according to the Foettinger fluid coupling principle and they use water both as a working fluid and cooling medium. Turning the rotor causes a water whirl inside the dynamometer chamber that generates a braking torque on the rotor. The mechanical energy is converted into heat and dissipated by the water.^[4]

Figure 3 shows a ship engine test stand at Weichai Power (China) with a hydraulic dynamometer on the left and the DUT on the right side. The hydraulic dynamometer type



Figure 3 Engine test stand with hydraulic dynamometer and ship engine (Weichai Power, China)^[5]

DT2-12600-2 has a rated torque of 150,000 Nm, a rated power of 12,600 kW and a maximum speed of 2,500 rpm. To give the reader a sense of the size of the test stand shown in Figure 3, the weight of the hydraulic dynamometer only is approx. 8,500 kg. The load unit uses a load cell for torque measuring and a pulse generator with 60-teeth wheel for speed measuring.

Diverse standard sizes and two designs (one or two rotors/directions of rotation) of the DT-series can cover a wide range of combustion engines. The product range starts with the DT400-1 that provides absorbing power of 400 kW and a torque of 1,300 Nm. A maximum torque of 180,000 Nm along with 9,800 kW can be reached with the DT9800-1 which is on top of the standard product portfolio.

The key advantages of the DT series are the compact design with a high power density and the excellent price/performance ratio compared with other dynamometers types. They can reach a maximum performance level at extremely low maintenance costs because of the robust design and the use of high-quality materials. The sturdy design enables reliable operation even under suboptimal cooling water conditions. The self-monitoring function for bearing and cooling water temperature reduces the risk of unexpected downtime.

The main application field of test benches with hydraulic dynos are production tests of large internal combustion engines. But they can also be used for endurance tests as well as test benches for simple research and development tasks. All these applications are stationary tests with constant load/speed working points and typical torque response times of minimum 1 second for changes between two load points.

Engine Test Stand with Tandem Dynamometer

A tandem dynamometer is a combination of two load units. In most of the cases an asynchronous machine (active

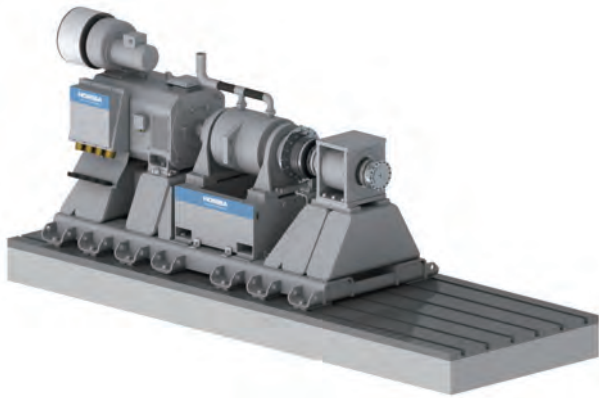


Figure 4 Tandem dynamometer (AC machine and hydraulic dynamometer)

loading unit) and a hydraulic dynamometer (passive loading unit) are combined. This kind of tandem systems are the right choice for large engines if a hydraulic dynamometer is not suitable because of its passive operation as well as non-dynamic behavior. Or a high-power electric machine cannot be installed due to cost reasons or limitations of mains supply. They are preferred in case of braking power above 800 kW combined with low motoring power demands.

Figure 4 shows as example the tandem configuration of the asynchronous load unit Dynas3 HT 350 and the hydraulic dynamometer DT1200-1. The AC machine (left), the hydraulic dynamometer (middle) and the intermediate bearing (right) are mechanically connected with two drive shafts and mounted on one common base frame. Between the middle dyno and the intermediate bearing is a torque measuring flange for highest measuring accuracy close to the specimen. The interface to the DUT is the flange connection on the right side of the bearing support. The engine (not illustrated) can be placed on the available space on the base plate.

The performance data of the tandem system are presented in Figure 5 and Figure 6. The complete system has a rated power of 1,550 kW (absorbing) from 3,400 rpm up to the maximum speed of 5,500 rpm (green line in Figure 5). The maximum absorbing power is a sum of the AC dynamometer (350 kW) and the hydraulic dynamometer (1,200 kW). The maximum driving power of 279 kW at 3,200 rpm is only provided by the AC machine (orange line).

The peak torque in absorbing operation of 8,505 Nm is available in a small speed range between 1,000 and 1,400 rpm (blue line in Figure 6). The maximum torque is as well a sum of the rated torques of the Dynas3 (1,005 Nm) and the DT dynamometer (7,500 Nm). The maximum driving torque of 999 Nm is provided at low speeds close to zero (yellow line).

Tandem dynamometers as shown above are mainly used

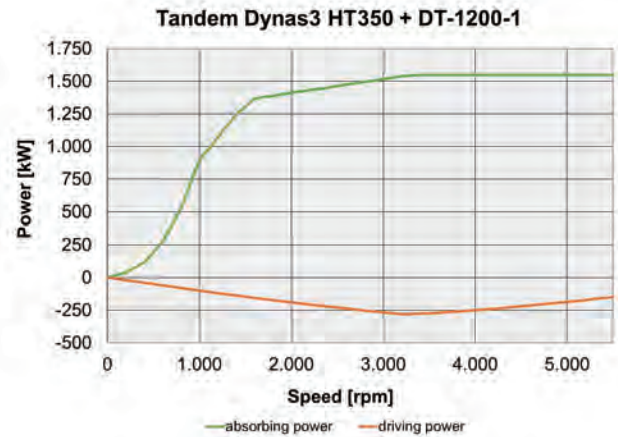


Figure 5 Power-speed diagram tandem dynamometer

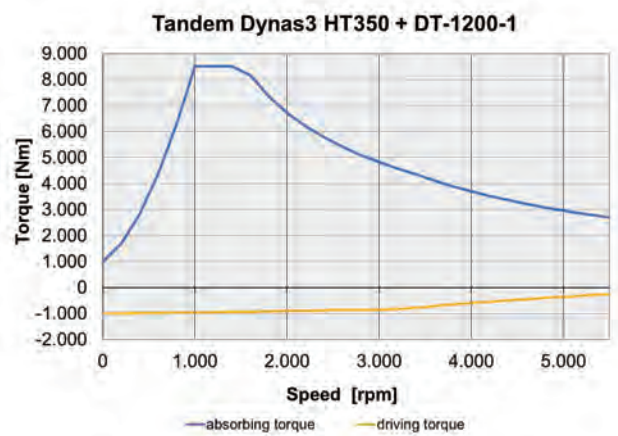


Figure 6 Torque-speed diagram tandem dynamometer

for stationary, for transient, and - with certain limitations - for dynamic engine testing of heavy-duty diesel engines. In steady-state working points, the full braking power of the hydraulic dyno is used and the AC machine runs in idle mode. In this case, the AC machine acts as an enhancement that can respond quickly when needed and provide full power for dynamic reactions.

Tandems cover a wide range of specimens with high power and torque demands. Due to their flexibility they are perfect for quality control and development test stands. They have the best price-performance ratio for absorbing power above 800 kW when low motoring power is needed (20% is in most of the cases enough). It is possible to combine all types of the proven HORIBA dynos. The maximum available tandem configuration from the HORIBA standard portfolio are the DT2100 (2,100 kW and 15,000 Nm) and HD1000 (1,025 kW and 5,000 Nm) for a total of 3,125 kW and 20,000 Nm.

NVH³ Dynamometer for Testing of Outboard Engines

NVH is both an attribute and a nuisance in road vehicles. NVH characteristics are carefully engineered to meet the

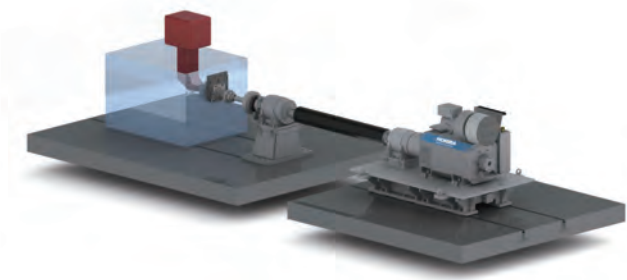


Figure 7 NVH test stand for outboard engines

design objectives of the developer to meet vehicle specific marketing objectives. But also for vessels there can be various reasons for influencing the noise level and characteristics of the engine. Like sports cars, speedboats should have a sporty sound characteristic. Noise topics for large ships have different interests such as protection of passengers and environment. Therefore, noise investigations are getting more and more important for marine applications. The measurement tasks of an NVH test stand have a major influence on the selection of test bench components and require a special test bench design. With audible noise measuring instruments, only the direct emissions from the DUT should be acquired without confounding indirect emissions like reflected noise within the test cell. Reflections must be reduced or dampened as good as possible by absorbing walls with special geometries. In addition, disturbances by the testing equipment (loading unit etc.) or external sources need to be avoided. Therefore, the test cell is vibration-decoupled from the building and the load unit is separated from the NVH test cell or enclosed with special housings.^[6]

Figure 7 shows the layout of a NVH test cell for outboard engines of small boats that was realized for a Japanese customer by HORIBA. The two independent baseplates represent an installation in different rooms with separation by a wall (not illustrated). The left part is the NVH test cell that contains a water basin with the outboard engine (red) inside. Beside the water basin is a bearing support that is connected to the propeller shaft of the outboard engine. On the right side - outside of the test cell - are the dynamometer and a second bearing support mounted on a base frame. The load unit is an AC dynamometer type Dynas3 HT 460 that provides a rated torque of 1,484 Nm and rated power of 460 kW. The system can be used for dynamic tests due to the max. speed gradient of the AC machine of nearly 10,000 rpm/s. All components of the system are specially designed for the torque of 1,500 Nm and maximum speed of 8,000 rpm.

For noise reduction optimization, the dynamometer is equipped with a speed controlled fan. The wall penetration between the dynamometer room and the test cell is realized with a 1,500 mm long black carbon (CFRP^{*4}) shaft

that connects both intermediate bearings in the dynamometer driveline. In addition the wall opening is acoustically sealed. The carbon shaft as well as the bearing support are covered with sound absorber on the specimen side.

Two most important parts of the design phase are mode shape frequency analyses of the main components and shaft torsional resonance calculations of all driving shafts between the dynamometer and the outboard engine. The frequency analysis is carried out for the full speed range of dynamometer. For the shaft torsional resonance calculation, the main components; namely, dynamometer, drive shafts and combustion engine need to be included. In the case of the engine, the engine type plays a significant role, as a excitation source, and is considered with its key characteristics in the calculation (number of cylinders, strokes, displacement, inertia, etc.). The multi-mass-model for torsional vibration analysis is created based on the schematic structure of the shaft connections with inertial mass allocations and torsional stiffnesses. Results are the resonance frequencies [Hz], critical speeds [rpm] and max operation speed [rpm] that influence the overall system design.

*3: NVH: Noise Vibration Harshness

*4: CFRP: Carbon Fiber Reinforced Polymer

Conclusion

Beside the automotive business HORIBA has a strong footprint in marine engine testing and can provide a wide range of dynamometer concepts for different applications. The standardized TITAN test stand can be adopted with AC machines for testing of engines between 20 and nearly 1,000 kW. Hydraulic dynos are the preferred solution for stationary tests of engines with power higher than 500 kW due to their cost advantage (purchase cost and total cost of ownership). The standard portfolio of DT dynos reaches depending on the DT version up to 12,600 kW power or 180,000 Nm torque. Tandem dynamometer systems can be the right solution for requirements of braking power above 800 kW in combination with low motoring power. The maximum available tandem configuration can provide 3,125 kW absorbing power and 20,000 Nm of torque. In addition to the standard test stand components and systems, there is a demand for customized testing solutions. The example of the NVH test stand for outboard engines shows the complexity in the design of such a special testing solution.

* This content is based on our investigation at this publish unless otherwise stated.

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