PROPULSION PLANT SIMULATION FOR FAST MILITARY VESSELS

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Abstract

Design and optimization of the propulsion system is a crucial task of the ship design. In fact the behaviour of the propulsion system is a key aspect of the global behaviour of a ship, mainly if the ship is a naval vessel.

Simulation techniques can be very effective to predict the propulsion plant behaviour during normal working conditions as well as during critical situations.

Numerical simulation gives the possibility to foresee, at design stage, the behaviour of the ship propulsion plant during manoeuvres and gives the designer the possibility to optimise the choice of the system parameters (choice of a suitable pitch/r.p.m. combination law, engine governor calibration, scantling of the shaft line) in order to prevent engine and mechanical overloads or faults. Moreover by simulation it is possible to study and optimise the machinery control system.

The paper presents a comprehensive approach to simulate the propulsion system behaviour during transients and off design conditions to be used for the control system setting and overall ship propulsion plants study.

The presented approach was successfully used for the design of the new high speed Italian Frigates FREMM class. This ships class has a new propulsion plant concept: the COmbined Diesel eLectric And Gas (CODLAG) type, with single gear and two shaft lines.

The application presented in this paper concerns the design of the propulsion control system with a detailed simulation of the Gas Turbine Control System (TCS) and of the controllable pitch propeller system. A comparison between simulation transients results and reference data is reported in the paper.

***Keywords*:** Ship propulsion, CODLAG plants, Governors

INTRODUCTION

Some new generation frigates, as the German Class F125 or the Italian-French FREMM, currently under construction, have only one gas turbine which mechanically drives the two propeller shafts via a cross-connected gearbox, further each shaft has its own electric motor.

The latest concept of this propulsion technology is the CODLAG system, where the electric propulsion drives the ship at cruising speeds or for silent running, while the gas turbine takes over for the maximum speed of about 30 knots.

The particular gears arrangement of this gearbox is able to provide many propulsive configurations, according to the several requirements of the vessel's mission profile. An increasingly interest, particularly evident in naval vessels applications, is currently shown in marine propulsion systems that combine mechanical drive with electric drive components.

Such systems can offer lower structural born noise and vibrations, a reduced number of prime movers and a greater flexibility in the operating profile of the vessel.

To achieve flexibility system are rather complex and the ship automation system must be able to manage and to control all the apparatus for all the possible ship's missions and configurations. In particular, the propulsion controller (the CPU that controls the propulsion system) must be able to handle the propulsion machineries for all the required navigation and manoeuvring modes, complying with the tight response requirements typical of an high speed naval vessel, but in a manner to prevent any damage to the system or injuries to the persons.

The propulsion controller design is a major issue to obtain the ship desired performance.

The simulation of the system behaviour is becoming a useful tool for the designer, mainly when the project deals with new configurations where no or little experience exists and/or where the complexity of the system is very high. Simulation at design stage gives the designer insight into the expected performance of the system, providing feedback that would otherwise be unavailable until the system is installed. This gives the possibility to check a number of design alternatives in order to find an optimum solution. Furthermore, this design approach greatly reduces the need of conducting costly and time-consuming full-scale trials.

Simulation has been successfully used in engineering for many years as a support of the design process [1-5]. Marine propulsion system simulations can be used for a variety of purposes, such as machinery performance analysis, ship performance analysis, manoeuvring analysis and machinery control systems development [5-7]. The authors developed a method for the design and test of the propulsion control system of the Italian aircraft carrier Cavour by simulation [8]. Ad hoc simulation models and different simulation techniques were developed and used in the different phases of the project, from basic controller design, to controller development and finally to controller tuning by hardware in the loop test bed in the factory. The final tuning at sea lasted less than half that scheduled and during sea trials all the desired performance were fulfilled.

The same design approach has been adopted for the propulsion controller of the Italian Navy FREMM frigates. The choice is justified by the complexity of the propulsion system, by the novelty of its configuration and by the positive results obtained with the Cavour project.

Particularly, for what the novelty of the configuration is concerned, the presence of a powerful gas turbine that simultaneously drives two propeller shafts, may lead to significant torque unbalances upon the reduction gears system, mainly during fast turning circles of the ship.

The paper describes the simulation procedure adopted for the development of the propulsion controller of this innovative CODLAG propulsion system for warships application.

CODLAG SYSTEM

Fig.1 shows the general architecture of the considered CODLAG system. In the same figure, the main propulsion plant control units are visualized.

Two Controllable Pitch Propellers (CPP) are driven via a cross connected gearbox by one Gas Turbine (GT), a LM 2500 General Electric/Avio, 32 MW at 3600 rpm. Two Electrical Propulsion Motors (EPM Jeumont, 2 x 2.2 MW), directly mounted on the two shaftlines, can be used for the low speeds of the vessel during the silent running or together with the gas turbine for the full power. The use of the two different kinds of prime movers (EPM and/or GT) is ensured by two clutches between the gearbox and the two EPM and by another clutch between the GT and the gearbox.

The electric power is supplied by Isotta Fraschini Diesel Generators and electric power can be produced in GT mode by the two EPM, working as Shaft Generators (SG).

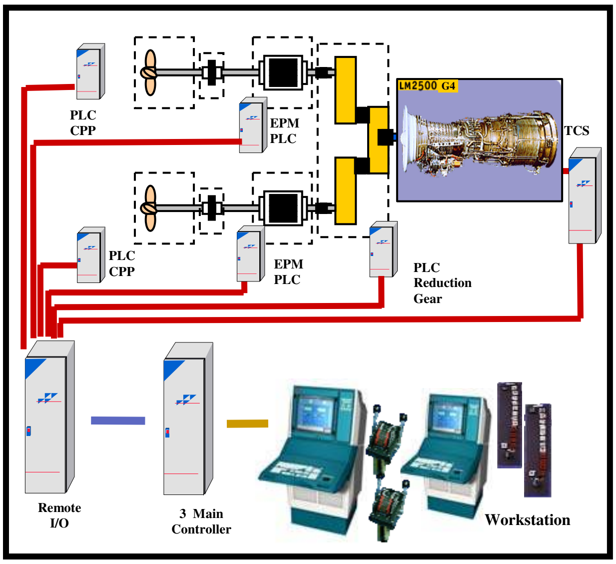

Fig. 1, CODLAG propulsion scheme and propulsion management integrated control

The hardware architecture of the CODLAG propulsion control system is visualized in fig. 1. The Main Controller is connected to the control operative units (CPP, EPM, Reduction Gear PLC's and Gas Turbine TCS) by the Remote I/O unit.

CODLAG SIMULATOR

The simulator consists of a set of differential equations, algebraic equations and tables that represent the various elements of the propulsion system and manoeuvrability behaviour of the ship. The following elements are modelled:

automation, engine and motors, propellers, pitch mechanisms, couplings, rudders and hull forces; the model includes mutual interactions among the elements.

Solving numerically the differential equations of motion allows to obtain time histories of propulsion system behaviour (power, torque, RPM, etc.) and of manoeuvrability (in particular, the three degrees of freedom considered are surge, sway and yaw). Such type of lumped parameters simulation models have proven their technical validity in previous works, including validation at sea [5, 8].

For the purpose of the paper, the electric propulsion component and pertinent management parts are not simulated.

Figure 2 shows the schematic of the CODLAG simulator.

The propulsion plant dynamics is represented by the two equations of motion of the two shaftlines of the type:

$$2\pi J_p \frac{dn(t)}{dt} = \sum_{i=1}^{I} Q_{engine(i)}(t) - \sum_{j=1}^{J} Q_{load(j)}(t) - Q_{friction}(t) \qquad (1)$$

The ship manoeuvrability is represented by the 3 degrees of freedom (D.O.F.) equations of motions in the horizontal plane:

$$\begin{aligned} \text{Surge:} \quad & \sum F_x = m\,(\dot{u} - vr) \qquad (2) \\ \text{Sway:} \quad & \sum F_y = m\,(\dot{v} + ur) \\ \text{Yaw:} \quad & \sum M_z = I_{zz}\dot{r} \end{aligned}$$

Hull forces and moments are evaluated from usual regression series which were tested in detail in [9]. In particular, regression formulae dedicated to twin screw vessels were obtained starting from Clarke and Inoue models with minor tuning in order to consider model tests results. Regarding rudder forces, the model described in [10] is adopted.

For each element illustrated in Figure 2, numerical models with different level of accuracy have been developed, taking into account the general objective of a good balance between the fidelity of the simulation results and the code performance.

Propellers are modelled by their open water characteristics in steady state condition (K_T and K_Q versus J at different blade angles).

EPM is modelled considering the maximum torque and the different control strategies, i.e. constant speed or constant power.

Gearbox is taken into account only by the reduction ratio and the inertia; couplings are considered in order to model all the possible propulsion configurations.

The model is able to consider also configurations with cross connected shaftlines, resulting in one unique differential equation of motion with two driving torques and two propeller torques (plus frictional losses due to shaftlines mechanical couplings and bearings).

Asymmetrical behaviour of shaftlines during manoeuvre is taken into account by means of the introduction of asymmetrical variations of both wake fraction w and thrust deduction factor t. In particular, during manoeuvres, values of coefficients Δw and Δt are computed for each shaftline, as functions of ship speed and ship drift angle; then they are added to values in straight motion, obtained from usual self propulsion tests. As a consequence, J value is different for internal and external shafts, thus different K_T and K_Q values will result.

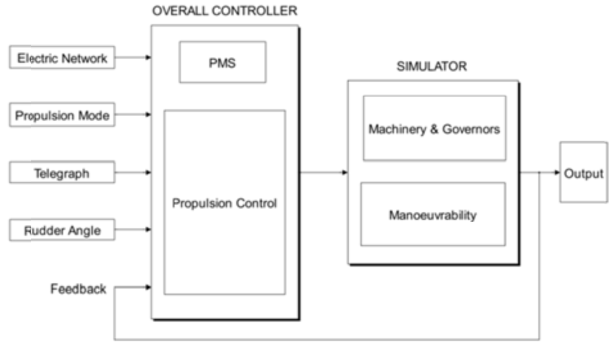

Fig. 2 – Propulsion and Manoeuvre Model

Figure 3 shows the functional scheme of the Propulsion System Controller. Five types of control schemes have been tested by simulation. Main inputs are the telegraph lever position and the propulsion mode (navigation, manoeuvre, ect.), both selected by the operator. Main controller outputs are: propellers pitch setpoint, GT setpoint, EPM setpoint. The blocks in Figure 3 represent the main functions. The engine set point calculation includes a PI governor based on shaft speed and a GT protection based on maximum torques. The propeller pitch set point calculation is based on an adaptive combinator curve and it includes

pitch reduction to avoid shaft overload. The torque balance between shaftlines prevents gearbox overload.
The previously described control strategy represents the ‘high level’ propulsion control. In addition each main subsystem (i.e. the engine, the electric motor, the propeller) has its own controller (modelled in the machinery & governos block) that operates concurrently with the ‘high level’ control.

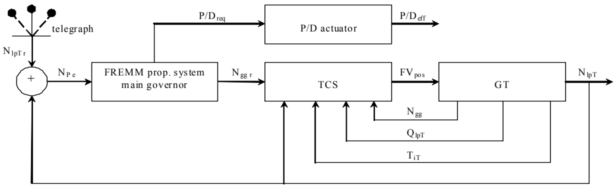

Fig. 3 – Propulsion Control scheme in GT mode

GAS TURBINE & TCS SIMULATOR

The **gas turbine** (GT) mathematical model is based on the intercomponent volumes method [11]. This calculation scheme is based on a thermodynamic approach to the gas turbine components simulation, as consequence during the transients the mass and energy accumulation into the GT volumes is considered by means of the energy and continuity dynamic equations, applied to GT intercomponent volumes. The thermodynamic approach for the GT simulation model is more important for the TCS simulator development, because eventually oversizing values in the GT parameters, caused by mass, energy and momentum accumulation in the quick transients, can be accurately reproduced with this GT simulation type.
A short description of the GT model is reported here, while for a more detailed explanation see [11].
The GT model is structured in a modular arrangement. Each module is pertinent to a GT component (i.e.: compressor, turbine, combustor and so on).
In the compressor and turbines modules the steady state performance maps [12] are used.
The combustor module is modeled as an adiabatic capacity, taking into account the time-dependent accumulation of mass and energy.
In the shaft dynamics module the time variation of the shaft angular velocity is determined by the classic shaft dynamic balance equation.

The **Turbine Control System** (TCS in fig. 4) manages the LM 2500 gas turbine in order to obtain the propeller speed value required from the telegraph position. The TCS model is developed in accordance to [13]. The gas turbine load is correlated to the GT gas generator speed; the required value of this parameter ($N_{gg\ r}$ in fig. 4) came from the FREMM propulsion controller, the TCS manage the fuel valve (FV_{pos} in fig. 4) by a PID control scheme. At the same time the TCS checks a series of GT parameters (mainly: the gas generator and power turbine speeds N_{gg} and N_{PT} respectively, the power turbine shaft torque Q_{PT} and the intermediate turbine gas temperature TIT) in order to not exceed their pertinent maximum admissible value. The signals generated by all the TCS PID controllers are compared, and the minimum signal value is adopted for the fuel valve managing. In the normal GT work conditions, the minimum PID controllers signals value is that of the N_{gg} controller.

TCS SETTING

For a preliminary TCS setting a test bench is simulated as reported in the SIMULINK scheme of fig. 4.

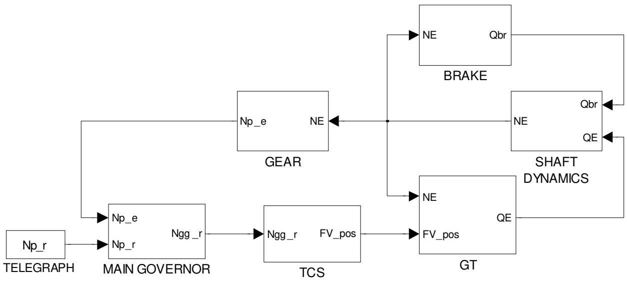

Fig. 4, Test bench for preliminary TCS setting

In this simulator the originally CODLAG plant components: telegraph, main governor, TCS, GT and gear are maintained, while the other originally ship propulsion plant component simulators: propeller and hull, with pertinent ship inertia, are substituted with a brake which torque law is a quadratic function of the propeller shaft speed.
This test bench is used to compare the transients results of the thermodynamic GT model, with

and without TCS governor, with a GT simulator model provided by the GT manufacturer (AVIO), that include also the TCS system.

Fig. 5 shows the transient results comparison referred to a step telegraph variation between 50 to 100%. In particular the fig. 5.2 shows that the developed TCS maintain the GT turbines intermediate temperature (TIT) into its corrected maximum value, that is not the case of the thermodynamic GT model without TCS.

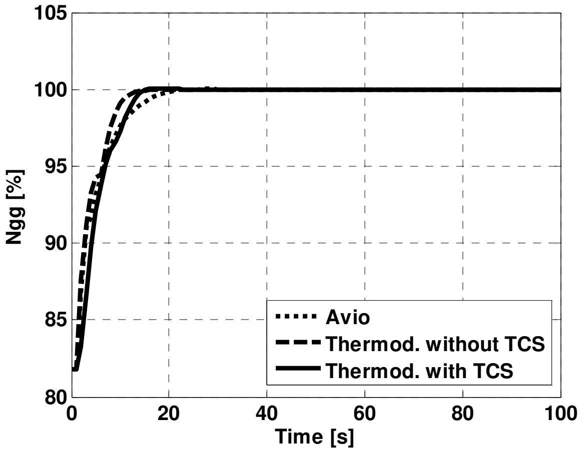

Fig. 5.1

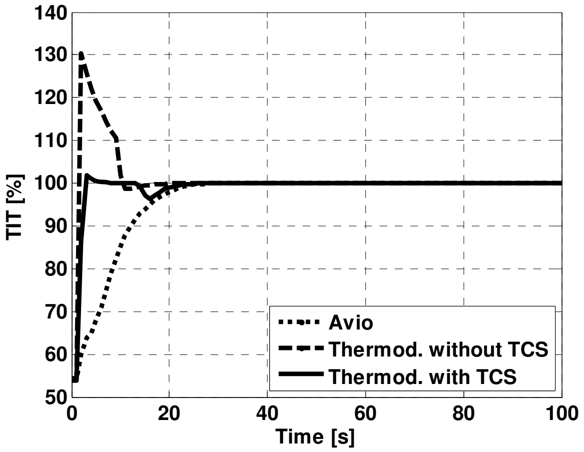

Fig. 5.2

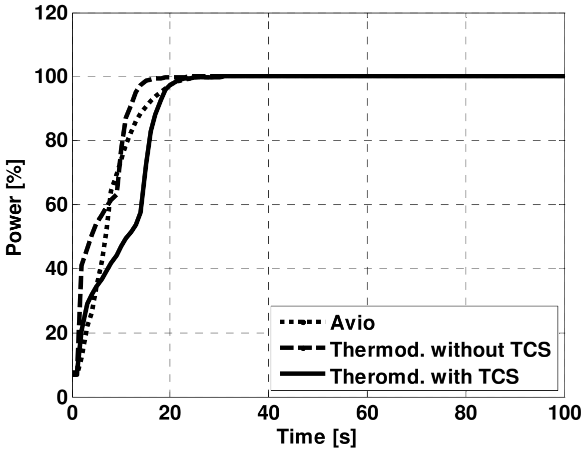

Fig. 5.3

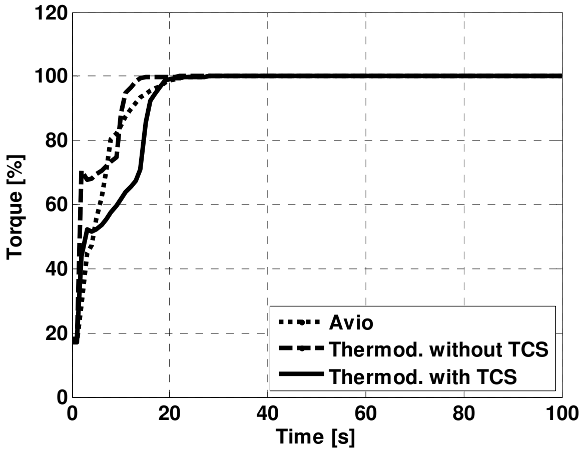

Fig. 5.4

Fig. 5, Telegraph 50 to 100 % step transient test bench gas turbine models results comparison

As shows in fig. 5, there is a substantial results accordance between the GT thermodynamic model with TCS and the AVIO model; an analogue results correspondence is observed in others acceleration-deceleration transients. Still from the same figure, it can be observe the influence of the TCS governor on the GT thermodynamic simulator results.

CODLAG SIMULATOR RESULTS

The CODLAG simulation model, including the developed TCS GT governor, is tested with a series of ship transient simulations. In Fig. 6 the results of a transient generated by a step telegraph variation between 50 to 100% are presented.

Despite the criticality of the manoeuvre, all the GT and plant data monitored remain into their pertinent corrected values intervals.

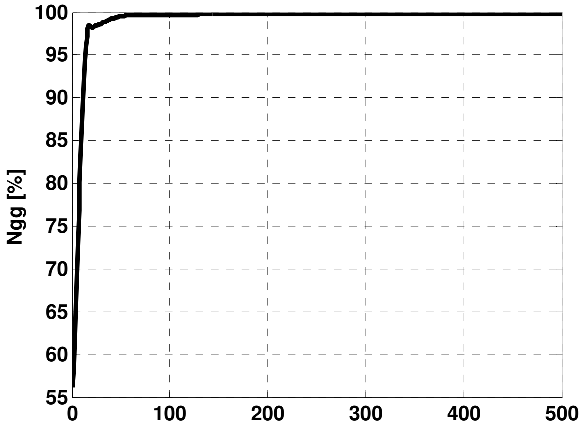

Fig. 6.1

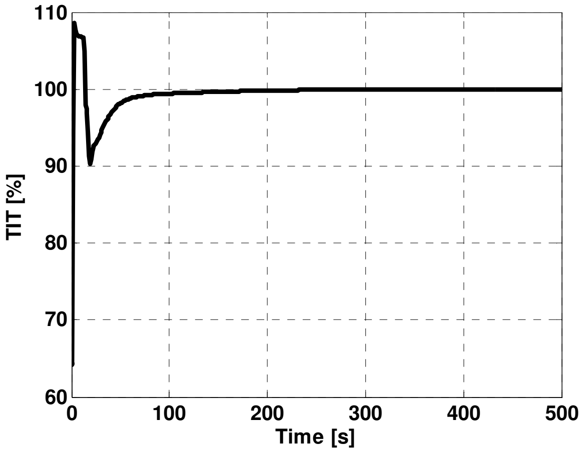

Fig. 6.2

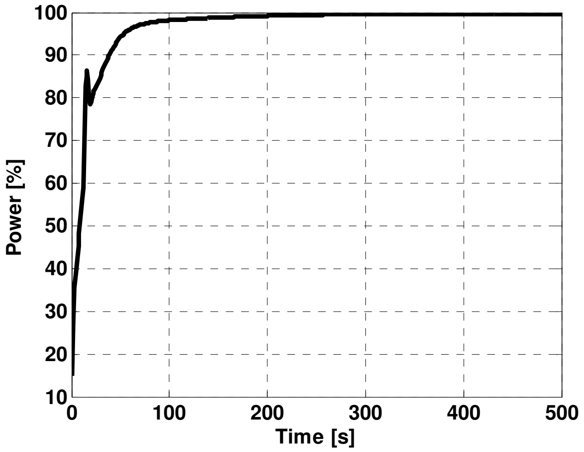

Fig. 6.3

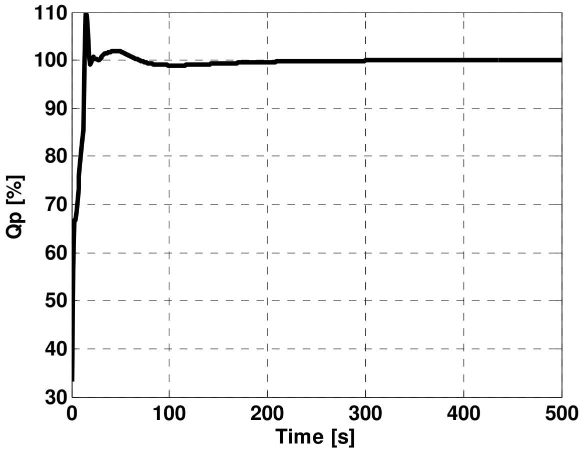

Fig. 6.4

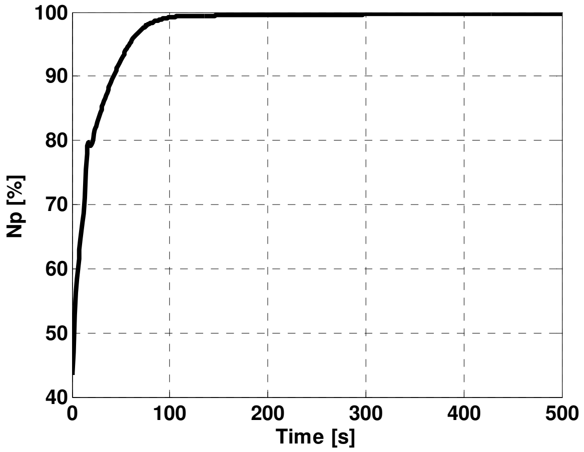

Fig. 6.5

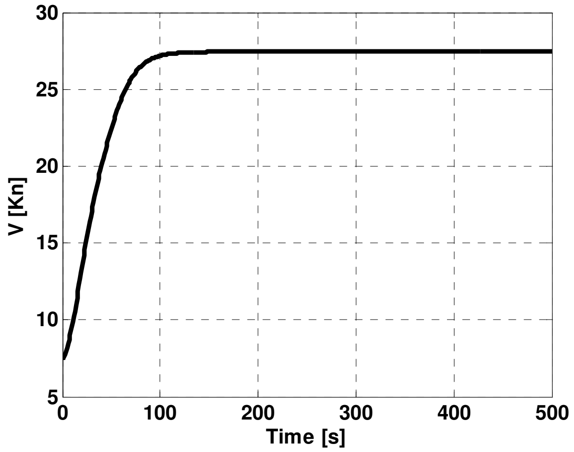

Fig. 6.6

Fig. 6, Telegraph 50 to 100 % step transient CODLAG simulator results

CONCLUSIONS

A design method for the propulsion control system of a high speed naval vessel has been presented. The method, developed for the Italian Aircraft Carrier Cavour, has been now adopted for the design of the propulsion control system of the new Italian FREMM frigates. The procedure integrates basic knowledge and experience of the manufacturer with massive use of numerical simulation. The presented approach is able to produce great advantages for ships where the complexity and versatility of the propulsion system requires a wide range of operating conditions that are difficult to analyse with traditional methods.

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