Application of the strain gauge alignment technique on slow-speed diesel propulsion shafting installations

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SYNOPSIS

Marine propulsion shaft alignment using the strain gauge alignment technique is becoming more common place as shipyards and owners find the technique is accurate, reliable and cost effective. There are a number of advantages of incorporating this technique on slow-speed diesel propulsion shaftlines. Accurate measurements of both the vertical and athwartships loads on the lineshaft and sterntube bearings can be obtained while the shaft is completely assembled. Direct measurement of the shear and bending moment at the thrust shaft flange can also be obtained, to ensure the load on the aft-most engine bearing is acceptable. Measurements can usually be obtained within thirty minutes, enabling shaft alignment to be evaluated at various loading conditions and machinery temperatures without significantly interfering with operations or production. The strain gauge alignment technique has also been shown to be more accurate and less time consuming than the traditional method using gap and sag and jack-up load measurements. The strain gauge alignment technique was incorporated into the alignment procedures for the Pure Car Truck Carrier "MV Jean Anne" built by VTHalter Marine Inc., and the first two CV-2600 container vessels built at Aker Philadelphia Shipyard. This paper describes the measurements and results of the strain gauge alignment technique used for these two classes of vessels.

INTRODUCTION

Propulsion shaft alignment on systems with slow-speed diesel engines is a critical element of ship construction. Typically, the propulsion shaftline arrangement consists of two outboard bearings (forward and aft sterntube) that support the propeller shaft and one to two bearings that support the lineshaft(s). The main engine has one aft bearing that supports the thrust shaft, and multiple bearings that support the crankshaft – one between each cylinder and one on either end of the crankshaft. Figure 1 provides a schematic of the propulsion shaftline on the CV-2600 Container class vessels. Bearing failures due to improper shaft alignment continue to occur, even with the advances in computer modeling and shipbuilding technology made in recent years. Such failures can delay ship delivery or interrupt service, both of which involve considerable financial penalty. To reduce the risk of such failures, it is becoming more common to implement the strain gauge alignment technique as part of the alignment procedure. This technique provides a direct measurement of the alignment condition to ensure that an acceptable alignment condition has been achieved and is maintained.

Author's Biography
Mr. Bruce Cowper graduated with a Bachelors of Applied Science in Mechanical Engineering from the University of British Columbia in 1982. From 1982 to 1984, Bruce worked as a Research and Project Engineer for Canadian Marine Drilling Limited and from 1985 to 1997 for Fleet Technology Ltd. In 1997 Mr. Cowper formed his own consulting company (LamaLo Technology Inc.), specializing in marine propulsion shafting alignment, vibration and powering: including trouble-shooting, design and construction. Bruce has worked on over 120 vessels, ranging from 30 m long 2.4 MW tug boats, to 290 m long 48 MW Ro-Ro vessels, and has been on over 60 sea trials in diverse conditions and environments, including the North Pacific, North Atlantic, Arctic Ocean, Beaufort Sea, Weddell Sea, Gulf of Mexico, and South China Sea.
Mr. David Rickman graduated with a Bachelors of Science in Physics and Mathematics from Baker University in 1975. He received nuclear propulsion engineering training while serving in the US Navy as a submarine line officer. David is the Chief Mechanical Engineer at VT Halter Marine. He has designed the machinery systems and propulsion arrangements for the vessels built by VT Halter Marine since 1990. His expertise is in the selection, design, installation, and troubleshooting of propulsion systems, including geared diesel, z-drive, and direct drive arrangements.
Mr. Dean Sahr studied Marine Engineering at The United States Merchant Marine Academy and Mathematics at Ferrum College and Chesapeake College. Before coming to the Aker Philadelphia Shipyard, Dean worked as a service engineer and project engineer for Wartsila Diesel Inc. on marine two stoke and four stroke propulsion plants and land based diesel power generation projects. Dean is the Aker Philadelphia Shipyard responsible engineer for new build propulsion plant installation and alignment and the production coordinator for shipboard machinery. Dean has serviced over 200 vessels in 20 years with propulsion plants ranging from 1.5 MW to 30MW, both two and four stroke diesel. Dean has also participated in 51 propulsion plant service and new build related sea trials in the North Atlantic, Baltic, Pacific, Indian and Southern Oceans.

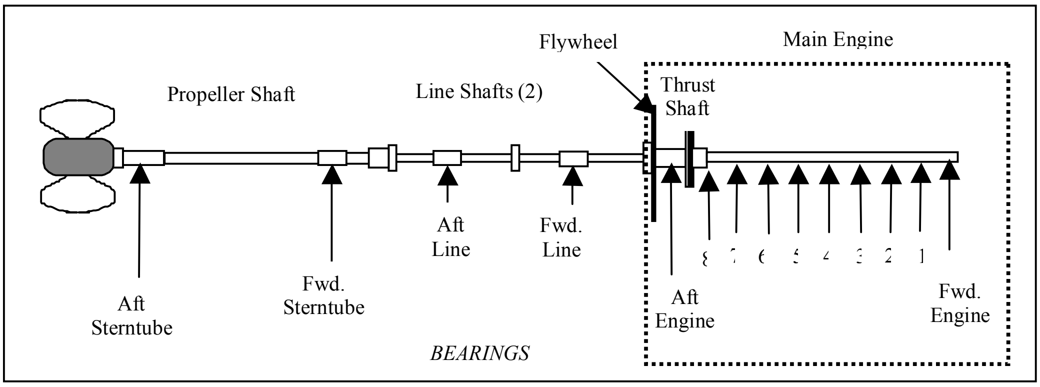

Figure 1 Schematic of CV-2600 Philadelphia Class Container Vessels

SHAFT ALIGNMENT TECHNIQUES

Optical

The optical alignment method is used to align the sterntube bearings to the projected positions of the line shaft bearings and the main engine crank shaft. A scope, piano wire, or laser is commonly used to measure the offsets of the bearing centers and foundations - all methods being equally acceptable. The vessel is on the building berth, out of the water, and the shafting is not in place. Measurements are taken when there is little solar affect on the hull structure, usually a few hours before sunrise. Generally the main engine is on its foundation, but not necessarily assembled. If the main engine is not in the ship, then the deflection of the hull with the addition of the engine mass needs to be accounted for in positioning the sterntube bearings for an acceptable alignment condition. If the hull deflection is not accounted for properly when the main engine is installed after the sterntube is chocked in place, removal and re-chocking of the sterntube may be required. Therefore, it recommended this affect be measured on the first of a class, since it is not practical to calculate with sufficient reliability using theoretical modeling techniques. It is common to have the sterntube arrive in the shipyard with the two white metal bearings already fitted into the sterntube. The sterntube is then aligned using an optical technique and chocked into the sterntube bossing.

Jack-Up Load

The jack-up load method is used to measure the vertical load on the lineshaft bearings and the aft two main engine bearings [1]. The measured bearing loads are compared to the desired aligned loads computed from a theoretical model and to the allowable loads as specified by the manufacturer. The vessel is afloat and the shafting is supported by the bearings. Measurements are taken at various stages of assembly up to and including the fully assembled condition. A jack is placed near the bearing, the shaft is raised and lowered, and the load is measured at a number of positions. Figure 2 shows a jack-up load tests being conducted on a lineshaft bearing.

Figure 2 Jack-Up Load Test on Lineshaft Bearing

The vertical load on the bearing is estimated from a projection of the load displacement curve. The athwartships (horizontal) load can not be determined by this method. The jack-up load measurement on the two aft most crankshaft bearings requires a correction factor, which is commonly more than 50%, since the bearings are very close together. The aft most engine bearing is usually required to have a very low load, or even unloaded, in the cold aligned light-ship condition. Therefore, the jack-up load measurements on this bearing can be subject to significant errors. In addition, it is a cumbersome measurement to perform since the location is very confined. The number of jack-up load measurements can be reduced significantly if the strain gauge technique is employed.

Gap and Sag

The gap and sag technique is an indirect method for establishing the positions of bearings and engine when the propulsion shaft is not connected. The offset between two flanges, radial (sag) and face (gap) are measured when two adjacent flanges are disconnected. The positions of the bearing(s) are adjusted to achieve the specified gap and sag values that were derived by a theoretical alignment analysis. In a number of cases, including the CV-2600 Philadelphia Container vessels, the gap and sag procedure does not provide sufficient accuracy to ensure proper alignment of the main engine to the line shafting. In the case of the CV-2600 container vessels, the shaft over-hang from the forward lineshaft bearing to the engine crank shaft flange was 7.7 m. With this relatively long over-hanging shaft, small errors in the estimates of the shaft flange mass or position can result in significant changes to the gap and sag values, which results in misalignment of the main engine to the lineshaft. Therefore, the gap and sag method is recommended only for a "rough" alignment of the main engine to the lineshaft, and obtaining the specified tolerances (sometimes as low as ±0.025mm) should not be considered critical to the alignment process.

Crankshaft Web Deflection and Bedplate Sag

Crankshaft web deflections are taken at the final stage of alignment. They are used to determine if the load on the crankshaft from the lineshaft is acceptable, and if the relative loading between crankshaft bearings are acceptable. Crankshaft web deflections should be as close to zero as possible in service condition (vessel loaded and warm) [2,3,4]. Special target values are applied during alignment to compensate for the affect of hull deflection on crankshaft bearing loads during loading of the vessel. These target values are developed based upon experience with different classes of vessels. In the case of 5S60MC-C for large bulk-carriers, the vertical crankshaft deflection target is between +0.06 mm and +0.22 mm. Figure 3 shows a crankshaft web deflection measurement being taken. Problems with crankshaft bearings have occurred when the aft most crankshaft bearing becomes unloaded when the engine is warm and the vessel is loaded. Typically the aft most engine bearing (on the thrust shaft) is aligned with little or no load in the cold static light ship condition. When the engine heats up and the vessel is loaded the load on this bearing increases and the load on the aft most crankshaft bearing decreases. The shear and bending moment combination at the thrust shaft flange, which provides an indication of the load on the aft most engine bearing, is specified by the engine manufacturer. To ensure a proper alignment is achieved within tolerance, strain gauge alignment measurements are used to directly measure this shear and bending moment.

Figure 3 Crankshaft Web Deflection Measurements

Engine sag measurements are conducted to ensure that the crankshaft bearings are in their prescribed position relative to the bedplate. These measurements are usually taken with the use of a piano wire. The engine manufacturer supplies a lower and upper tolerance for the sag of the engine. Measurements are taken typically taken at the location of the center of each main bearing. Again target values taken in the cold static light-ship condition are established to compensate for the affects of engine warming and hull deflection when loaded.

Strain Gauge

Strain gauge measurements provide bearing loads (athwartships and vertical), shaft stresses, and shear and bending moment at the main engine thrust shaft flange with the propulsion shafting system completely assembled [5,6,7,8,9]. Sterntube and lineshaft bearing offsets can also be estimated using strain gauge measurements along with results from a finite element analysis. Strain gauges are mounted on the shaft at selected locations along the shaftline between the sterntube seal and the main engine. The ship is in the water and the shafting system is completely assembled, with lineshaft bearings and the main engine supported by jacking screws/hydraulic jacks. Shaft bending strains are measured at 90° intervals of shaft rotation, starting from top dead center. The output of strain gauges provides a measurement of the bending strain in the shaft, from which the bending moment and shear can be determined. Force and moment equilibrium equations are used to develop equations that relate the bending strain measurements to the bearing loads. These equations are then put into a spreadsheet to compute the bearing loads shortly after the measurements are taken. After the strain gauges are installed, the alignment condition can typically be measured and assessed within less than 30 minutes. Bearing load measurement accuracy is typically better than ±6%, and the accuracy of the measured bending moment and shear at the thrust shaft flange is typically better than ±5%. This technique was applied with success on two classes of vessels built in the United States of America, one on the 2600 TUE container ships built at Aker Philadelphia Shipyards, and the other on the Pure Car Truck Carrier "MV Jean Anne" built by VTHalter Marine Inc. The following provides a discussion of the measurements and results of the strain gauge alignment technique used on these two classes of vessels.

STRAIN GAUGE ALIGNMENT ON THE CV-2600 PHILADELPHIA-CLASS CONTAINER VESSELS

Figure 4 Sea Trials of the MV Manukai (CV-2600 Container Vessel)

Background

CV-2600 Philadelphia-Class container vessels are constructed at Aker Philadelphia Shipyard. The vessels have a displacement of approximately 30,000 metric tons, a cargo capacity of 2,600 TEU, a length overall of 217 meters and an operating speed of 22.7 knots, powered by a 28,880 kW slow speed diesel engine. The vessel design is similar to other vessels built in Europe during the mid 1990's. After launching and installation of the main engine on the first German vessel, it was found that the engine could not be properly aligned to the line shafting. This misalignment was attributed to a change in the relative position of the engine support structure that resulted from an unfavourable hull deflection that occurred after the engine was installed and the vessel was launched. Subsequently, the vessel was re-docked, and the sterntube was removed, realigned and then re-chocked. After the ship was completed and while under service, failures occurred to the main bearings on the engine crankshaft. These failures were reported to be caused by a misalignment of the main engine to the line shafting, as a result of errors in the theoretical model used to calculate the required gap and sag at the engine output flange. The misalignment was corrected by appropriate changes to the selected crankshaft bearing clearances, and the engine support structure was stiffened. Similar failures occurred on the second vessel. Further empirical alignment information was obtained during the construction of nine other similar vessels. It was determined that misalignment problems could be corrected by fitting the forward end of the main engine support structure 28 mm higher than a straight line projected through the center of the sterntube bearings. This empirical solution was implemented with success on the CV-2600 ships built in Philadelphia.

An analysis of the CV-2600 shafting system indicated the gap and sag procedure would not provide sufficient accuracy to ensure proper alignment of the main engine to the line shafting. The shaft over-hang from the forward lineshaft bearing to the engine crank shaft flange is 7.7 m. With this relatively long over-hanging shaft, small errors in the estimates of the shaft flange mass or position can result in significant changes to the gap and sag values, which results in misalignment of the main engine to the lineshaft. This may have been one of the sources of the problems encountered on the class of vessels built in Europe. Therefore, it was recommended that gap and sag measurement should not be used as the final verification of the alignment of the lineshaft to the main engine. To reduce the risk of alignment problems on the CV-2600 class vessels, the strain gauge alignment technique was added to the standard alignment procedure for the first 2 vessels, the MV Manukai and MV Maunawili, and was used as the final verification of the shaft alignment.

Shaftline Description

The CV-2600 class vessel has a single screw propeller configuration. The 6 bladed fixed pitch propeller is directly driven by a MAN B&W 8K 80 MC-C, turbo-charged, two stroke, 8 cylinder, diesel engine rated at 28,800 kW (39,200 HP) at 106.7 RPM. The operating speed range is 22 to 104 RPM. The propulsion shaftline is approximately 32 m long, and is supported by two sterntube bearings and two line shaft bearings. The thrust shaft has one support bearing between the turning wheel and the thrust bearing. The main engine crankshaft is supported by nine (9) bearings. An illustration of the finite element model of the shaftline is shown in Figure 5 illustrating the approximate locations of the strain gauges.

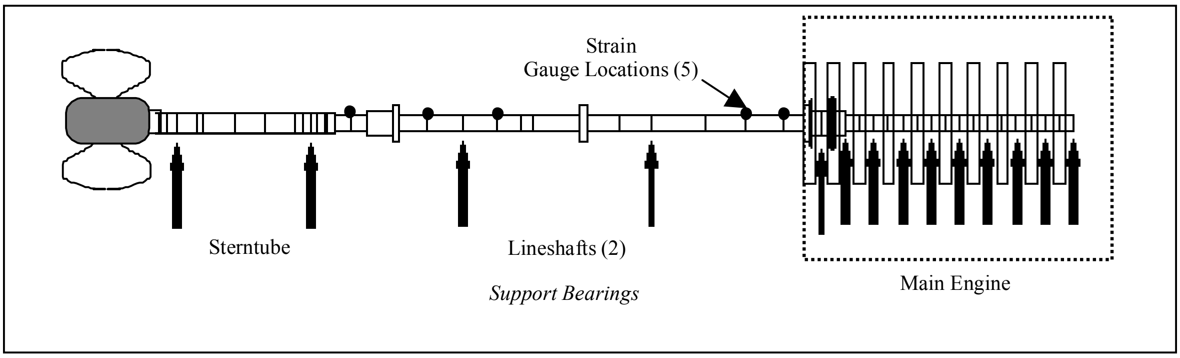

Figure 5 Schematic of CV-2600 Philadelphia Class Propulsion Shafting

Shaftline Alignment Analysis and Requirements

A finite element model of the shaftline was developed and used to conduct the theoretical shaft alignment analysis. This included bearing loads, gap and sag values, shaft stresses, deflection, and slopes, and bearing reaction influence numbers. Alignment criteria were developed based upon the Author's experience, manufacturers' specifications, industry standards and classification society rules. They are listed in Table 1. A set of bearing offsets were developed to produce a satisfactory alignment condition. These offsets are listed in Table 2. The main engine was required to be sloped 1.516 mm/m upwards looking forward to reduce the load on the aft most engine bearing (on thrust shaft) in the cold static condition. This is a common method to reduce the load on this bearing and maintain acceptable loads on the other main engine bearings. The theoretical bearing loads for the prescribed bearing offsets are shown in Table 3. The theoretical straight-line condition indicates that main engine #8 bearing is top loaded, and the aft line shaft bearing is overloaded. The prescribed condition provides for a more even bearing load distribution, and all bearing loads within their allowable limit. The prescribed alignment condition had the following limitations:

(i) The prescribed engine rotation requires a difference in chock thickness of 19 mm across the length of the engine. The allowable range of chock thickness is 20 to 70 mm.
(ii) The load on the forward lineshaft bearing is about 90% of the rated load. The operating temperatures for all bearings were satisfactory after 8 hours running at 100% MCR during sea trials on the MV Manukai (1st vessel of this class). Therefore, the prescribed loads on these bearings can be considered acceptable for this class of vessel. However, an alternative alignment condition which would have a higher load on the forward sterntube bearing and a lower load on the lineshaft bearings would be recommended for other vessels with a similar arrangement.

Table 1 Alignment Criteria: CV-2600

Description	*Design Limit*
Maximum relatives shaft slope across sterntube bearings	0.30 mrad
Maximum shaft bending stress	41 MPa
Maximum horizontal offsets of sterntube bearings	0.48 mm
Minimum bearing load	103 kN - Fwd. Sterntube 113 kN – Line shaft Bearings 40 kN – Aft Engine (0 kN Cold Static) 40 kN – Crankshaft Bearings
Maximum bending in engine crank shaft	15 MPa – Stress; 654 kNm – Moment
Maximum shear force and bending moment at engine flange in static condition	See Figure 8
Bearing	***Maximum Allowable Static Bearing Loads** (kN)*
Aft Sterntube	855
Fwd. Sterntube	429
Aft Line shaft	235
Fwd. Line shaft	235
Aft Engine	793
Engine Main	793

Table 2 Prescribed Bearing Offsets: CV-2600

Bearings	*Cold Vertical Offsets (+ve is upwards) (mm)*
Aft Sterntube	0.000
Fwd. Sterntube	0.000
Aft Line shaft	-2.130
Fwd. Line shaft	0.000
Aft most Engine (AE)	8.600
Main Engine # 8	10.344
Main Engine # 7	12.503
Main Engine # 6	14.662
Main Engine # 5	16.821
Main Engine # 4	18.980
Main Engine # 3	21.139
Main Engine # 2	23.298
Main Engine # 1	25.457
Main Engine Fwd.	27.616
Engine Rotation around Aftmost Engine Bearing	1.516 mm/m

Table 3 Theoretical Vertical Bearing Loads: CV-2600

Bearings	*Bearing Loads (kN)*				
	Straight All Bearings Aligned Concentric		*Prescribed Cold*	*Prescribed Warm*	*% Allowable Warm*
	Chain Force	*No Chain Force*	*No Chain Force*	*Chain Force*	*Chain Force*
Aft Sterntube	685	685	658	659	77%
Fwd. Sterntube	62	62	129	127	30%
Aft Line shaft	249	249	203	209	89%
Fwd. Line shaft	205	205	227	212	90%
Aft Most Engine	327	389	148	151	19%
Main Engine # 8	-19	36	271	160	20%
Main Engine # 7	333	330	320	327	41%
Main Engine # 6	307	307	312	311	39%
Main Engine # 5	314	314	310	311	39%
Main Engine # 4	311	311	311	311	39%
Main Engine # 3	317	317	314	314	40%
Main Engine # 2	295	295	295	295	37%
Main Engine # 1	375	375	376	376	47%
Main Engine Fwd.	107	107	105	105	13%

Strain Gauge Alignment on the MV Maunawili

The strain gauge alignment technique was employed after the engine flywheel flange was bolted to the forward lineshaft flange. Initially, the two lineshaft bearings were lowered 1.2 mm in an attempt to achieve the prescribed bearing loads on the forward sterntube and aft line shaft bearings. In this position, the forward lineshaft bearing load was about 84 kN lower than the prescribed loading, and the BM and Shear combination on the thrust shaft flange was out of the acceptable range (see Table 4 and Figure 8). This misalignment could only be corrected by movement of the engine, primarily by lifting the forward end of the engine. The forward end of the engine was then raised about 14 mm to achieve acceptable crankshaft web deflections. The aft lineshaft bearing was also raised 1.6mm. Figures 6 and 7 provide a view of the lineshaft during the alignment and inside the crankcase, respectively.

Figure 6 Jack Up Load Tests on Lineshaft

Figure 7 Standing on Crankshaft Web

Table 4 lists the measured bearing loads from the strain gauge technique. Figure 8 presents the measured shear and bending moment at the thrust shaft flange. The results indicated that an acceptable alignment condition was achieved. The measured vertical loads on the propulsion shaft bearings were at most 8% different than the prescribed loads, and the lineshaft bearings were about 1.2 mm higher than the prescribed position. The higher line shaft bearing positions were required to obtain a low to zero load on the aft most engine bearing, which was acceptable for the cold static condition for this type of vessel. This resulted in the thrust shaft flange shear-moment point to be at the far left side of the acceptable range as shown in Figure 8. The measured athwartships bearing loads indicated that the propulsion shaft bearings were straight-aligned athwartships to less than 0.10 mm, which was also considered acceptable. The maximum lineshaft bending stress measured was 14 MPa, which was considerably lower than the maximum allowable stress of 41 MPa. The bearing temperatures and shafting vibrations were satisfactory throughout the sea trials, and since the vessels entered service in 2003 (1st ship) and 2004 (2nd ship).

Table 4 Measured Bearing Loads: Cold Condition CV-2600

Bearing	*Bearing Loads (kN)*					
	Initial		*Lowered Both Line Shaft Bearings 1.2 mm*		*Final Forward Engine up 14 mm Aft Line Shaft Bearing Up 1.6 mm*	
	Vertical	*Athwartships*	*Vertical*	*Athwartships*	*Vertical*	*Athwartships*
Aft Sterntube	667	-1	661	-2	666	2
Fwd Sterntube	106	1	132	1	111	-2
Aft Lineshaft	255	0	225	2	232	0
Fwd Lineshaft	258	-6	143	-3	242	1

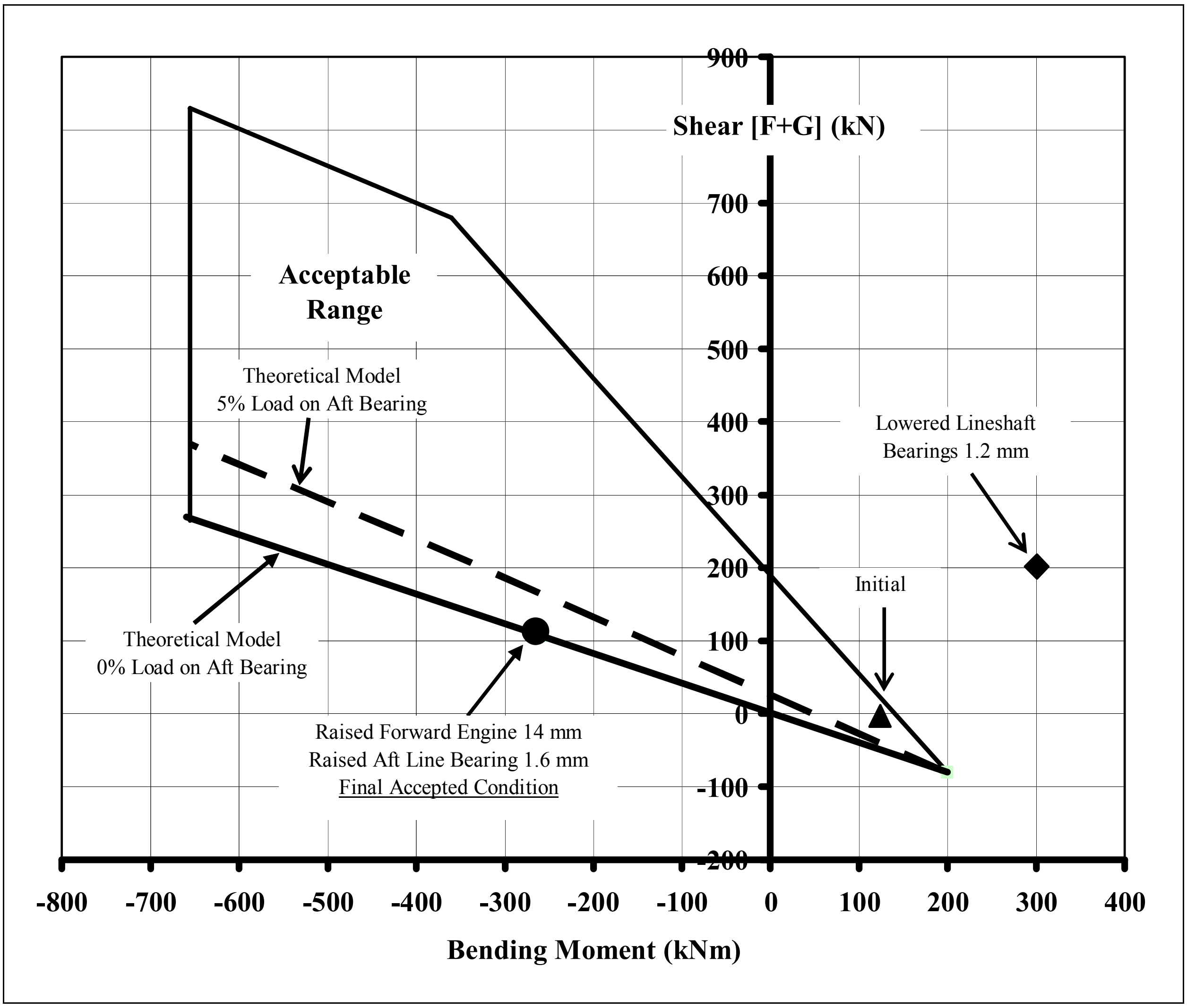

Figure 8 Thrust Shaft Flange Bending Moment and Shear: CV-2600

STRAIN GAUGE ALIGNMENT
ON THE MV JEAN ANNE – PURE CAR TRUCK CARRIER

Figure 9 MV Jean Anne

Background

The MV Jean Anne is a 579' Car Carrier that was constructed by VT Halter Marine, Inc. The vessel is a roll on / roll off car and truck carrier, suitable to carry passenger cars and trucks, in world-wide and U.S. coast-wise service. It has a displacement of 12,850 tonnes, with a dead weight of 8,818 tonnes. The same class of vessel was constructed in Croatia. During sea trials of the vessels built in Croatia the lineshaft bearings were found to run hot, and realignment was required after sea trials. To reduce the risk of similar alignment problems on the MV Jean Anne, the strain gauge alignment technique was added to the standard alignment procedure and was used as the final verification of the lineshaft alignment.

Shaftline Description

The vessel has a single screw propeller configuration. The 4 bladed fixed pitch propeller is directly driven by a MAN B&W 7-S50MC-C, turbo-charged, two stroke, 7 cylinder, diesel engine rated at 11,060 kW at 127 RPM. The propulsion shaftline is approximately 22 m long, and is supported by two sterntube bearings and two lineshaft bearings. The thrust shaft has one support bearing between the turning wheel and the thrust bearing. The main engine crankshaft is supported by eight (8) bearings. A schematic of the shaftline is shown in Figure 10, illustrating the approximate locations of the strain gauges.

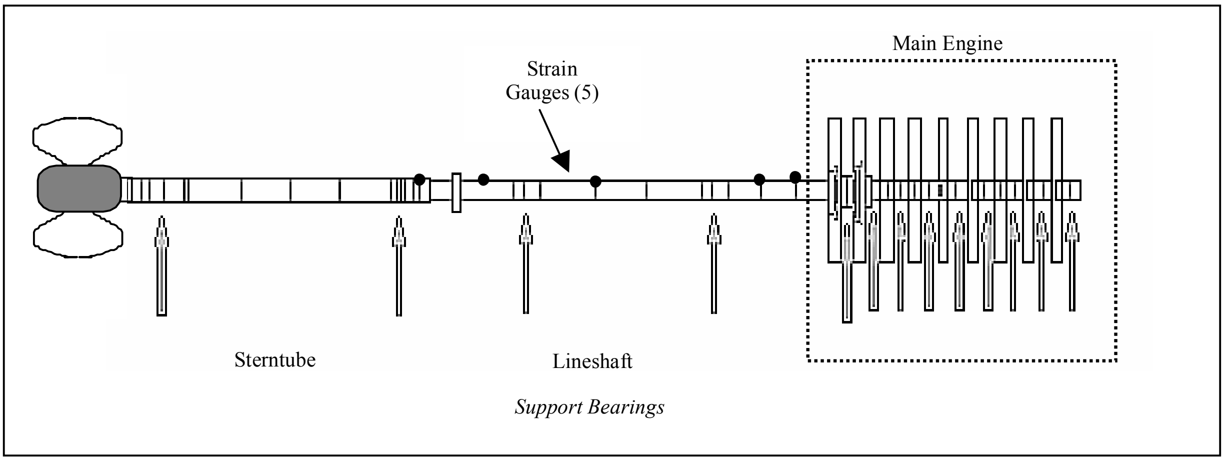

Figure 10 Schematic of MV Jean Anne Propulsion Shafting

Shaftline Alignment Analysis and Requirements

A finite element model of the shaftline was developed and used to conduct the theoretical shaft alignment analysis. This included bearing loads, gap and sag values, shaft stresses, deflection, and slopes, and bearing reaction influence numbers. The analysis indicated that the shafting system is relatively stiff in way of the forward lineshaft bearing. For example, a change in the vertical offset of the forward lineshaft bearing of 0.25 mm results in a change in load of the forward lineshaft bearing of 17 kN and the aft main engine bearing of -52 kN. These load changes are in the range of the corresponding prescribed alignment loads, and therefore can result in unloading of the No. 7 main engine bearing or the forward lineshaft bearing. Therefore, the ship's structure is required to be sufficiently stiff, such that the relative deflection between the engine and lineshaft bearings is less than 0.12 mm (5 mils) under all loading conditions. An arrangement where only one lineshaft bearing is fitted, mid-span between the engine and the forward sterntube bearing would provide a much more flexible system (about 3 times more flexible), and would permit larger relative hull deflections without changing shaft alignment condition significantly. This arrangement was recommended to be considered for the next vessel of this class.

Alignment criteria were developed based upon the authors' experience, manufacturer's specifications, industry standards and classification society rules. They are listed in Table 5. A set of bearing offsets were developed to provide an alignment condition that would satisfy all the alignment criteria. These offsets are listed in Table 6. Similar to the CV-2600 vessels, the main engine was required to be sloped upwards looking forward 1.00 mm/m to reduce the load on the aft most engine bearing (on thrust shaft) in the cold static condition. The theoretical bearing loads for the prescribed bearing offsets are shown in Table 7. The theoretical straight-line condition indicates that main engine #7 bearing is under-loaded. The prescribed condition provides a better load distribution and maintains loads within allowable limits.

Table 5 Alignment Criteria: MV Jean Anne

Description	*Design Limit*
Maximum Relative Shaft Slope Across Sterntube Bearings	0.30 mrad
Maximum Shaft bending stress	41 MPa
Maximum Horizontal Offsets of Sterntube Bearings	0.35 mm
Minimum Bearing Load	33 kN - Fwd. Sterntube 13 kN - Aft Lineshaft 13 kN – Fwd. Lineshaft 15 kN – Aft Engine (0 kN Cold Static) 15 kN – Crankshaft Bearings
Maximum Permissible bending in engine crank shaft	15 MPa– Stress; 169 kNm – Moment
Maximum Shear Force and Bending Moment at engine flange in static condition	See Figure 12
Bearing	***Maximum Allowable Static Bearing Loads** (kN)*
Aft Sterntube	402
Fwd. Sterntube	99
Aft Line shaft	112
Fwd. Line shaft	112
Aft Engine	291
Engine Main	291

Table 6 Prescribed Bearing Offsets: MV Jean Anne

Bearings	*Cold Vertical Offsets (+ve is upwards) (mm)*
Aft Sterntube	0.00
Fwd. Sterntube	0.00
Aft Line shaft	-0.75
Fwd. Line shaft	-1.00
Aft most Engine (AE)	1.90
Main Engine # 7	2.66
Main Engine # 6	3.51
Main Engine # 5	4.36
Main Engine # 4	5.21
Main Engine # 3	6.06
Main Engine # 2	6.91
Main Engine # 1	7.76
Main Engine Fwd.	8.61
Engine Rotation around Aftmost Engine Bearing	1.00 mm/m

Table 7 Theoretical Vertical Bearing Loads: MV Jean Anne

Bearings	*Bearing Loads (kN)*						
	Maximum Allowable	*Minimum Allowable*	*Straight*	*Prescribed Cold*		*Prescribed Warm*	
			Chain Force	*No Chain Force*	*Chain Force*	*No Eccentric Thrust*	*Eccentric Thrust*
Aft Sterntube	402	NA	207	203	203	203	182
Fwd. Sterntube	99	33	42	54	54	52	68
Aft Lineshaft	112	13	55	58	58	62	55
Fwd. Lineshaft	112	13	51	34	34	22	24
Aftmost Engine (AE)	291	15	56	49	15	57	45
Main Engine # 7	291	15	4	88	54	20	39
Main Engine # 6	291	15	96	92	93	95	85
Main Engine # 5	291	15	90	91	91	90	93
Main Engine # 4	291	15	91	91	91	91	90
Main Engine # 3	291	15	92	92	92	92	93
Main Engine # 2	291	15	86	86	86	86	86
Main Engine # 1	291	15	109	109	109	109	109
Main Engine Fwd.	291	15	31	31	31	31	31

Strain Gauge Alignment on the MV Jean Anne

Prior to the strain gauge alignment, the shafting was aligned according to gap and sag and jack-up load methods. The strain gauge alignment was conducted with the lineshaft bearings and main engine on jacking screws and with the engine flywheel bolted to the forward lineshaft flange. Warm alignment measurements were conducted immediately after sea trials. The cranks shaft web deflections were measured at the same time as the strain gauge alignment measurements. Table 8 lists the measured bearing loads for both the cold and warm conditions. Table 9 provides the estimated bearing offsets based upon the strain gauge alignment measurements and the finite element model analysis. The Figure 11 presents the measured shear and bending moment at the thrust shaft flange. Jack-up load tests were also conducted on the lineshaft bearings to provide an independent check of the strain gauge alignment model. Figure 12 presents the results, which indicate excellent agreement with the strain gauge alignment results. The strain gauge measurements indicated that the bearings were aligned to their prescribed vertical positions, and were straight-aligned athwartships to within 0.25 mm and to less than 30% of the vertical bearing load, which is considered acceptable. The bending moment and shear measured at the thrust shaft flange was within the acceptable range for both the cold and warm condition. The maximum lineshaft bending stress measured was 11 MPa, which is considerably lower than the maximum allowable stress of 41 MPa. The bearing temperatures and shafting vibrations were satisfactory throughout the sea trials, and since the vessel entered service in the spring of 2005. Figure 13 shows alignment measurements being taken.

Table 8 Bearing Loads: MV Jean Anne

Bearing	*Bearing Loads (kN)*				
	Measured				*Theoretical*
	Prior to Chocking (Cold)		*After Sea Trials (Warm)*		*Prescribed Loads (Warm)*
	Strain Gauge Method				
	Vertical	*Athwartships*	*Vertical*	*Athwartships*	*Vertical*
Aft Sterntube	208.4	-2.7	209.3	-1.8	203.1
Fwd Sterntube	49.3	12.9	42.9	7.1	52.2
Aft Int. Shaft	54.2	-14.2	65.0	-21.6	61.6
Fwd Int. Shaft	36.0	-4.4	19.7	0.8	22.0
	Jack-Up Load Method				
Aft Int. Shaft	54.0	NA	NA	NA	NA
Fwd Int. Shaft	36.0	NA	NA	NA	NA

Table 9 Bearing Offsets: MV Jean Anne

	Estimated Offset (mm)				*Prescribed Offset (mm) Cold Condition*	
	Cold Condition		*Warm Condition*			
	Vertical	*Athwartships*	*Vertical*	*Athwartships*	*Vertical*	*Athwartships*
Aft Sterntube	0.00	0.00	0.00	0.00	0.00	0.00
Fwd Sterntube	0.10	0.00	0.20	0.25	0.00	0.00
Aft Lineshaft	-0.75	-0.25	-0.75	-0.13	-0.75	0.00
Fwd Lineshaft	-1.00	0.00	-1.00	0.00	-1.00	0.00
Aft Most Engine	1.90	0.00	2.14	0.00	1.90	0.00

Table 10 Measured Shear and Bending Moment at Thrust Shaft Flange: MV Jean Anne

	Shear (kN)	*BM (kNm)*
Prescribed Cold	48	-33
Measured Cold	48	-50
Measured Warm	64	-32

Figure 11 Alignment Measurements on Lineshaft: MV Jean Anne

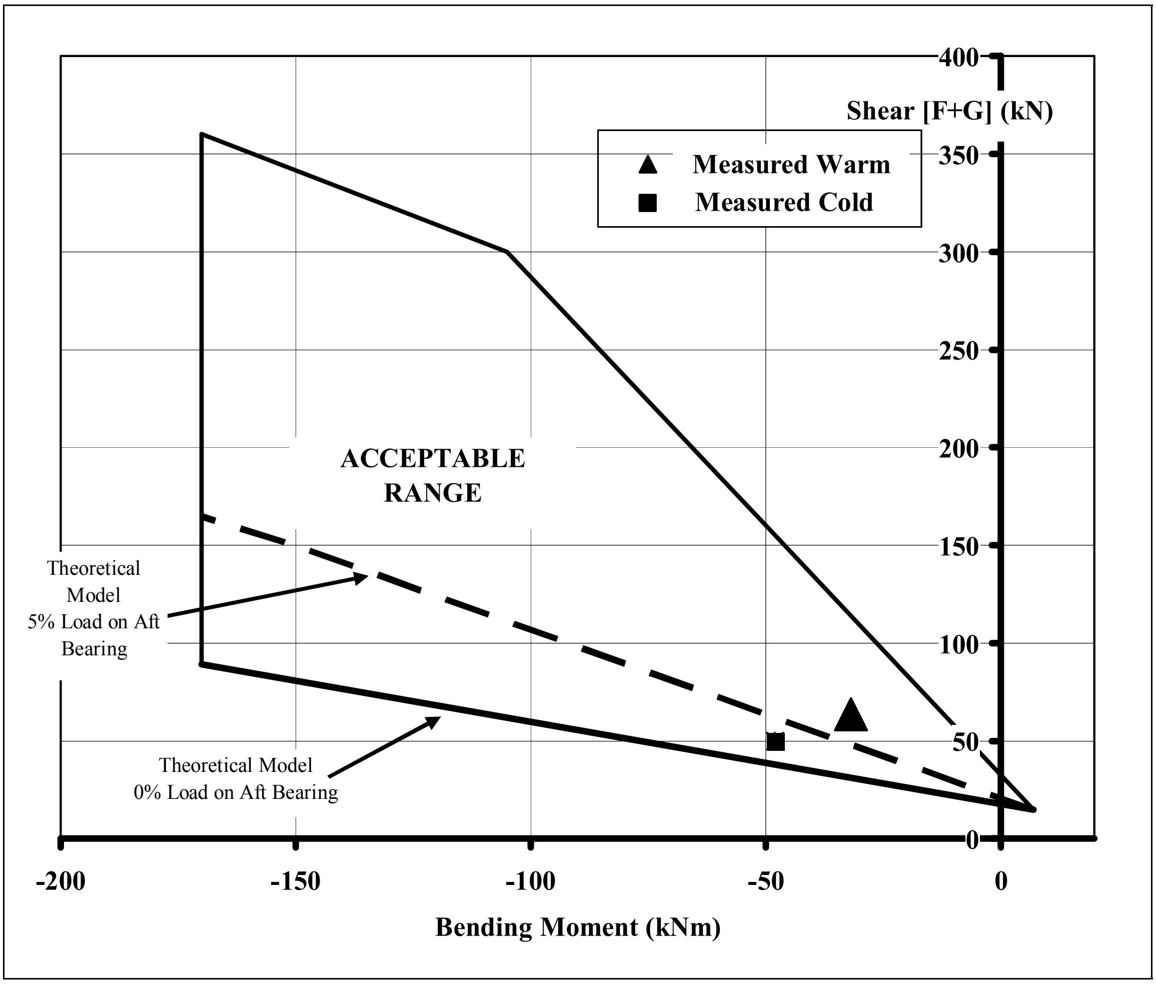

Figure 12 Thrust Shaft Flange Bending Moment and Shear: MV Jean Anne

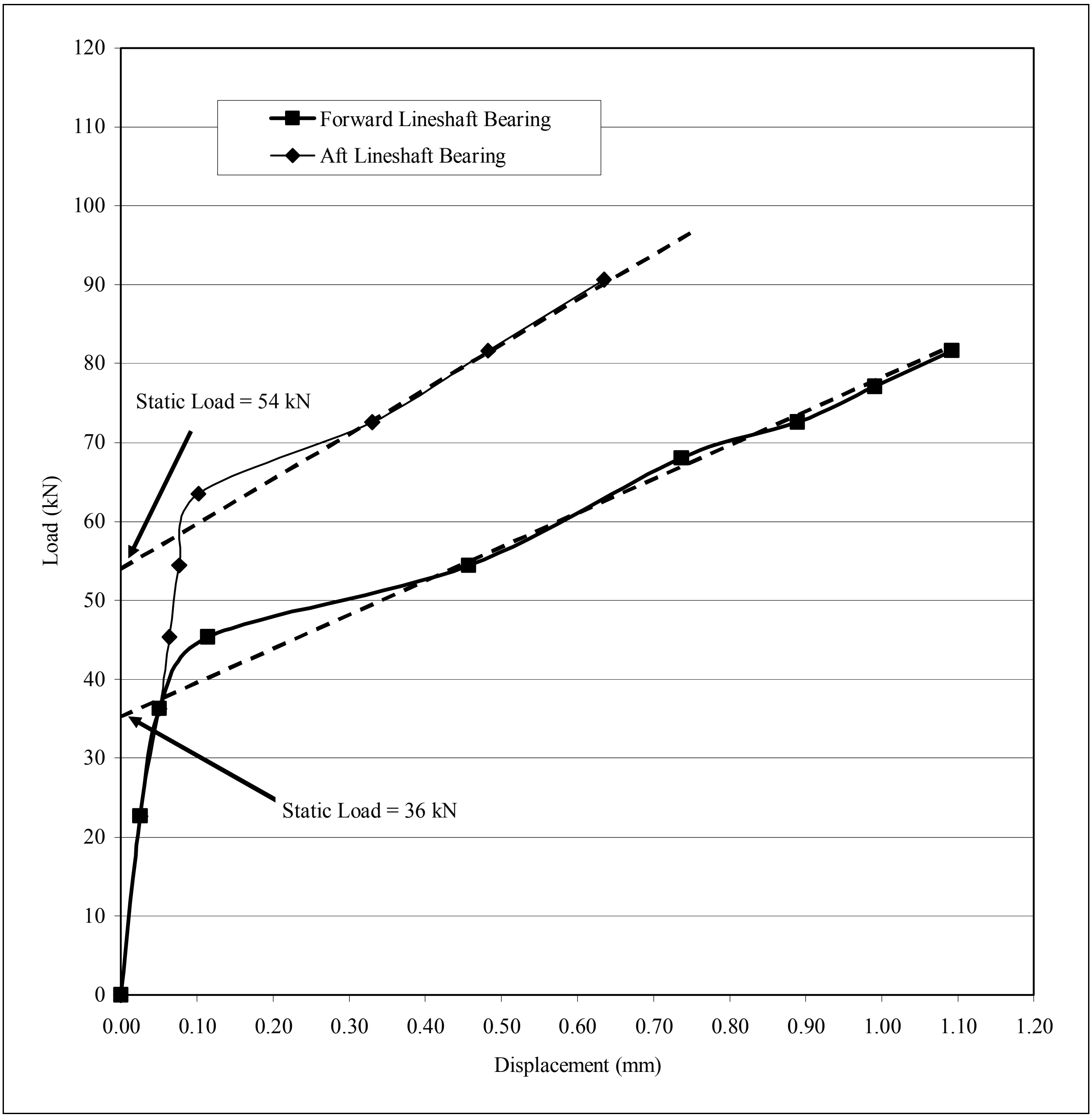

Figure 13 Jack-Up Load Tests Results on Lineshaft Bearings: MV Jean Anne
(Cold Condition – Prior to Chocking Engine and Lineshaft Bearings)

CONCLUSIONS

It is concluded that the strain gauge alignment technique is a reliable, accurate and cost effective method of alignment for slow-speed diesel shafting systems. The following additional conclusions were drawn from the work presented in this paper.

1. The vertical and athwartships loads on the lineshaft and sterntube bearings were obtained, with the shaft completely assembled, in less than 30 minutes.
2. Strain gauge measurements of the shear and bending moment at the thrust shaft flange agreed with the results from crankshaft web deflection.
3. Gap and sag measurements do not generally provide sufficient accuracy for final alignment of the main engine to the lineshaft.

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