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CASE EXAMPLE IN SYSTEMATIC DESIGN ENGINEERING – PROPELLER SHAFT BEARING ARRANGEMENT

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Keywords: design engineering, systematic method, case example

1. Introduction

The systematic and methodical design process followed in this case example illustrates the theoretical models usable for design engineering [Eder and Hosnedl 2008, 2010]. This process is only necessary in limited situations [Eder 2009a], but is best learned in a low-threat environment. *Systematic* design engineering is the heuristic-strategic use of a theory about technical products – Engineering Design Science [Eder and Hosnedl 2008, 2010], [Hubka and Eder 1996] is recommended on the basis of an extensive comparison [Eder 2012] – from which a recommended prescription of an engineering design process is derived. *Methodical* design engineering is the heuristic use of newly developed and established methods within the engineering design process, including theory-based and 'industry best practice', strategic and tactical, formalized and intuitive methods. Systematic and methodical procedures overlap, but are not co-incident. The full procedure should be learned, such that the practitioner can select appropriate parts for his/her current applications and design situation.

Creativity [Eder 1996] is usually characterized by a wide search for solutions, especially innovative ones, a search that can be supported by the recommended systematic and methodical approach. All generated alternatives should be kept on record, to allow re-tracing and recovery from subsequent detection or generation of a better alternative. Each step in the overall procedure need not and cannot be completed before starting the next, steps will overlap, iterative working is necessary [Eder 2010a]. New insights from a later step will often suggest improvements for a previous step. Nevertheless, each step should be concluded by selecting the most appropriate (one or two) solutions for further processing, in order to control a tendency towards 'combinatorial complexity'.

The first case example, systematic according to the state of the theory and method at that time, appeared in 1976 [Hubka 1976] – a machine vice. The second was published in 1980 [Hubka and Eder 1992] – a welding positioner. The next three, also systematic, were published in 1981 in German – a riveting fixture, a milling jig, and a powder-coating machine, the first two were systematic, the third took a more industrial-artistic design approach. Another set was published in 1983 – a P-V-T-experiment, a hand winding machine for tapes, and a tea brewing machine – again, the first two were systematic, the third took an industrial-artistic design approach. An English edition was published in 1988 [Hubka et al. 1988], and included the six case examples in these two sets, plus two new items – a wave-powered bilge pump, and an oil drain valve – and again the bilge pump only loosely followed the systematic method. Three further case studies were published in 2008 [Eder and Hosnedl 2008] – the tea machine revised to current procedures showing enhanced engineering information; re-design of a water valve [Eder 2006]; and an electro-static smoke gas dust precipitator, with rapper for dust removal [Eder 2009b]. Three more case examples were published in 2010 [Eder and Hosnedl 2010] – a trapeze demonstration rig [Eder 2010b], re-design of an automotive oil pump [Eder 2010c], and a hospital emergency bed, with compensation devices for the support arrangement. No other methodology known to the author offers any such formalized case examples.

The primary purpose of these case examples is to present examples for procedural application of the recommended engineering design method that students and practitioners can follow and study to help learn the scope of the method and its models. This purpose has been applied in courses at the Eidgenössische Technische Hochschule (ETH) by Dr. Vladimir Hubka (1976-2000, undergraduates), at The Royal Military College of Canada (1981-2006, undergraduates), and at the University of West Bohemia (1990-present, for all levels of university education and for industry consultations). A secondary purpose was to verify and validate the theory and its models, and the method derived from the theory. The emphasis in all case examples was on the engineering design procedure and use of the models, the chosen technical systems in several case studies were not necessarily optimal. Some of the case examples have resulted in manufactured technical systems that have found use in appropriate applications, especially the trapeze demonstration rig, and the example presented in this paper.

The systematic procedure must be adapted to the problem. The cases demonstrate that an engineering designer can idiosyncratically interpret the models to suit the problem, and develop information in consultation with a sponsor. Opinions will vary about whether a requirement should be stated in the class of properties as shown, or would be appropriate in a different class.

This case example is presented to show application of the recommended method, and the expected scope of the output, with emphasis on the stages of conceptualizing. The *embodying/laying out and detailing* stage is regarded as more routine.

The international standard ISO 9000:2005 defines two sorts of technological, artificial, human-made systems, (a) *process systems*, consisting of *operations* – transformation process (TrfP); and (b) *tangible object systems*, consisting of *constructional parts*, with organs and functions – technical systems (TS), if they have substantial engineering content.

The basic model on which the theory and method are based is the general model of a transformation system, TrfS, which declares:

An *operand* (materials, energy, information, and/or living things – M, E, I, L) in state Od1 is transformed into state Od2, using the active and reactive *effects* (in the form of materials, energy and/or information – M, E, I) exerted continuously, intermittently or instantaneously by the *operators* (human systems, technical systems, active and reactive environment, information systems, and management systems, as outputs from their internal processes), by applying a suitable technology Tg (which mediates the exchange of M, E, I between effects and operand), whereby assisting inputs are needed, and secondary inputs and outputs can occur for the operand and for the operators.

Using this model as basis, the stages and steps of a novel design process [Eder and Hosnedl 2008,2010 (Figure 11.1, pages 219-221)] are summarized as:

- *task defining*:

(P1) establish a design specification for the required system, a list of requirements;

(P2) establish a plan and time-line for design engineering;

- *conceptualizing*:

(P3a) from the desirable and required output (operand in state Od2), establish a suitable transformation process TrfP(s),

(P3.1.1) if needed, establish the appropriate input (operand in state Od1);

(P3.1.2) decide which operations in the TrfP(s) will be performed by technical systems, TS, alone or in cooperation with other operators; and which TS(s) (or parts) need to be designed;

(P3.1.3) establish a technology (structure, with alternatives) for that transformation operation, and therefore the effects (as outputs) needed from the technical system;

(P3b) establish what the technical system needs to be able to do (its internal and cross-boundary functions, with alternatives);

(P4) establish what organs (function-carriers in principle and their structure, with alternatives) can perform these functions. These organs are found in prior art, especially the machine elements, in a revised arrangement as proposed by Weber [Weber and Vajna 1997, Eder 2004,2005];

- *embodying/laying out and detailing*:

(P5a) establish what constructional parts and their arrangement are needed, in sketch-outline, in rough layout, with alternatives;
(P5b) establish what constructional parts are needed, in dimensional-definitive layout, with alternatives;
(P6) establish what constructional parts are needed, in detail and assembly drawings, with alternatives.

Only those parts of this engineering design process that are thought to be useful are employed. Such an 'idealized' procedure cannot be accomplished in a linear fashion, iterative and recursive working is essential [Eder 2010c]. The suffix '(s)' indicates that this TrfP and/or TS is the subject of interest.

PROCEDURAL NOTE*: Compare the output of each stage with the theoretical figures from [Eder and Hosnedl 2008, 2010] to check whether any important elements may be missing.*

2. Propeller shaft nearing arrangement

Founded in 1970, the Caravan Stage Company [Caravan] travelled in Canada and the U.S.A., entered a community with horse-drawn gipsy-style caravan carriages, pitched a large (24 *m* diameter) decorated tent in a park, and using the caravans in the tent as their scenery performed self-scripted plays. Around 1992 they decided to have a steel replica of a wooden River Thames (London, England) sailing barge designed and fabricated in a small dockyard in Kingston, Ontario, Canada. It took four years to complete, 30 *m* length, 7.2 *m* beam, 1.3 *m* draft, single mast, fore-and-aft rigged sails, 316 m^2 sail area, about 90 *tonne* displacement. All materials and OEM parts were donated to the Caravan Stage Company, about Cdn$ 2,000,000.00. The newly designed superstructure, mast and rigging were intended to double as the stage for performances, with the audience on shore. The stage barge was to be fully independent, with its own power supply (two diesel motors), lighting and amplification system, galley and sleeping accommodation, etc.

The author was initially contacted in 1994 by Paul Kirby, producer of the Caravan Stage Company, via the Head of Mechanical Engineering, The Royal Military College of Canada (RMC) to help by designing various needed items. The first among these (October 1994) was a thrust-bearing and shaft arrangement to connect each of the two diesel motors to the propeller shafts.

Steps from the procedural model [Eder and Hosnedl 2008, 2010] were considered, and the following review cycle was applied for each step:

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P1) Establish a list of requirements, a design specification – investigate alternatives

Requirements are listed only under the most relevant TrfP and/or TS-requirements class as judged by the engineering designer, and cross-referenced if they are repeated in any other relevant requirement class [Eder and Hosnedl 2010 (Figure 11.4, p. 226-227)]. Indication of priority – F ... fixed requirement, must be fulfilled; S ... strong wish; W ... wish; N ... not considered.

Rq1 OrgRq		Organization requirements (Rq1A – Rq1E)
	F	The project must be accomplished within the available funding.
	F	Coordination needed between Stage Barge Company and Mech. Eng. Department.
Rq2 TrfRq		Requirements of the Transformation (Rq2A – Rq2E)
	F	Process of assembling the propeller shaft thrust bearings to be done by Stage Barge personnel.
	F	Maintenance and adjustment to be done by Stage Barge personnel.
	F	Instructions for assembly and maintenance to be provided by the main engineering designer (W.E. Eder).
	F	Must resist saltwater (coastal ocean).
Rq3 EfRq		Effects requirements of the TS (Rq3A – Rq3C)
	F	Propulsion from Detroit Diesel 120 hp 6 cylinder motor: power maximum 89.5 *kW* (120 *hp*) at 2800 *rpm*, normal 78.3 *kW* (105 *hp*) at 2200 rpm; propeller thrust maximum 11.56 *kN* (*2599* lb) at 1143 *rpm*, normal 9.74 *kN* (2190 *lb*) at 898 *rpm* (90 % running time).
	F	Main bearings as supplied: SKF 29413E spherical roller thrust bearing, and SKF

21313EW spherical roller double-row self-aligning bearing, must be mounted with coincident spherical race centers, and at least 445 *N* (100 *lb*) radial force to avoid under-loading and possible roller sliding.

F Propeller shaft end and hub to conform to Society of Automotive Engineers standard SAE J755 (June 1980) for 57.15 mm (2¼ inch) diameter shaft.

F Oil lubrication must be provided for SKF roller bearings– added in step (P4).

Rq4 MfgRq Manufacturing requirements

S welded and mechanically assembled.

F Standard machine shop equipment, no special requirements.

Rq5 DiRq Distribution requirements

Rq6 LiqRq Liquidation requirements

Rq7 HuFRq Human factors requirements (Rq7A – Rq7G)

F Stage Barge actors/crew to handle.

F Safety of crew is essential.

Rq8 TSFRq Requirements of factors of other TS (in their TrfP) (Rq8A – Rq8G)

Rq9 EnvFRq Environment factors requirements, LC1 - LC7 (Rq9A – Rq9B)

Rq10 ISFRq Information system factors requirements, LC1 - LC7 (Rq10A – Rq10F)

Rq11 MgtFRq Management factors requirements

Rq11A Management planning, LC1

Rq11B F Management of design and manufacturing process, LC2 - LC4, by main engineering designer (W.E. Eder) in cooperation with Technical Officer (O. Koroluk)

Rq11C S Design documentation, LC2, kept by both Stage Barge and Mech. Eng. Department

Rq11D Situation, LC2

Rq11E Quality system.

Rq11F Information requirements

Rq11G Economic requirements

Rq11H F Must be completely manufactured and tested before mid-July 1995

Rq11J F Materials acquired from standard suppliers

Rq11K Organization

Rq11L Supply chain requirements

Rq11M Other management aspects

DesRq Engineering design requirements for TrfP(s) and TS(s) (Rq12 – Rq14)

None.

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P2) Establish a plan and time-line for design engineering

Aim for completed design documentation end of April 1995.

(P3a) Establish a suitable transformation process TrfP(s)

The first and last operations in figure 1 treat the propeller shaft thrust bearing as operand (answers to ‘what is done to the propeller shaft thrust bearing?’), the operand in second operation is the rotation motion and torque (power) delivered by the motor and transmitted to the propeller.

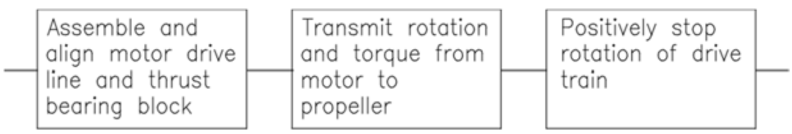

Figure 1. Transformation process (TrfP)

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P3.1.3) Establish technology Tg

Preferably, a kinematically correct thrust bearing mounting should be used, especially considering that the propeller shaft axis is (radially) located by two water-lubricated sliding bearings.

(P3b) Establish TS-internal and cross-boundary functions – with alternatives

In figure 2, the propeller shaft thrust bearing is now the technical system as operator (answers to 'what can the propeller shaft thrust bearing and its mount do?'). This results in the main TS-internal and cross-boundary functions.

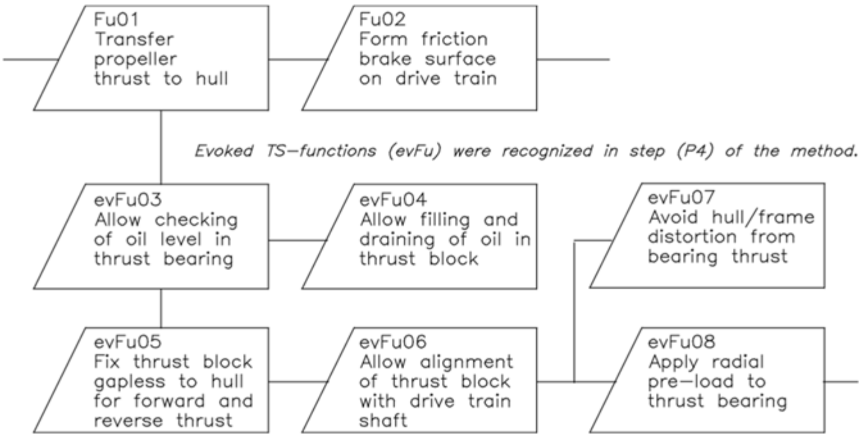

Figure 2. TS-Function structure (FuStr)

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P4) Establish organ structure – with alternatives

Figure 3 shows alternative ways of operating each of the solvable TS-functions, as numbered in figure 2 (answers to 'with what means-in-principle can the functions be realized?'). Because the requirements include the use of specific SKF roller bearings, several evoked functions (evFu) are now recognized as necessary, and shown in figure 3.

TS–Function	Action Principles and Organs			
1 Permit rotation 80 from vertical 1A React leeboard weight to hull	Sliding journal bearing	Self–aligning (spherical) roller bearing (2–row)		Reinforced hole in hull chain plate (hull; leeboard and pin)
2 Permit articulation +2.5 to – 3.5 2A Lay leeboard on hull side	Sliding spherical bearing			
3 Permit pin sliding 3A Damp shock from water	Axial sliding journal bearing	(empty)		
4 Retract pin to 25 mm position	Cable con–necting two leeboards	Cable and weight for each leeboard	Helical spring	Belleville disk springs in series

Figure 3. Morphological matrix

Combining the means from figure 3 in suitable ways should allow exploring the TS in a skeleton (organ structure) form, evaluating the alternatives, and selecting the most promising. In this case, it seems preferable to select the best organ from each line of the morphological matrix, and combine them in a suitable way. No formal selection method was used. This procedure permits a direct entry into the next step, (P5a).

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P5a) Establish constructional structure in rough layout – with alternatives

Drawings of the proposed hull arrangement at the propeller shaft thrust bearing location, see figure 4, and the diagram of donated items (machine elements), figure 5, were provided by the Caravan Stage Company. These acted as preliminary layouts for this case. The propeller shaft mounting is unusual, two journal bearings in the hull locate the axis, the thrust bearing must therefore align with this pre-determined axis.

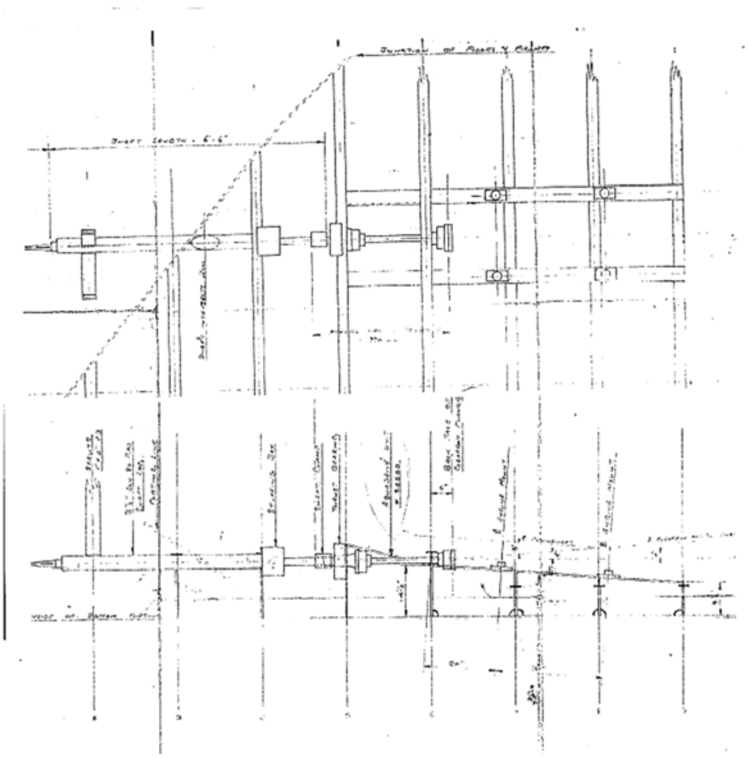

Figure 4. Hull and propeller shaft general arrangement

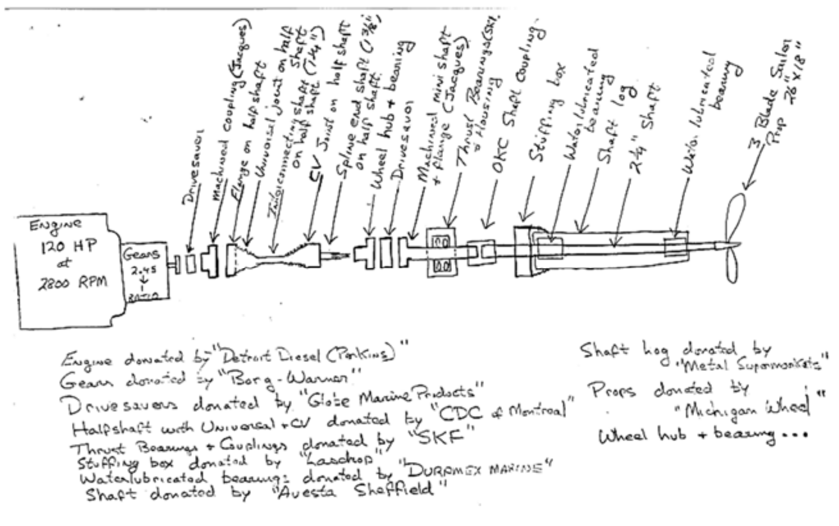

Figure 5. Donated machine elements for propeller shaft

Some investigations of sizes allowed the designer to sketch the preliminary layout in figure 6.

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P5b) Establish constructional structure in dimensional-definitive layout – with alternatives

The dimensional layout of figure 7 was produced.

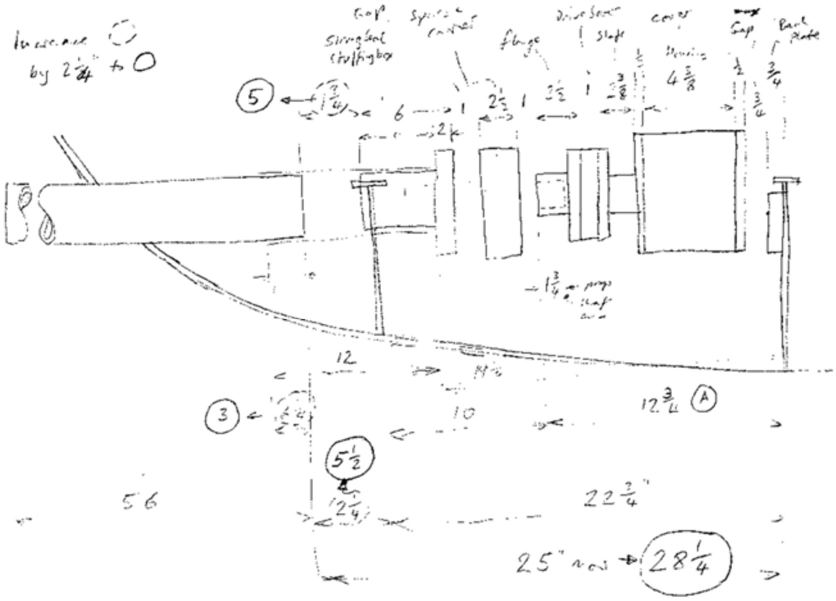

Figure 6. Preliminary layout of propeller shaft arrangement

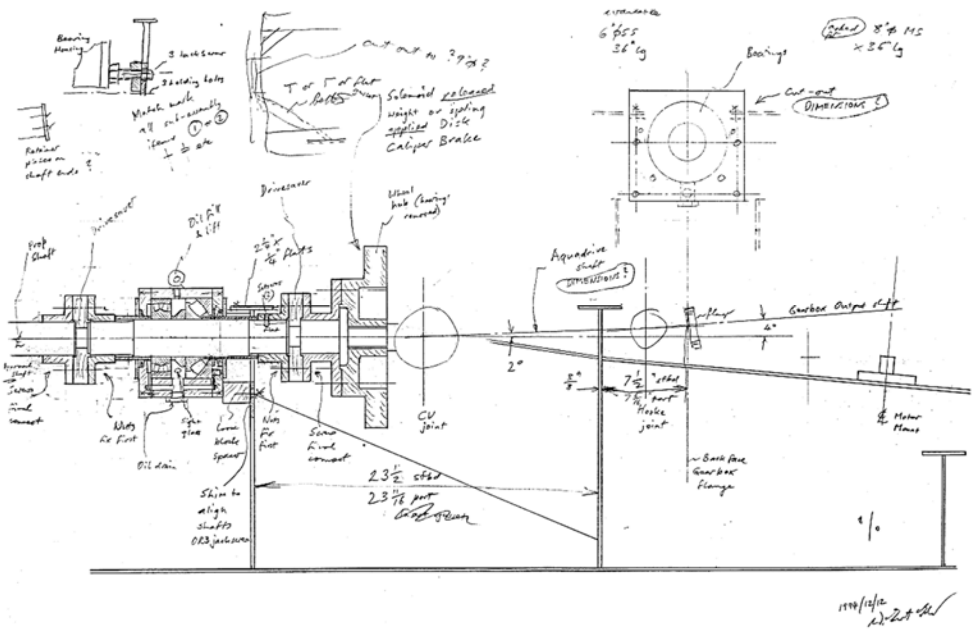

Figure 7. Layout of propeller shaft thrust bearing mounting

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

(P6) Establish constructional structure in detail and assembly drawings – with alternatives

Detail drawings were prepared. Even though computer graphics were available, these drawings were prepared by hand with pencil on paper – a repeat use for this project was not anticipated. figure 8 shows the main housing for the thrust bearing arrangement. The designer decided to rely on the two felt oil-seal rings to ensure alignment of the bearing housing with the shaft. figure 9 shows the modifications needed for the hull frame to accommodate the jackscrew and clamp rod fittings to ensure kinematically correct abutment for forward thrust, and good reaction for reverse thrust with minimal 'play'.

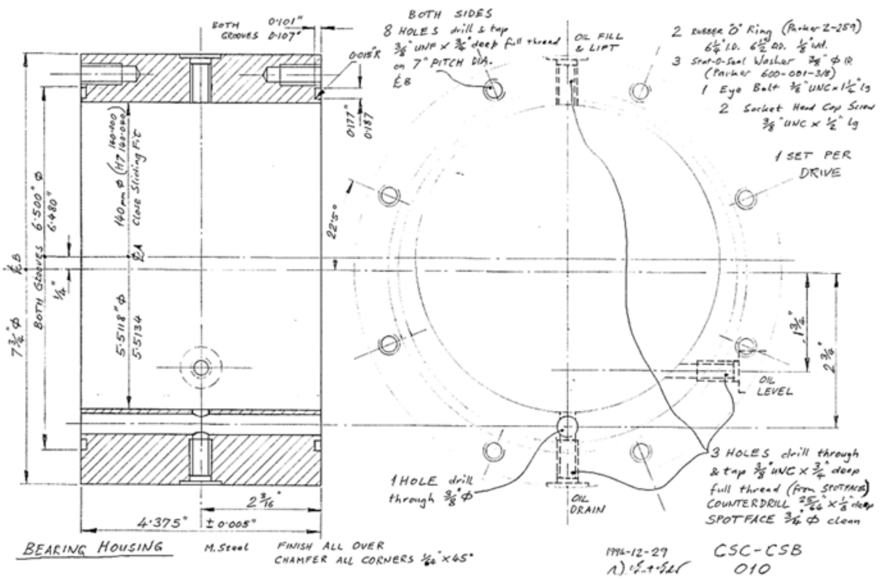

Figure 8. Propeller shaft thrust bearing housing

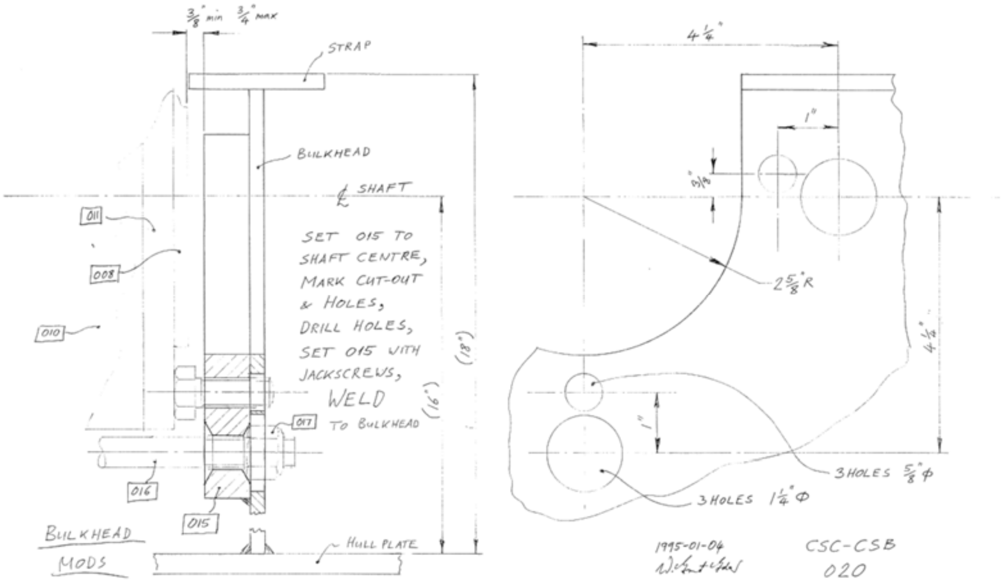

Figure 9. Hull frame modifications

All drawings and manufactured parts were supplied to the Caravan Stage Company, together with a complete listing of these drawings, a parts list, and full instructions for assembly and adjustment. Sections of this document are shown in figure 10.

{Improve, optimize} <Substantiate, evaluate, select, decide> {Verify, check, reflect}

3. Closure

The launch of this stage barge was successful. After a short time of operation, the barge was brought back to Kingston, one of the thrust bearings had failed. It seems that a marine inspector would only

Caravan Stage Company – Caravan Stage Barge

Drive Shaft and Thrust Bearing Arrangements

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Royal Military College of Canada, Kingston, Ontario, Canada K7K 5L0
1995-01-05; *REVISION A*: 1995-04-28 {marked as ----(A)}

Documents supplied by Caravan Stage Company – Caravan Stage Barge – Paul Kirby
Engine Installation, dated 25/4/94, scale 1"=1', drawn by J.A. Dearden
Schematic sketch of drive train with list of donated items, undated
FAX (2) from SKF, Chris Ozolins, (1) re selection data and recommendations of thrust bearings, dated Jun 21 '94 10:45 (7 pages); (2) re fits for supplied bearings, dated 30/6/94

List of drawings – CSC-CSB: 17 sheets 11"x17" ---- (A)

001	General layout	1/4 scale dimensional investigation
002	Gear Box Adapter	
003	Brake Hub Adapter	
004	Shaft Flange	
005	Flange. Retainer	sheet also contains 006

...

PARTS LIST – numbers for ONE drive train – need TWO in Stage Barge ---- (A)

Drg# No.		*Name & Sizes*
001		no details
002	1	Gear Box Adapter
	10	Hex socket head cap screw 3/8" UNF x 1" lg
	4	Lockwasher 3/8"
	4	Hex nut 3/8" UNF
003	1	Brake Hub Adapter
	8	Hex nut 1/2" UNF

...

Assembly Instructions:

use *general layout and assembly 001* as guide – some changes have been made for detail drawings

Sub-Assembly Thrust Bearing: – **CLEAN ASSEMBLY AREA IS ESSENTIAL**

soak *felt seals 018 & 019* (4 rings) in lubricating oil

...

mount and fit *sub-assembly thrust bearing* by drive flange on shaft (reverse/stern end of sub-assembly), using hex-head bolts and lockwashers, and brass washers (between drivesaver and flange face) supplied with drivesaver

align *spacer 015* with shaft and *sub-assembly thrust bearing* on stern side of thrust bulkhead, mark location of spacer, and of holes according to *bulkhead modification 020*

remove *sub-assembly thrust bearing*, drill bulkhead, weld *spacer 015* onto bulkhead, cut out bulkhead opening to suit inner profile of *spacer 015*

weld *bulkhead strap bracing 021*

screw 3 hex head bolts into *spacer 015* from stern side

re-mount and fit *sub-assembly thrust bearing* by drive flange on shaft (reverse/stem end of sub-assembly), using hex-head bolts and lockwashers supplied with drivesaver

adjust gap from *spacer 015* to *seal cover 008* according to *bulkhead modification 020* – 3/8" preferred minimum

lift *sub-assenibly thrust bearing* by ring bolt, upward force should be 150 to 200 lb

adjust all 3 hex head bolts in *spacer 015* to lightly touch *thrust cover 011*

mount *retainer 014* on reverse (stern) face of *sub-assembly thrust bearing*

insert all 3 *clamp rod 016* through *retainer 014* and *spacer 015*, fit *clamp nut 017* both ends of each *clamp rod 016*, and tighten nuts evenly

Final Assembly:

mount and fit *sub-assembly motor shaft* to bow end of *sub-assembly thrust bearing*, using hex-head bolts and

...

Figure 10. Drive shaft and thrust bearing arrangement – documentation

allow the Stage Barge to be operated, if each thrust bearing block was encased in a standing bearing housing bolted to the ship floor – this was ordered without reference to the engineering designer (the author), negating the lateral pre-load and kinematic abutment, and in one case the correct alignment of bearing housing with the shaft was disturbed. The felt-ring oil seal was destroyed, the shaft partly worn by metal-to-metal contact, oil was lost, and the bearing failed. A new bearing housing and shaft were made, the 'standard bearing housing' removed, and the Stage Barge sent on its way again – the author has heard of no further difficulties. Moral: standard solutions are usually tested by time, but novel solutions may be improvements and need to be allowed to succeed when they can be justified. The Company has since then toured the Great Lakes, and the Atlantic and Pacific coasts of the U.S.A. and Canada. It is currently touring in Europe and the Mediterranian regions [Caravan].

This case example demonstrates that a systematic and methodical engineering design process can be usefully applied, especially if the designer's situation demands risk or safety operation [Eder 2009a]. Systematic design engineering allows a wide search for alternative solutions, and is potentially a good tool for engineering education.

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