2nd-order ship hull vibrations and balancing

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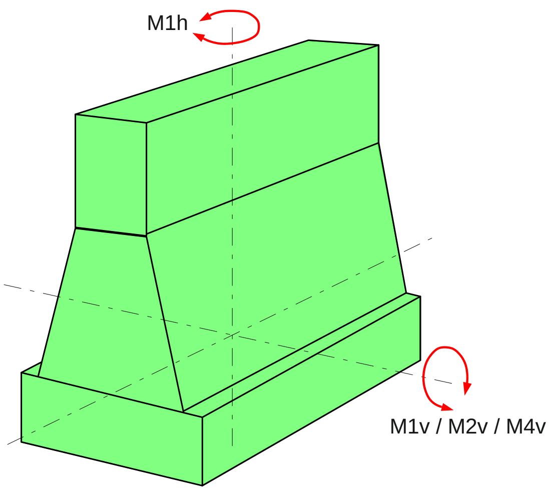
1 Introduction

As any structure, a ship is a mass-elastic system with various natural frequencies and mode shapes. These natural hull girder frequencies depend on the mass distribution and the stiffness of the hull structure as well as on the draft of the ship. Ship hull resonances occur if the frequency of an excitation is equal to one of the natural hull girder frequencies. In general, the main excitation sources for ship hull vibrations are:

- Main engine(s)
  In most ships, the primary vibration excitation source is the main engine or engines
- Propeller(s)
  Propellers contribute excitation frequencies of the first and second blade frequency (4th and 8th orders in case of four-bladed propellers)

Normally, auxiliary engines do not transmit significant excitations to the ship hull because they are mounted on elastic elements which decouple the engine excitations from the hull.

Vibration excitations of 2-stroke engines of various frequencies are caused by the reciprocating and rotating masses of the running gear, and the gas forces of the combustion process. Engine speed, crankshaft web design and the reciprocating masses determine the magnitude of free external mass forces and moments. Engines with more than four cylinders and a regular crank sequence have no relevant free external mass forces, only free external mass moments as shown in Figure 1.



M1v : free external 1st order vertical mass moment
M2v : free external 2nd order vertical mass moment
M4v : free external 4th order vertical mass moment
M1h : free external 1st order horizontal mass moment

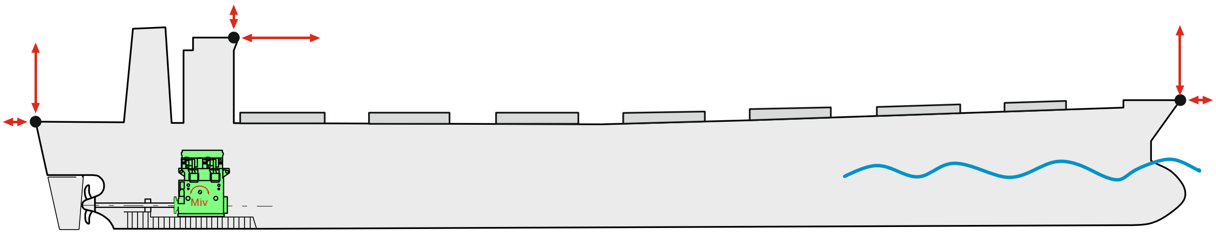
Figure 1: Free external mass moments

Typically, only 4-, 5- and 6-cylinder engines have free external mass moments of significant magnitude. For these engines, an external vertical 2nd-order mass moment (M_{2V}) can lead to disturbing hull vibrations under some conditions.

On 4-cylinder engines, the external horizontal 1st -order mass moment (M_{1H}) and the vertical 1st -order mass moment (M_{1V}) may also lead to disturbing hull vibration.

In rare cases, 4th -order vertical mass moment (M_{4V}) is a problem, exclusively with 7-cylinder engines. In a resonance condition, the vertical mass moments lead to strong vibration in the vertical direction at the stern and bow of the ship and in the longitudinal direction on top of the superstructure.

The horizontal mass moments lead to horizontal vibrations at the stern and bow of the ship (see Figure 2). Since the stiffness of the hull in the horizontal direction is considerably higher than in the vertical direction, horizontal hull vibrations are seldom a problem, except on ships with 4-cylinder engines.



Vertical hull girder vibrations due to M1v / M2v / M4v

Horizontal hull girder vibrations due to M1h

Figure 2: Ship hull response to external mass moments

2 Requirement for 2nd-order balancing

For ships with 4-, 5- and 6-cylinder engines, 2nd-order balancing is a solution where 2nd-order vibrations may be a problem. 2nd-order balancers can prevent potential build-up of disturbing hull girder vibrations due to excitation by a free external 2nd-order vertical mass moment (M_{2V}). For safe operation, the engine itself does not require any 2nd-order moment balancing. 2nd order mass moments do not result in harmful or disturbing engine vibrations. However, the free external vertical mass moment (M_{2V}) produced by the engine can excite hull vibrations if the moment's magnitude is sufficient and if the hull structure has a vibration resonance within the engine's operating speed range. Since complex investigation is required during ship design to predict the effects of M_{2V} on the hull, precautionary 2nd-order balancers are installed on many ships based on the magnitude of M_{2V} for a given engine.

The requirement of 2nd-order moment balancing depends on several parameters such as:

- Magnitude of M_{2V}
- Mass of the ship
- Load condition of the ship
- Natural vertical hull girder frequencies of 1st to 4th modes (2 to 5 nodes) for ballast and full draft conditions
- Engine speeds corresponding to critical frequencies of the 2nd-order resonances
- Position of the nodes of the natural vertical hull girder frequencies with respect to the engine
- Response of the hull to the M_{2V} excitation

2.1 Magnitude of M_{2V}

The nominal value of M_{2V} at Contracted Maximum Continuous Rating (CMCR) engine speed is given by the engine design. It alone is not sufficient to judge if 2nd-order moment balancing is required. The size, mass and load condition of the ship are other important factors.

2.2 Load condition of the ship

Natural frequencies and the resonance level depend very much on the load condition of the ship. Typically, 2nd-order hull vibrations are only a problem in ballast condition. In fully loaded condition, required excitation amplitudes are bigger due to the higher mass and damping effect of a greater draft. As the total mass of the ship increases, a higher M_{2V} is required to excite excessive hull vibration.

2.3 Natural vertical hull girder frequencies

The natural vertical hull girder frequencies and mode shapes depend on the ship type, design and load condition. In Figure 3, typical natural vertical hull girder frequencies and mode shapes of a 30000 DWT Bulk Carrier are shown.

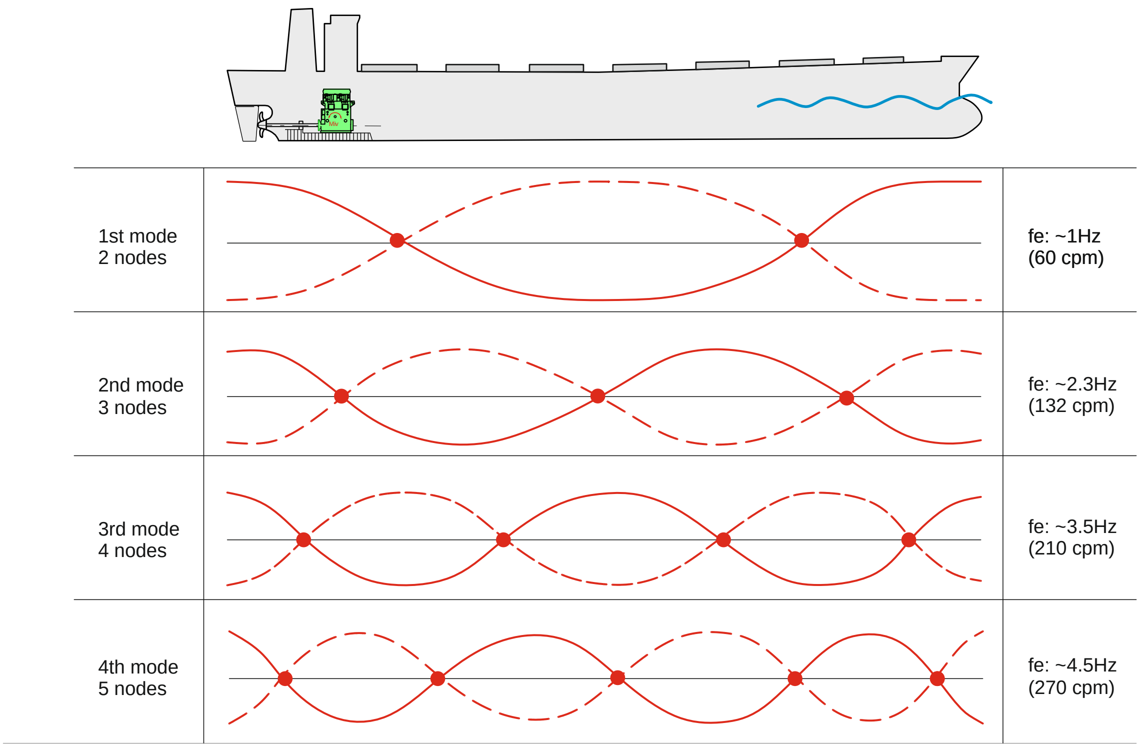


Figure 3: Vertical natural hull girder frequencies

2.4 Critical speeds of the 2nd-order resonances

The critical engine speed range of 2nd-order hull resonances is very narrow, typically only about 2-3 rpm. A hull resonance can only build up to its full level if the engine remains at the resonant speed for some time. Changing the engine speed by ±2 rpm will stop the resonance.

2nd-order resonances below approximately 80% CMCR speed normally do not cause problems, since the engine is only operated at fixed manoeuvring speeds in this speed range. Provided a resonance is not exactly at one of the manoeuvring speeds, a 2nd-order hull resonance cannot build up because the engine passes between the manoeuvring speeds too quickly. Additionally, the magnitude of M_{2V} is proportional to the square of engine speed and is thus less relevant at lower engine speeds (e.g. at 50% CMCR speed M_{2V} is only 25% of the value at CMCR).

Usually, M_{2V} balancing must only be considered if both of the following conditions are met:

- 2nd-order critical resonance is expected in the speed range 80-105% CMCR speed
- Position of the engine with respect to the node of the relevant mode is unfavourable (see section 2.5)

It is also possible to stop resonance by changing the engine speed by ±2 rpm, but this may not be possible for operational reasons (see Figure 4).

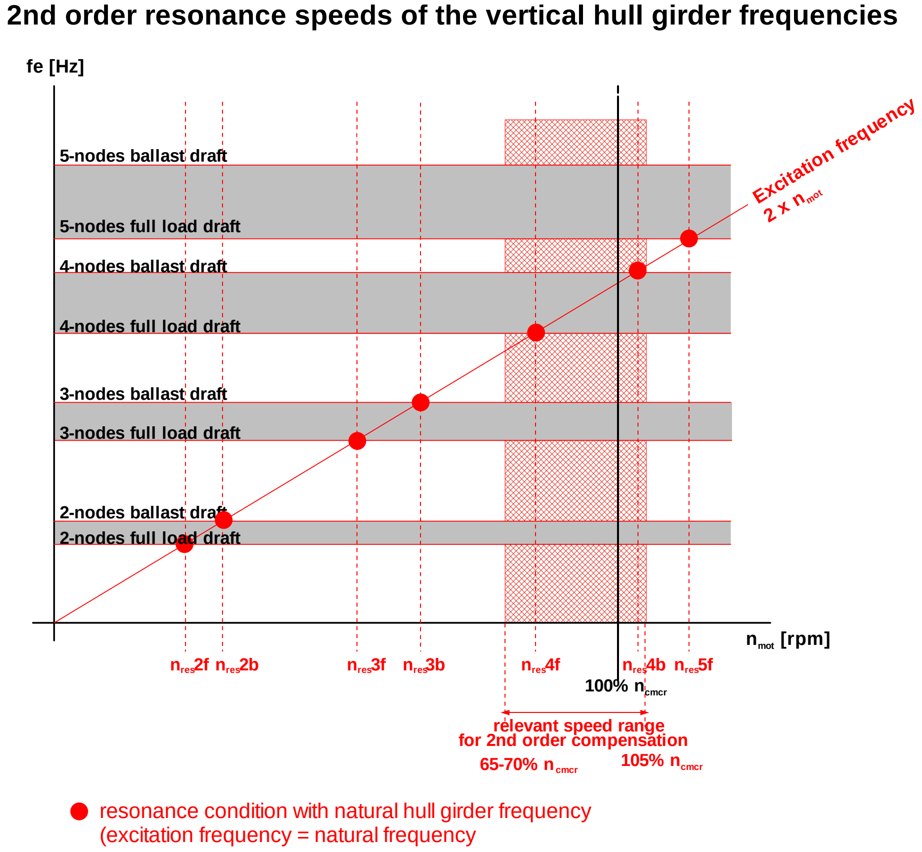


Figure 4: 2nd-order resonance speeds

2.5 Position of the engine with respect to the node of the relevant mode shape

Even if the calculation of the natural vertical hull girder frequencies shows possible 2nd-order resonances in the speed range 80-105% CMCR, it does not necessarily mean excessive hull vibration will occur. The final magnitude of 2nd-order resonances depends on the position of the engine relative to the nodes of the mode shape of the relevant resonant frequency. If the relevant node of the natural vertical hull girder frequency is on the vertical axis of the engine centre of gravity, M_{2V} has the most impact on the ship hull vibrations (see Figure 5). Similarly, the iELBA compensating forces (F_{2V}) will have the most influence.

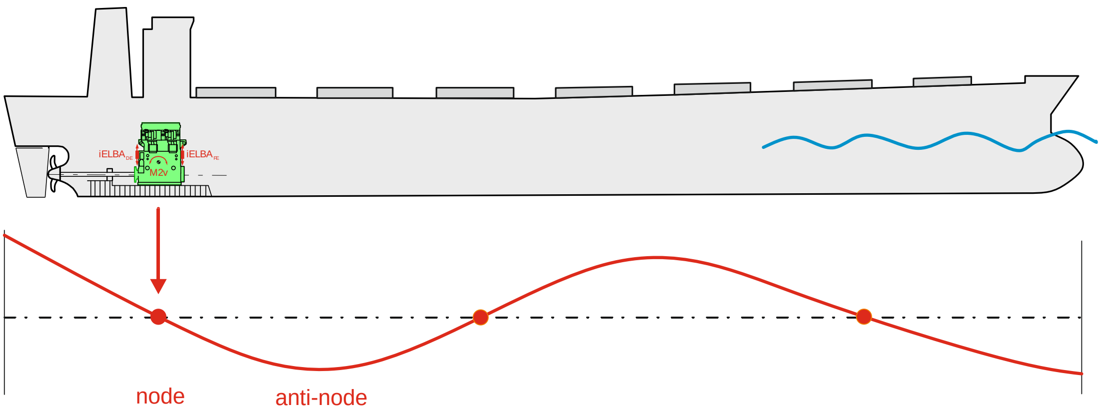


Figure 5: Maximum effect of M_{2V} with iELBAs fitted at both ends of the engine

In contrast, if the engine is located at the anti-node of the relevant mode shape (as is often the case on container ships), the effect of M_{2V} and iELBA are very small. In such cases even a high M_{2V} will not cause disturbing 2nd-order ship hull vibrations and 2nd-order vibration balancing is not required (see Figure 6).

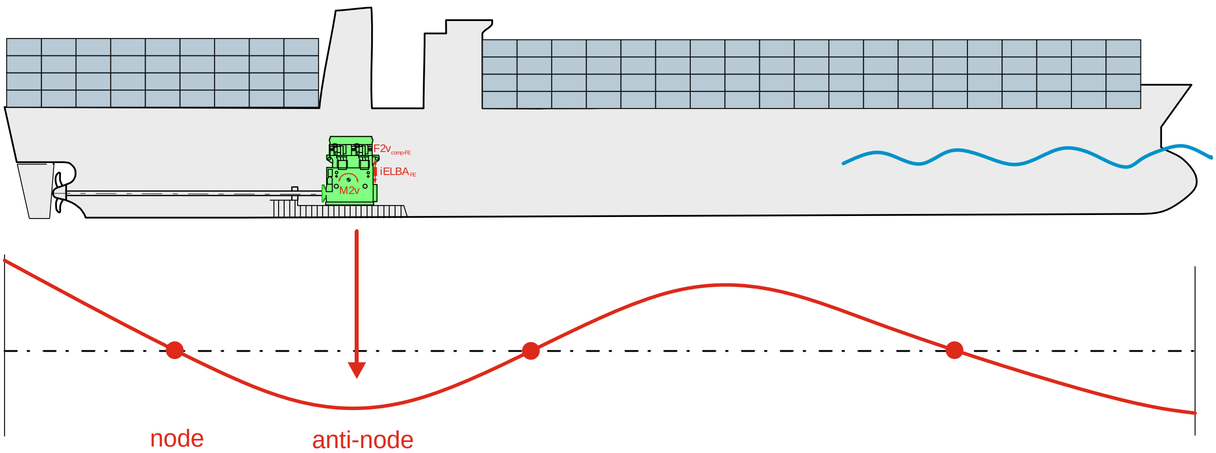


Figure 6: Minimum effect of M_{2V} with iELBAs fitted at both ends of the engine

2.6 Contribution of iELBA to the 2nd -order balancing

The effectiveness of each iELBA is heavily influenced by the distance of the iELBA compensating forces (F_{2V}) to the relevant node. If the node is on the vertical axis of the engine centre of gravity, both iELBAs contribute equally to the balancing (see Figure 7).

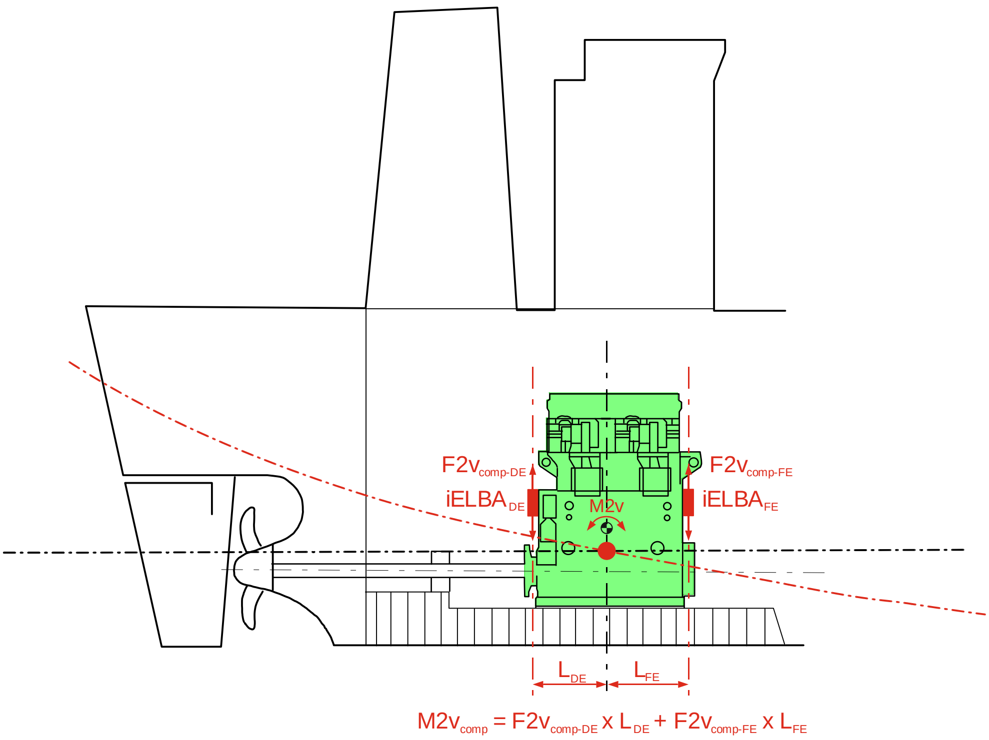


Figure 7: Node in the centre of the engine

If the node is at the vertical position of either iELBA, the vertical dynamic 2nd-order force of that iELBA has no effect. In such cases, the other iELBA performs the only effective balancing (see Figure 8).

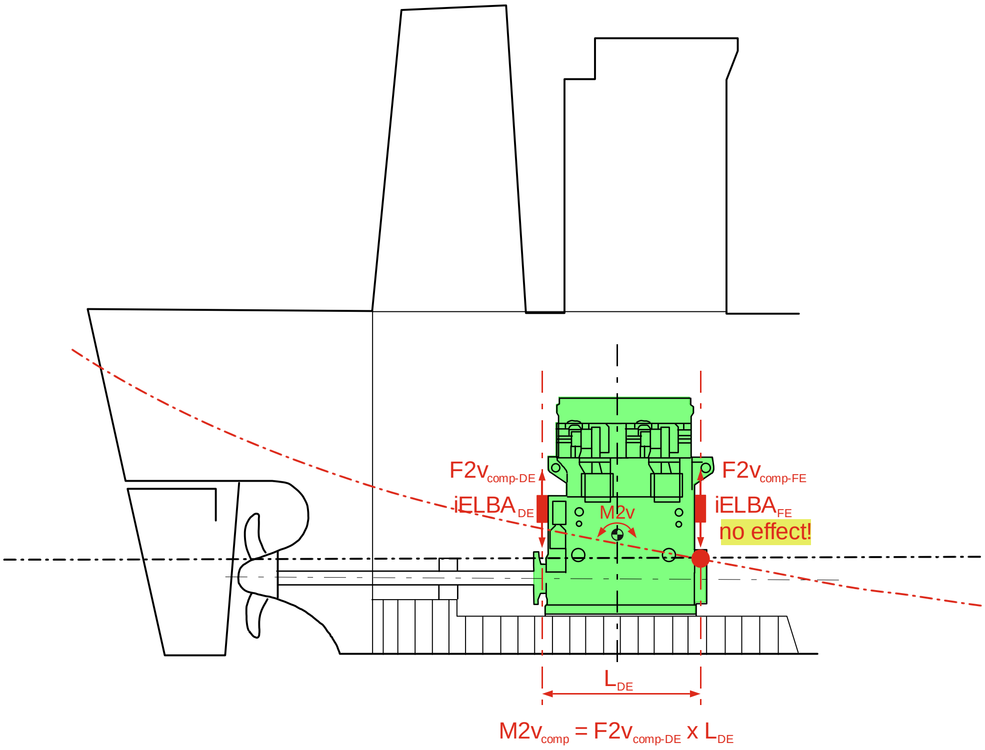


Figure 8: Vibration node at the iELBA position on the free end

2.7 Application of a single iELBA

In some cases it is not possible to fit an iELBA on both sides due to space restrictions (e.g. turbocharger and scavenge air cooler positioned at the engine driving end). In such cases it is possible to apply a single iELBA, however, the exact mode shape of the natural vertical hull girder frequencies (i.e. the position of the relevant node) must be known for both ballast and fully loaded conditions. A single iELBA only has an effect if it is at sufficient distance to the node of the relevant mode shape (i.e. the iELBA and engine centre of gravity must be on the same side of the node). Therefore, a comprehensive finite element calculation of the hull is required, which must be performed by the shipyard. Correct phasing of a single iELBA must be set based on hull vibration measurements taken during sea trials.

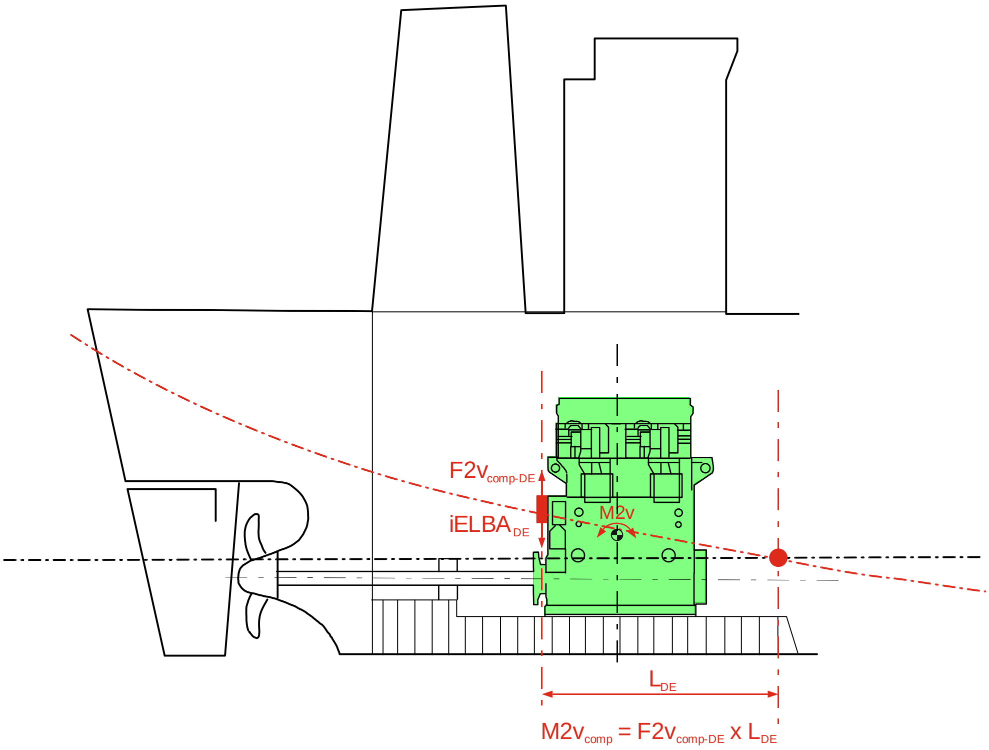


Figure 9: Application of a single iELBA (example of an aft-end only installation)

2.7.1 The adverse effect of a single iELBA

If a single iELBA is close to an anti-node of a relevant mode shape, , the iELBA itself can excite 2nd-order hull girder vibrations. In this position, relatively low vertical excitation energy is required to excite the natural hull frequency.

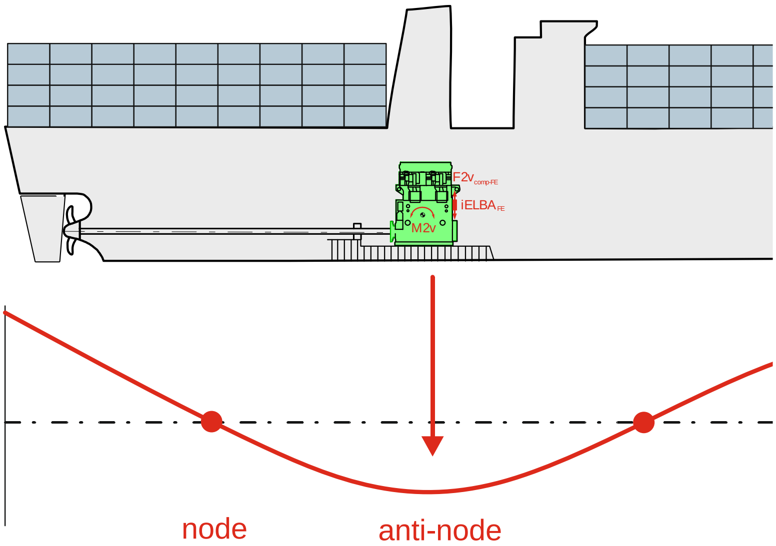


Figure 10: The adverse effect of a single iELBA

2.8 Additional forces from iELBA

Due to the large iELBA masses rotating in the vertical plane, iELBA will produce minor 4th -order vertical force. This must also be considered during the ship design process.

2.9 Externally-fitted 2nd -order balancers

If iELBA is only possible on one end of the engine and the finite element study shows that it is too close to the relevant node (or if the finite element study is not completed), the application of an external 2nd -order balancer is recommended (see Figure 11). Such balancers are usually placed in the aft section of the ship in the steering gear room. The balancer size depends on the magnitude of M_{2V} and the distance between the balancer and the nodal point (see Figure 12). Typically, this position has a much larger distance to the relevant node. The effectiveness of such balancers is usually much higher than iELBA due to the longer effective lever of the compensating force. As a result, a much smaller device with lower compensating forces is required.

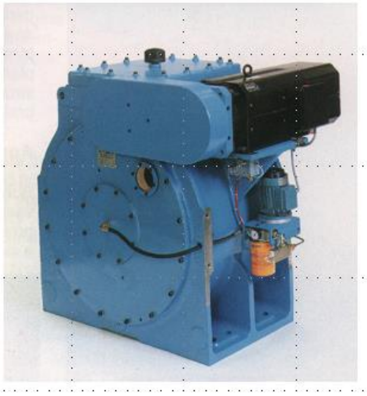


Figure 11: Externally-fitted electrically-driven balancer

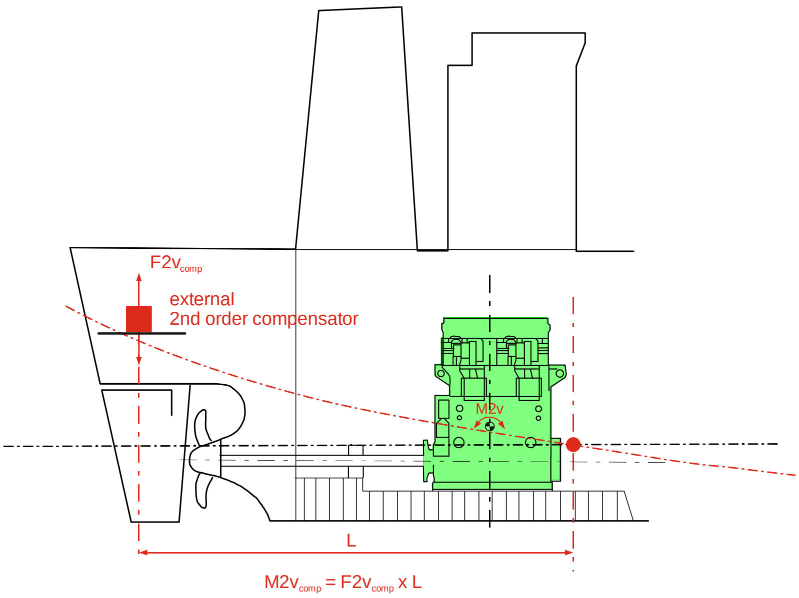


Figure 12: Externally-fitted balancer at the aft end of the ship

In general, it is sufficient to balance approximately two-thirds of the magnitude of M_{2V}. An externally-fitted 2nd -order balancer offers the following advantages:

- The compensating force required is much smaller than with iELBA due to the longer effective lever between the balancer and nodal point
- The balancer forces do not load the engine structure

2.10 Response of the ship hull to the excitation M_{2V}

The necessity of 2nd -order balancing should be investigated during the design stage of the ship by finite element calculation of the ship hull. Such investigations are normal practice for shipyards, design institutes, and classification societies. However, some shipyards cannot accurately predict the position of the mode shapes and node positions of relevant natural hull girder frequencies. Furthermore, the natural frequencies and their mode shapes are influenced by the load (draft) condition of the ship. For these reasons, it has been common practice to apply iELBA at both ends of the engine. Typically, in such cases no adverse 2nd -order vibration occurs when one or both iELBAs are switched off due to a favourable position of the relevant node. Nevertheless, iELBA at both ends of the engine results in the maximum possible 2nd -order balancing, independent of the position of the relevant node with respect to the engine. Especially in the case of new ship designs, shipyards can also check the natural vertical hull girder frequencies by running an exciter test prior to sea trials to verify whether balancing of 2nd -order vibration is required.

2.11 Power related unbalance

WinGD's published Power Related Unbalance (PRU) values are the ratio of the free external mass moments to the engine power (see Figure 13). PRU values must be considered as a very rough guide for estimating the severity of free external mass moments and the likelihood of a requirement to balance them. The indicated PRU limits of 60 Nm/kW and 120 Nm/kW are based on long-term experience and consider the relationship between engine power and ship size. Higher engine power is broadly an indication of a bigger ship with higher total mass, requiring higher excitation force to create disturbing hull vibrations.

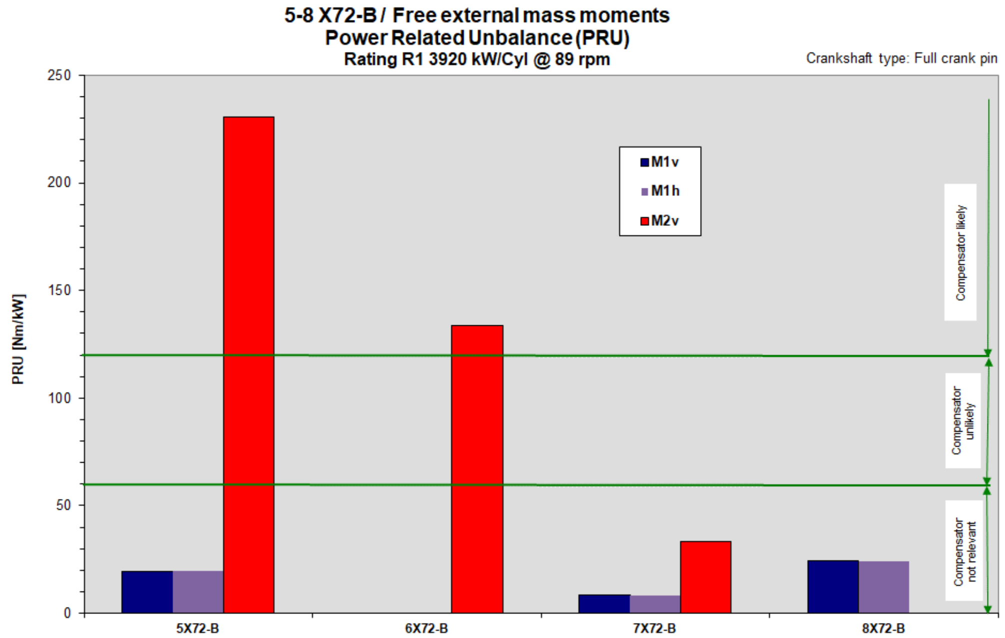


Figure 13: Graphically displayed PRU values

3 Summary

- 2^{nd} -order balancers (iELBA or off-engine) can mitigate 2^{nd} -order hull girder vibrations
- The engine itself does not require 2^{nd} -order balancing for safe, long-term operation
- PRU values provided in WinGD's documentation can be used as a rough guideline to judge if 2^{nd} -order balancing is required
- The requirement for 2^{nd} -order balancing depends on the magnitude of M_{2V}, the location of the engine with respect to the mode shape of a particular natural hull girder frequency, the location of the resonance speed and the load condition of the ship
- A 2^{nd} -order balancer is in general only required if a disturbing 2^{nd} -order hull resonance occurs between ~80 – 105 % CMCR engine speed.
- The decision to apply a 2^{nd} -order balancer should be based on a finite element calculation of the entire ship hull, especially if only one iELBA is to be applied
- It is the shipyard's responsibility to decide whether to apply 2^{nd} -order balancing